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RESEARCH

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Strength, Environmental Impact and Cost Assessment of Alkali-Activated Concrete with Pre-treated Coarse Recycled Aggregates

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Abstract
Alkali-activated concrete (AAC) has been extensively developed to reduce the environmental impact caused by ordinary Portland cement (OPC), when used in plain cement concrete (PCC). This study supports sustainable construction and a global effort to reduce environmental impact and implement eco-friendly AAC through the effective use of industrial wastes (such as ground-granulated blast furnace slag and fly ash). In this work, natural coarse aggregates (NCA) are gradually substituted with coarse recycled aggregates (CRAs) and pre-treated coarse recycled aggregates (PCRAs). AAC, with a characteristic compressive strength of 40 MPa, was designed, cast, cured and tested (such as ultrasonic pulse velocity, strength, embodied energy (EE), CO_2 emission and cost analysis) of AAC and PCC incorporating various coarse aggregates were investigated and presented to establish the suitability. The results indicate that 100% CRAs in AAC achieved a compressive strength of 41.33 MPa, with a substantial reduction in EE consumption by 70% and a 62% reduction in CO_2 emission when compared to PCC cast with 100% CRA. The analysis clearly indicates that the OPC in PCC remains the major contributor towards both EE and CO_2 emission. On the contrary, the binding activators, used in AAC, contribute relatively lesser EE and CO_2 emission. Analysis revealed that AAC is 1.8–2 times costlier than the comparable PCC mixtures. The AAC mixtures with 100% PCRAs achieved 90% of the strength of those specimens with 100% NCA. The use of PCRAs in place of NCAs has resulted in substantial cost reduction.

Keywords Alkali-activated concrete, Plain cement concrete, Embodied energy, CO_2 emission, Pre-treated coarse recycled aggregates, Cost analysis

1 Introduction

The rapid growth of urbanization and industrialization in emerging countries has preceded a substantial upsurge in construction and demolition waste (CDW). In India alone, the volume of CDW reached over 150 million tonnes in 2020, with less than 1% being effectively recycled or reused (Roychowdhury et al., 2020). For instance, Singapore, Japan, Australia and the Netherlands have recycling rates for CDW of over 90%. At the same time, China has a recycling rate of over 50% for CDW (Zhang et al., 2023). Conventional waste management practices, such as landfilling, strain the environment by requiring additional land space and contribute significantly to carbon emissions (Colangelo & Cioffi, 2017). However, a large portion of CDW comprises reusable materials like natural stone, brick, and scrap concrete, presenting an opportunity for sustainable reuse. One promising approach is to use CDW as coarse recycled aggregates

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(CRAs) in concrete mixtures, allowing for the partial or complete replacement of natural coarse aggregates (NCA) (Ahmad et al., 2024). This method reduces environmental burdens and aligns with the growing emphasis on sustainability in civil engineering (Khan et al., 2023; Silva et al., 2021; Valencia-Saavedra et al., 2021; Wang et al., 2021).

Plain cement concrete (PCC) is one of the most widely used materials worldwide (Shen et al., 2015). However, the PCC sector faces two significant difficulties. The production of ordinary Portland cement (OPC) releases a substantial quantity of carbon dioxide (CO_2) into the atmosphere, and natural resources are used in the process. OPC accounts for over 5% of human-caused CO_2 emissions and approximately 14% of global industrial energy consumption (Thwe et al., 2021). The manufacturing process of OPC, particularly the calcination of limestone, results in significant energy consumption (Adamu et al., 2024; Shen et al., 2015). The manufacturing of OPC results in a considerable amount of embodied energy (EE) consumption, leading to CO_2 emissions ranging from 0.82 to 1.0 metric tonnes per tonne of OPC (Tayeh et al., 2022). In light of the significant annual consumption of OPC and its substantial EE, researchers have initiated investigations into alternative, ecologically sustainable materials to mitigate CO_2 emission (Lu et al., 2018).

Blended cement, which combines OPC with alternative binding materials (ABMs) like ground granulated blast furnace slag (GGBFS), metakaolin, silica fume and fly ash (FA), has emerged as a viable solution to reduce the environmental footprint of traditional cement. These ABMs are often by-products of other industrial processes; thus, their use reduces landfill waste and lowers CO_2 emission. Studies suggest incorporating blended cement can reduce CO_2 emission by approximately 13–22% (Arora et al., 2019; Ikramullah Khan et al., 2020; Khan et al., 2021).

Alkali-activated concrete (AAC) has garnered significant attention in the quest for even more sustainable construction materials. AAC utilizes industrial by-products and various waste materials to develop green concrete, which has a reduced environmental impact (EI) compared to conventional PCC. This has been demonstrated in several studies (Niş & Altundal, 2023; Rafeet et al., 2019). Researchers have explored several aluminosilicate materials, such as industrial by-products and agricultural wastes, to generate activated binders. These materials vary in availability, reactivity, costs, and CO_2 emission (Azevedo et al., 2020; Jurado-Contreras et al., 2022). Furthermore, because of their positive influence on the environment, several researchers have proposed alkali-activated binders (AABs) as an alternative to OPC because of their commendable mechanical qualities and long-lasting performance (Çevik et al., 2018; Jurado-Contreras et al., 2022; Manjunatha et al., 2021; Mohamed et al., 2022).

Numerous studies have been conducted on using CRAs in PCC manufacturing (Ibrahim et al., 2023; Sasanipour & Aslani, 2020). For example, Mesgari et al. (Mesgari et al., 2020) demonstrated that the PCC with CRAs had acceptable mechanical characteristics. It was shown that the strength decreased as the amount of CRAs in PCC increased. According to Poon et al. (Kou & Poon, 2015), the mix with 60% CRAs was the best for making PCC, and the slump loss of PCC was unaffected by the higher CRAs concentration. Nevertheless, there are several issues with the characteristics of concrete made with CRAs, including significant porosity, cracking, and poor durability (Abbas et al., 2009; Fathifazl et al., 2010; Juan & Gutiérrez, 2009). The adhered mortar (AM) on the surface of CRAs significantly impacts their quality. The interfacial transition zone (ITZ) inside the concrete microstructure may be weakened by this AM's microcracks and porous nature (González-Fonteboa et al., 2011; Kim et al., 2018; Kumar, 2017).

To overcome these obstacles, several pre-treatment techniques for CRA have been investigated. The CRAs have been subjected to abrasive action by ball milling (Kim et al., 2018), heating and then rubbing (Shima et al., 2005), and ultrasonic cleaning (Katz, 2004) to remove the weak AM attached to CRAs. In surface pre-treatment methods, the CRA's properties were improved by coating them with a mixture of FA, SF, and PC. According to the test findings, coating RCA with PCC and PC-SF slurry enhanced the ITZ (Sasanipour et al., 2021). Intense acid treatments and high-temperature procedures, such as H_2SO_4, HCl and increased temperatures between 250 and 300 °C, have been investigated in previous investigations as ways to treat CRAs (Ismail & Ramli, 2013; Katz, 2004; Purushothaman et al., 2015; Sui & Mueller, 2012). Although these techniques have successfully improved the CR's morphological characteristics, they are notoriously expensive and environmentally harmful.

Furthermore, the impregnation of pre-treated CRAs (PCRAs) (i.e., silane-surface modification-based CRAs) with concrete shows potential for improving the freeze–thaw, permeability and strength characteristics compared to unprocessed CRAs (Ahmad et al., 2024). The use of CRAs with AAB shows potential for improving the engineering properties, which typically decrease as the replacement rate of CRAs increases compared to PCC (Mesgari et al., 2020; Nuaklong et al., 2018; Tammam et al., 2023). The use of PCRAs (i.e., CRCFS-15000 chemical pre-treatment with 0.1 M solution followed by 5 min mechanical pre-treatment with abrasion) with

AAB shows potential for improving the durability and mechanical properties compared to unprocessed CRAs (Khan et al., 2023, 2024, 2025).

Despite the potential of AAC, there are still significant gaps in the current research. At the same time, several studies have examined the EI, such as EE and CO_2 emission of AAC and PCC (Tempest et al., 2009; Turner & Collins, 2013). Life cycle assessment (LCA) is a methodological methodology used to assess the EI of a material during its entire lifespan (Salas et al., 2018). The decrease in CO_2 emission of AAC compared to PCC is estimated to be between 26 and 45% (Habert et al., 2011). AAC's CO_2 emission are estimated to be between 26 and 45% lower than those of the PCC (Habert et al., 2010, 2011), with some studies showing an 80% reduction in CO_2 emission compared to the PCC (Duxson et al., 2007a, 2007b). The decline in intensity can be attributed to various variables, such as the transportation of raw materials, manufacturing procedures, and the type of materials employed. Although AAC is an eco-friendlier substitute for PCC, more research is needed to compare sustainable binder formulations (i.e., individual effect of FA, GGBFS and combined effect of both) and the impact of various aggregates, i.e., (NCA, CRAs and PCRAs) for different compressive strengths with their PCC counterparts.

This study also aims to achieve the Sustainable Development Goals (SDGs) stated by the United Nations (Goals & Report, 2023.https:, , unstats.un.org, sdgs, report, 2023, . 2023). SDGs 12 (responsible consumption and production) is in line with the use of dissipate materials (like slag) and CDW in the production of AAC because it encourages sustainable resource use, waste reduction, and the incorporation of industrial by-products in the production of cement-free concrete. AAC's smaller carbon footprint, which results from its lower CO_2 emissions than regular PCC, also supports efforts to combat climate change, which aligns with SDGs 13 (climate action). AAC's high-strength performances and potential for use in demanding engineering applications support sustainable infrastructure development and innovation in sustainable building materials, which align with SDGs 7 (industry, innovation, and infrastructure) and SDGs 9 (affordable and clean energy).

2 Research Scope

For the chosen AAC and PCC mixtures with a characteristic compressive strength of 40 MPa, different aggregate options namely NCAs, CRAs, PCRAs; FA, GGBFS, air-entraining admixture (AEA), superplasticiser, OPC, NaOH, Na_2SiO_3 were being considered. Also, a detailed Environmental Impact Assessment (EIA) was being carried out for all the combinations of AAC and PCC. This research provides valuable insights into the potential for creating AAC with reduced EI. The findings of this study contribute to the development of more sustainable concrete solutions, maximizing resource efficiency, minimizing carbon footprints, and enhancing long-term financial viability in construction practices. This work advances the field of sustainable construction materials and offers practical solutions for reducing the EI of the construction industry.

3 Experimental Materials and Methods

3.1 Materials

This section provides a detailed description of the materials used in the study. The study used OPC 53 grade, which complies with the Indian Standard Code IS: 269–2015 (Bhawan et al., 2015; IS, 2015). OPC was selected for its widespread use in construction and its known properties, which serve as a baseline for comparison with alternative materials. The specific gravity of the OPC was 3.14, indicating its density relative to water. The Blain's surface area, a measure of the fineness of the cement particles, was recorded at 295 m^2/kg. Fineness is critical as it influences the rate of hydration and the strength development of the cement. The soundness of the cement, which measures its volumetric stability, was 0.6 mm, ensuring minimal expansion after setting. FA and GGBFS were employed as supplementary cementitious materials in the AAC mixtures. FA was classified as Class F, conforming to ASTM C618 standards (Astm C618–19, Standard Specification for Coal Fly Ash & Raw or Calcined Natural Pozzolan for Use, Annu., 2019). It was sourced from the Ramagundam Thermal Power Plant in Telangana. Class F FA, derived from burning bituminous coal, is low in calcium and has pozzolanic properties, making it suitable for enhancing the durability of concrete. The specific gravity of FA was 2.04, and its fineness was measured at 327 m^2/kg, indicating its particle size distribution, which impacts the reactivity and overall performance of the concrete. The GGBFS, obtained from Astrra Chemicals in Chennai, is a byproduct of iron manufacturing and was selected for its latent hydraulic properties, which contribute to the long-term strength of AAC. The specific gravity of GGBFS was 2.85, and its fineness was 390 m^2/kg. The higher fineness of GGBFS compared to FA indicates a greater surface area for chemical reactions, which can enhance the strength and durability of the AAC. The chemical constituents of OPC, FA and GGBFS are shown in Table 1. An APEROS high-resolution FESEM was used to conduct SEM analyses to observe the surface morphologies of FA and GGBFS. Fig. 1 displays SEM images of the FA and GGBFS. The SEM images demonstrate the spherical and symmetrical shape of the FA particles. The GGBFS particles exhibit an asymmetrical grain structure, primarily angular.

Table 1 Constituents of FA and GGBFS

Constituents (%)	OPC	FA	GGBFS
MgO	3.95	0.7	7.73
Al_2O_3	5.01	31.4	16.81
SiO_2	3.95	48.81	33.06
CaO	60.76	3.80	35.37
Fe_2O_3	4.46	7.85	0.58
LOI	–	3	0.26

The alkali activators used in the synthesis of AAC were NaOH and Na_2SiO_3. These chemicals are crucial in initiating the geopolymerization process, which binds the aluminosilicate materials in the AAC mix. NaOH pellets and Na_2SiO_3 solution were acquired from M/s Amrutha Organics, Hyderabad. The Na_2SiO_3 solution comprised approximately 9.4% Na_2O, 30.1% SiO_2, and 60.5% H_2O, providing the necessary silica content for the reaction. The activator solution was prepared by first dissolving NaOH in water and then adding Na_2SiO_3 to achieve the desired modulus (Ms = 1.25). This modulus was selected based on literature (Khan et al., 2023, 2024), ensuring a balance between workability and the strength of the AAC. The solution was homogenized and stored in a sealed container for 24 h before use, ensuring consistency in the chemical reactions during mixing.

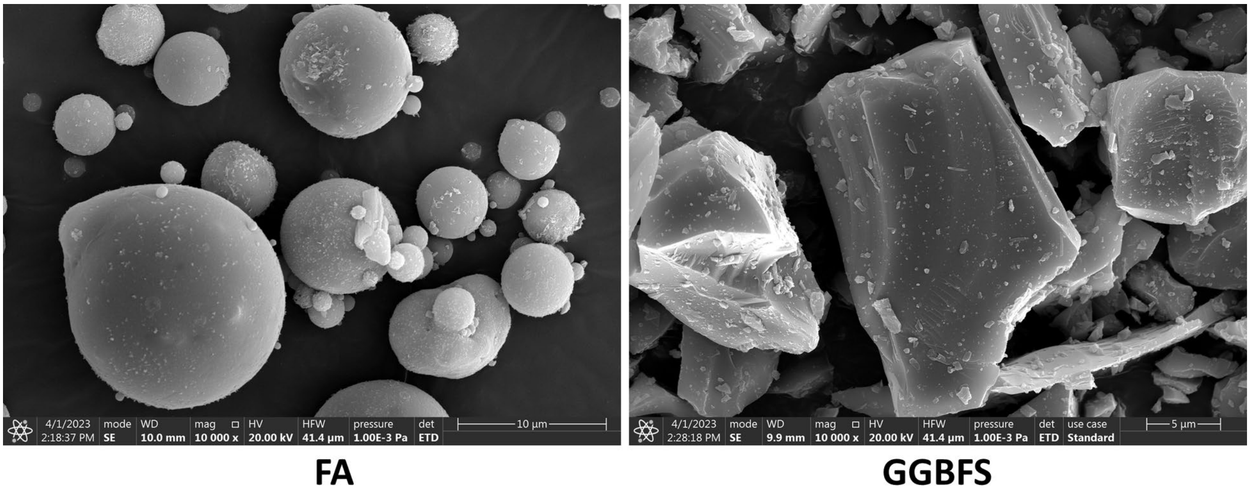
The study used a combination of NCA, CRAs, and PCRAs as the primary aggregates in the AAC mix. CRAs were supplied by M/s Re Sustainability Limited, Nagole recycling plant. The higher water absorption indicates the presence of adhered mortar, which can affect the mix design and performance of the concrete. The river sand (RS) and NCA of maximum particle size 4.75 mm and 20 mm, respectively, used in this study were obtained from the local vendor (IS, 1963). Following the method by Khan et al. (Khan et al., 2023), PCRAs were prepared by pre-treating CRAs with a 0.1 M acidic solution (i.e., chemical pre-treatment), followed by a short mechanical pre-treatment (i.e., 5 min abrasion with 12 balls). The same acidic solution was reused 20 times for pre-treating CRAs. This process aimed to remove weak mortar adhering to the recycled aggregates, improving their performance in the AAC mix. The properties of RS, NCA, CRAs and PCRAs are shown in Table 2.

The angular shape of NCA contributes to the mechanical interlock within the concrete matrix, enhancing its compressive strength. The AAC mixtures were prepared using tap water and carefully selected to meet the purity standards specified in IS 456 (IS, 2000).

To enhance the performance of AAC, the study employed an air-entraining admixture (AEA) and a superplasticizer (Bakharev et al., 2003; Khan et al., 2024). MASTERAIR 721 was used as the air-entraining agent, known to improve workability and durability by introducing tiny air bubbles into the concrete. The chemical composition of AEA includes a pH of 6, a relative density

Table 2 Properties of RS, NA, CRAs and PCRAs

Properties	RS	NCA	CRAs	PCRAS
Water absorption (%)	1	0.26	4.67	0.87
Specific gravity	2.56	2.67	2.34	2.62
Los Angeles test (%)	-	21	38	34
Crushing test (%)	-	21	33	23
Impact test (%)	-	22	35	23
Bulk density (kg/m^3)	1618	1543	1263	1537



FA

GGBFS

Fig. 1 SEM images of FA and GGBFS

of 1.020, and a chloride ion content of less than 0.2%. This admixture appears as a pink free-flowing liquid and was chosen for its ability to improve freeze–thaw resistance, particularly in AAC mixtures with varying aggregate types. Armix HyyeCrete PC 30(M), conforming to IS 9103 (IS9103, 2020), was used as the superplasticizer to reduce water content while maintaining workability. This admixture was crucial for achieving the desired flow characteristics in the AAC mixtures, especially when using low-quality aggregates like CRAs and PRCAs.

3.2 Mix Design Proportion of AAC

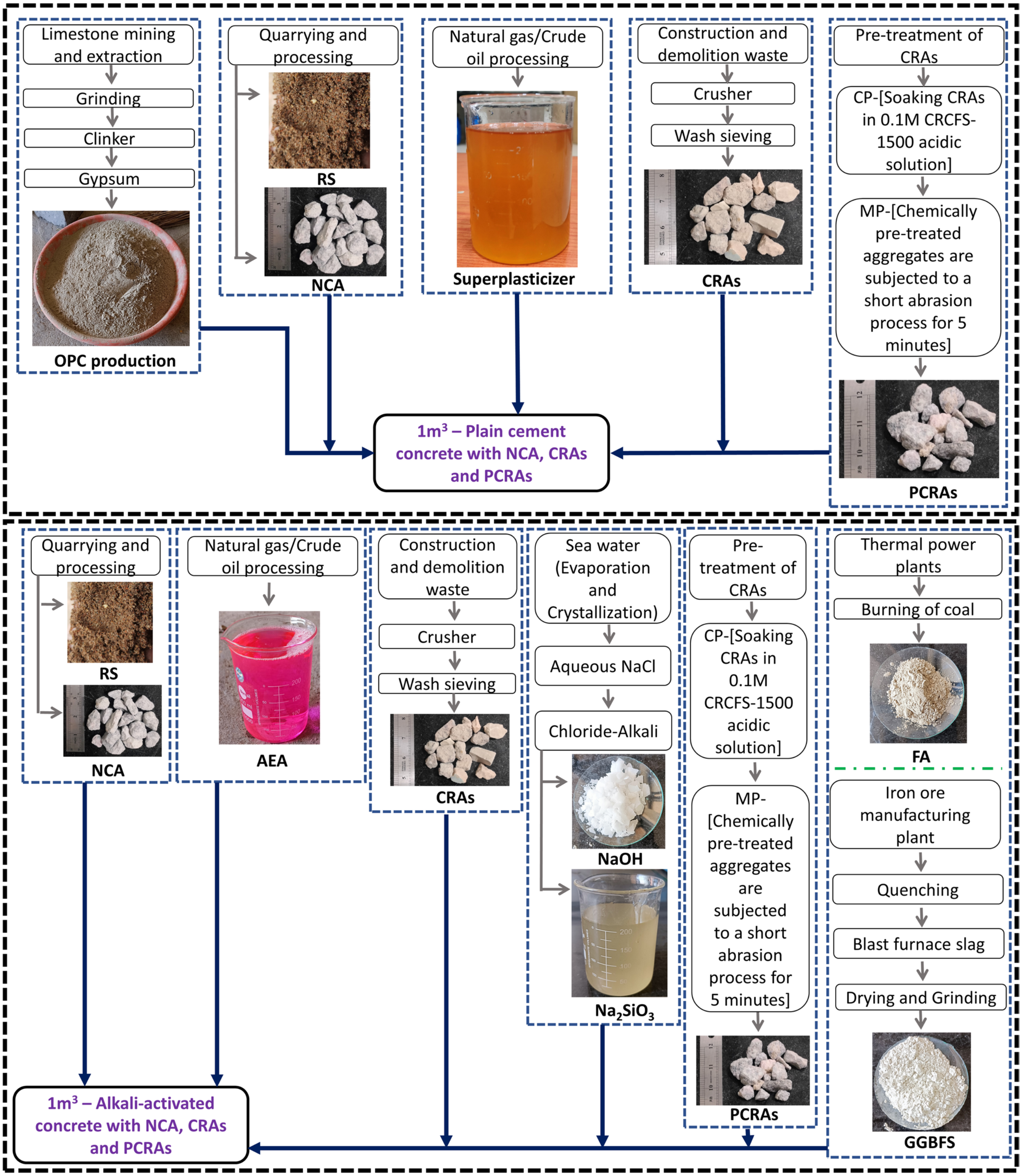
A comprehensive experimental study was conducted to optimize the mix design of AAC, with a focus on balancing the ratios of FA and GGBFS to achieve enhanced compressive strength. The pilot study was conducted at BITS Pilani (Hyderabad Campus), involved systematically varying the weight percentages of FA to GGBFS, explicitly testing the ratios of 100:0, 80:20, 60:40, 40:60, 20:80, and 0:100. The primary objective was to determine the ideal mix ratio that yields the highest compressive strength while ensuring material efficiency and cost-effectiveness. The specimens were subjected to ambient curing conditions immediately after demoulding, with compressive strength testing conducted at 28 days. This curing approach was selected to simulate real-world conditions where AAC utilized without the aid of accelerated curing methods. The results show that a ratio of 60:40 for FA and GGBFS provided the most promising compressive strength values, indicating an optimal balance between the pozzolanic reaction of FA and the cementitious properties of GGBFS. As a result, this ratio FA:GGBFS::60:40 was adopted for the entire project. The PCC mix design was formulated based on the guidelines of IS 10262 (I., 2019), maintaining a consistent water–binder ratio of 0.36 and incorporating an admixture content of 0.9 kg/m^3. The objective was to create a high-strength concrete mix that could serve as a baseline for comparison with AAC. The mix proportions are presented in Table 3. Several concrete mixtures were prepared using NCA, CRAs, and PCRAs to evaluate the effect of these aggregates on the mechanical properties of both PCC and ACC. A total of 60 cubes of size (150 mm × 150 mm × 150 mm) were cast for each case, with three replications per mix, as outlined in Table 1. The specimens were cured under ambient conditions, with the AAC cubes envelopes in a 70-micron plastic sheet to retain moisture, while the PCC specimens underwent conventional water curing for 28 days. The intent was to assess the compressive strength of each mix under standard curing conditions, as specified by IS 516 Part 1/Sec 1 (IS:516 Part-1, Sec-1, Hardened concrete - Methods of test & Bur., 2021). Compressive strength testing was performed using a fully automated compression testing machine with a 3000 kN load cell. The rate of loading was controlled to ensure consistent results across all specimens. In addition, the UPV test was performed on each cube in three orthogonal directions (xx, yy, and zz) to evaluate the homogeneity and quality of the concrete as specified in IS 516 Part 5/Sec 1 (IS:516 Part-5, Sec-1, Hardened concrete - Methods of test & Bur., 2021). The yy direction corresponded to the compaction direction, while the xx and zz directions were perpendicular to the compaction direction. Calibration of the UPV equipment was carried out before each test to ensure the accuracy and reliability of the results. The UPV results provided insights into the internal microstructure of the AAC and PCC specimens, allowing for the correlation between pulse velocity and compressive strength. The use of UPV testing in multiple directions helped in understanding the anisotropy

Table 3 Mix proportions (kg/m^3)

Constituents	**Mix ID**									
	PCC1	**AAC1**	**PCC2**	**AAC2**	**PCC3**	**AAC3**	**PCC4**	**AAC4**	**PCC5**	**AAC5**
OPC	450	–	450	–	450	–	450	–	450	–
FA	–	240	–	240	–	240	–	240	–	240
GGBFS	–	160	–	160	–	160	–	160	–	160
RS	710	604.91	710	604.91	710	604.91	710	604.91	710	604.91
NCA	1080	1171.69	432	468.67	432	468.67	–	–	–	–
CRAs	–	–	648	703.02	–	–	1080	1171.69	–	–
PCRAs	–	–	–	–	648	703.02	–	–	1080	1171.69
NaOH	–	66.40	–	66.40	–	66.40	–	66.40	–	66.40
Na_2SiO_3	–	12.58	–	12.58	–	12.58	–	12.58	–	12.58
Extra water	–	99.21	–	99.21	–	99.21	–	99.21	–	99.21

PCC1 = 100% OPC with 100% NCA; **AAC1** = 60% FA + 40% GGBFS with 100% NCA; **PCC2** = 100% OPC with 60% CRAs + 40% NCA; **AAC2** = 60% FA + 40% GGBFS with 60% CRAs + 40% NCA; **PCC3** = 100% OPC with 60% PCRAs + 40% NCA; **AAC3** = 60% FA + 40% GGBFS with 60% PCRAs + 40% NCA; **PCC4** = 100% OPC with 100% CRAs; **AAC4** = 60% FA + 40% GGBFS with 100% CRAs; **PCC5** = 100% OPC with 100% PCRAs; **AAC5** = 60% FA + 40% GGBFS with 100% PCRAs

introduced during the compaction process, particularly in AAC, which is more susceptible to variation due to its lightweight nature. In parallel to the mechanical testing, a LCA was conducted to evaluate the EI of the AAC and PCC mixtures, mainly focusing on their EE and CO_2 emissions (refer to Fig. 2). The analysis covered the entire life cycle of the materials, from raw material extraction to final disposal, excluding transportation, mixing, and



CP – Chemical pre-treatment; **MP –** Mechanical pre-treatment

Fig. 2 Comparison of the PCC and AAC life cycle inventory flow with NCA, CRAs, and PCRAs compaction, which were considered negligible in the overall energy consumption. In this work, the methodology illustrated in Fig. 2 was used to assess the life cycle inventory of CRAs and PCRAs as a coarse aggregate in PCC and AAC, with FA and GGBFS used as binders instead of OPC. EE and CO_2 emission of all the combinations of PCC and AAC of M40 strength grade with NCA, CRAs and PCRAs are assessed. This approach is accomplished by extracting the EE and CO_2 emission of each component of the mixture proportions from existing literature sources. Next, the EE and CO_2 emission of 1 m^3 of PCC and AAC are computed for each mixture.

This study is based on the following assumptions:

The selected functional unit of measurement for analysis was 1 m^3 of PCC and AAC with NCA, CRAs and PCRAs.

- The analysis did not examine the contribution of material transportation, mixing, and compaction to the EE and CO_2 emission because it was deemed insignificant.
- The calculations for EE and CO_2 emission did not consider water usage.
- The study conducted an analysis that can be considered a comprehensive assessment, examining the whole life cycle of PCC and AAC with NCA, CRAs, and PCRAs, including the manufacturing stage. However, the analysis did not consider transportation factors.

3.3 Embodied Energy Variables

EE is a critical metric in LCA, used to measure the total energy consumption across the entire life cycle of a material or product. This includes energy consumed during the extracting of raw materials, processing, transporting, manufacturing, usage and disposal. EE provides a comprehensive measure of the EI of construction materials, offering insights beyond mere operational energy consumption. By evaluating EE, the sustainability of materials can be assessed, leading to more informed decisions in material selection for building and infrastructure projects. EE is commonly quantified as energy per unit of mass (e.g., MJ/kg) or volume (e.g., MJ/m^3). The EE of construction materials is influenced by several factors, including the energy-intensive nature of certain manufacturing processes, transportation logistics, and the raw material composition. For example, cement production requires substantial energy due to the high-temperature processes involved in clinker production. Similarly, the production of superplasticizers (SP), which are essential for enhancing the workability and strength of concrete, involves complex chemical processes that significantly contribute to their high EE. Transportation, especially over long distances, adds to the EE by increasing fuel consumption and emissions, further impacting the overall environmental footprint of construction materials. The production of AAC involves several variables that contribute to its EE including FA, GGBFS, NCA, RS, CRAs, SP, AEA, NaOH, Na_2SiO_3, chemical process (CP) and mechanical process (MP). Each of these components has a specific EE associated with its production, which collectively determines the EE of AAC. Industrial waste materials, such as FA and GGBFS, are AAC's most often utilized binders. These binders have a low energy requirement for manufacture, which sets them apart from other components. Prior research presumed that the energy required to manufacture NaOH, Na_2SiO_3, SP, and AEA is negligible for determining the overall energy consumption 1m^3 of AAC (Gopalakrishna & Dinakar, 2024a, 2024b; Gopalakrishna & Pasla, 2024). Hence, it is imperative to consider the energy value to establish a valid comparison and obtain a precise estimation.

The energies required to produce OPC, FA and GGBFS are 6.4, 0.82 and 0.7 MJ/kg, respectively (International Finance Corporation, 2017). Due to the difference in basic materials between PCC (i.e., OPC) and AAC (primarily FA and GGBFS), the volume taken up by aggregates (i.e., RS, NCA and CRAs) varies. The variation in the specific gravity of OPC, FA and GGBFS is responsible for this disparity. According to IFC (International Finance Corporation, 2017), the energy required to manufacture RS and NCA is 0.11 MJ/kg, while the energy needed to produce CRAs is around 0.0083 MJ/kg.

The production of AEA and SP also requires energy. When using a relatively low water-to-AAB ratio, admixtures (i.e., AEA and SP) are typically needed to produce high-strength concrete. The energy required for these admixtures (i.e., AEA and SP) is incorporated to accurately evaluate the total energy of AAC and PCC. However, they are typically used in small proportions by the weight of a binder compared to other constituents. The required energy for producing AEA and SP is 12.1 and 29.1 MJ/kg (I.B. and U. e. V. (IBU) 2021; IBU), EPD-EFC-, 20210198-IBG1-EN Environmental Product Declaration Concrete admixtures - Plasticizer & superplasticizer. 2021).

Alkali activating solution (AAS) (i.e., a combination of NaOH and Na_2SiO_3) mainly contributes to AAC's strength. Sodium hydroxide requires energy of 9.5 MJ/kg (Gao et al., 2021; Liang et al., 2023). On the other hand, the energy needed to produce Na_2SiO_3 is approximately 5.371 MJ/kg (Alsalman et al., 2021). The energy required for the production of OPC is primarily dependent on the kind of kiln used, such as wet (5.9 MJ/kg), semi-wet (4.6 MJ/kg), dry (3.3 MJ/kg), or semi-dry kiln (3.5 MJ/kg)

(Hammond & Jones, 2008). The energy needed to produce low-impact acid for the chemical process of CRAs is approximately 1.86 MJ/kg (Althaus et al., 2007). Power consumption for the mechanical process (i.e., abrasion for 5 min of 50 kg of CRA) is 0.0375 kWh. The energy required is calculated as 0.01368 MJ/kg (Gupta et al., 2023). Fig. 3 summarizes the EE needed for PCC and AAC constituent materials and uses it to estimate the energy of the resulting PCC and AAC mixtures.

3.4 *CO_2 Emission Variables*

Global warming potential (GWP) is a crucial metric used in LCA to evaluate the environmental effect of materials or products based on their contributions to global climate change. GWP measures the cumulative emissions of greenhouse gases (GHGs) over the complete life cycle of a material, represented as carbon dioxide equivalents (CO_{2e}). This metric is critical in construction because it helps evaluate the sustainability of materials, from raw material extraction through production, use, and disposal. N_2O, CO_2, and methane (CH_4) are the primary greenhouse gases (GHGs) considered in LCA. Each of these gases has a different GWP, with CO_2 being the baseline (GWP = 1). In contrast, CH_4 and N_2O have significantly higher GWP values due to their greater impact on trapping heat in the atmosphere. Several key factors come into play when assessing the GWP of construction materials. The energy required to produce construction materials varies significantly, affecting the overall GWP. For example, the manufacturing of OPC, a critical component of concrete,

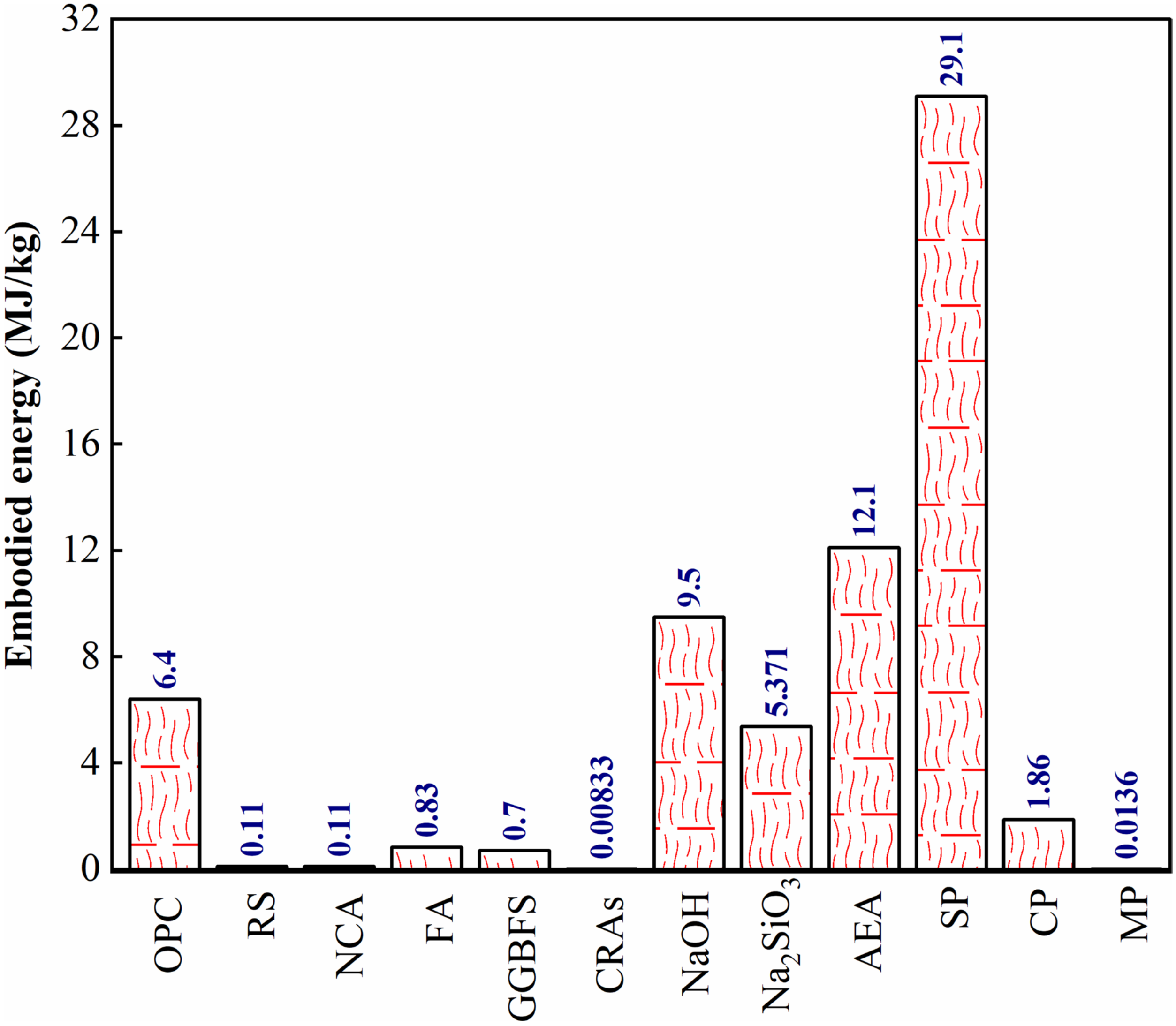


Fig. 3 The EE of materials. Note: OPC—ordinary Portland cement; RS—river sand; NCA—natural coarse aggregate; FA—fly ash; GGBFS—ground granulated blast furnace slag; CRAs—coarse recycled aggregates; NaOH—sodium hydroxide; Na_2SiO_3—sodium silicate; AEA—air-entraining admixtures; SP—superplasticizers; CP—chemical pre-treatment; MP—mechanical pre-treatment; MJ—Megajoule; and kg—kilogram

is energy-intensive, particularly during the calcination of limestone. This process not only consumes substantial energy, but also releases CO_2 as a byproduct of the chemical reaction. Consequently, OPC production is one of the largest sources of GHG emissions in the construction industry.

Moreover, acquiring and treating primary resources like steel or aluminum can lead to significant greenhouse gas emissions due to the energy demands associated with these procedures.

CO_2 emissions are discharged into the atmosphere due to the energy consumed in producing AAC and PCC materials, which includes diesel, electricity, liquefied petroleum gas, explosives, and coal. OPC generates more significant emissions than cementitious materials such as FA and GGBFS. According to IFC (International Finance Corporation, 2017), OPC releases around 0.91 Equivalent kg of CO_2. In contrast, aggregates have a lower energy need for manufacturing than other materials, leading to comparatively low levels of CO_2 emission. The CO_2 emission of FA and GGBFS is 0.004 Equivalent kg of CO_2 and 0.33 Equivalent kg of CO_2, respectively (International Finance Corporation, 2017). According to IFC (International Finance Corporation, 2017), the CO_2 emission values for RS, NCA, and CRAs were 0.009, 0.009 and 0.089 Equivalent kg of CO_2, respectively. The manufacture of admixtures, such as SP and AEA, emits 1.88 and 0.439 Equivalent kg of CO_2, respectively (I.B. and U. e. V. (IBU) 2021; IBU), EPD-EFC-, 20210198-IBG1-EN Environmental Product Declaration Concrete admixtures - Plasticizer & superplasticizer. 2021).

Manufacturing activating solutions, such as NaOH and Na_2SiO_3, necessitates substantial energy, leading to notable CO_2 emission. The CO_2 emission of sodium hydroxide amounts to roughly 0.75 Equivalent kg of CO_2 (Gao et al., 2021; Liang et al., 2023). This estimate corresponds to sodium hydroxide in its pure solid form. Conversely, sodium silicate generates more significant emissions than sodium hydroxide, with a value of 1.222 Equivalent kg of CO_2 (Alsalman et al., 2021). The chemical and mechanical pre-treatment of CRAs generate emissions, which are included in the calculations. The chemical and mechanical pre-treatment emissions are approximately 0.0371

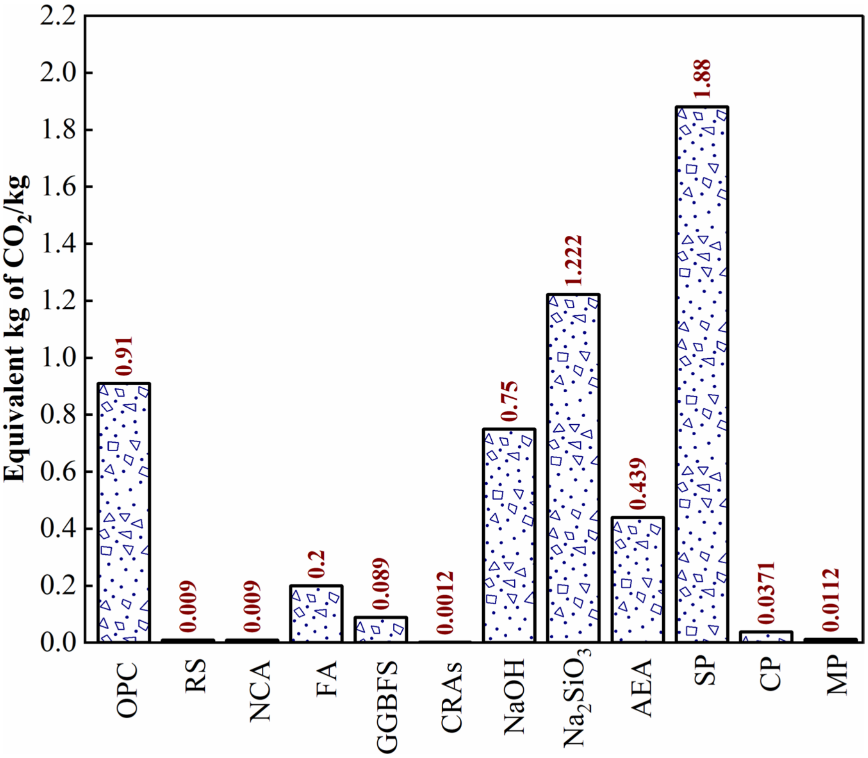


Fig. 4 The CO_2 emission of materials. Note: OPC—ordinary Portland cement; RS—river sand; NCA—natural coarse aggregate; FA—fly ash; GGBFS—ground granulated blast furnace slag; CRAs—coarse recycled aggregates; NaOH—sodium hydroxide; Na_2SiO_3—sodium silicate; AEA—air-entraining admixtures; SP—superplasticizers; CP—chemical pre-treatment

Equivalent kg of CO_2 (Althaus et al., 2007) and 0.0112 Equivalent kg of CO_2 (Gupta et al., 2023), respectively. Fig. 4 illustrates all the CO_2 emission values considered in this work.

The EE and CO_2 emission values for all the concrete samples were determined by the following equations:

$$\text{Net Equivalent kg}\,\mathrm{CO_2}\big/\mathrm{m^3} = \sum \left(\begin{array}{l} CO_{2e(OPC)} \times OPC\left(kg\big/m^3\right) + CO_{2e(RS)} \times RS\left(kg\big/m^3\right) + \\ CO_{2e(NCA)} \times NCA\left(kg\big/m^3\right) + CO_{2e(SP)} \times SP\left(kg\big/m^3\right) \end{array} \right), \tag{1}$$

$$\text{Total EE}\left(\mathrm{MJ}\big/\mathrm{m^3}\right) = \sum \left(\begin{array}{l} EE_{(OPC)} \times OPC\left(kg\big/m^3\right) + EE_{(RS)} \times RS\left(kg\big/m^3\right) + \\ EE_{(NCA)} \times NCA\left(kg\big/m^3\right) + EE_{(SP)} \times SP\left(kg\big/m^3\right) \end{array} \right). \tag{2}$$

3.5 Cost Analysis

The cost analysis conducted aims to assess both the economic feasibility and environmental sustainability of AAC mixtures incorporating NCA, CRAs and PCRAs compared to conventional PCC mixtures. The price of both PCC and AAC mixtures mainly relies on the costs associated with their key components, including OPC, RS, NCA, CRAs, PCRAs, SP, FA, GGBFS, AEA, NaOH and Na_2SiO_3 solutions. Obtaining prices for constituents is challenging due to their dependence on multiple factors:

Location: Commodity pricing can vary significantly between regions or countries due to factors such as market fluctuations, availability, and the influence of traders and producers. This variation is particularly pronounced for OPC, which can show significant price disparities even within different regions of the same country.

Energy costs: The price of many materials, especially those derived from industrial processes (such as cement and aggregates), is affected by energy costs, especially the fluctuating price of crude oil.

Quantity: Bulk purchases typically result in lower costs per unit, especially for chemicals, where the price difference between small and large quantities can be substantial. Wholesale prices are often negotiable with suppliers and may not be readily available. Approximate pricing for each component was acquired through industry contacts, quotations, and searches on trading websites. These prices can be regarded as indicative of large-scale purchases in the Indian market. Table 4 summarizes the cost of key constituents used to produce 1 m^3 of AAC and PCC based on the mix proportions discussed earlier. Table 4 lists the cost of each material used in the AAC and PCC mixtures, including freight.

Table 4 Constituent material cost

S. no.	Materials	Cost (including freight)	
		Rs/kg	US $/kg (converted as per the conversion rates prevalent on 20.01.2025)
1	OPC	8.3	0.096
2	RS	2.6	0.03
3	NCA	1.8	0.021
4	SP	93.2	1.08
5	FA	5	0.058
6	GGBFS	7	0.081
7	NaOH	105	1.21
8	Na_2SiO_3	75	0.87
9	AEA	52.5	0.61
10	CRAs	0.45	0.0052
11	PCRAs (CP + MP + CRAs)	(0.03 + 0.95 + 0.45) = 1.43	0.017

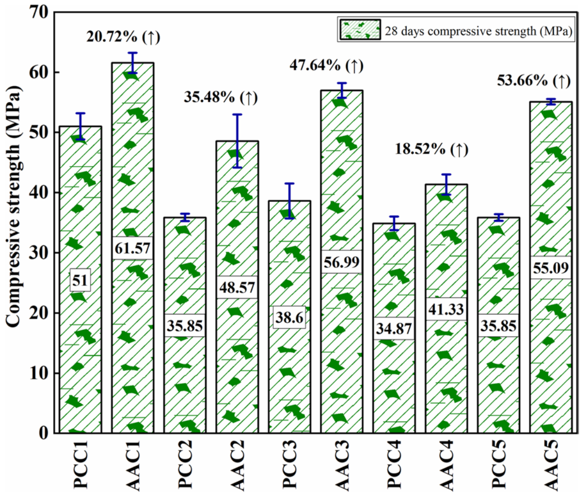


Fig. 5 Compressive strength of PCC and AAC specimens

4 Results and Discussion

4.1 Compressive Strength

Fig. 5 presents the compressive strength results for PCC and AAC mixtures, incorporating NCA, CRAs, and PCRAs. The target strength of the M40 grade of concrete is set at 48.25 MPa, represented by the dotted line. It can be seen from the figure that AAC consistently demonstrates higher compressive strength than PCC, regardless of the aggregate type. This strength gain in AAC can be attributed to the formation of calcium silicate hydrate (C-S-H) and sodium alumino-silicate hydrate (N-A-S-H) gels, products of the alkali activation process. These gels contribute significantly to the binding properties of the concrete matrix, leading to higher overall strength in AAC samples compared to PCC. For instance, in PCC samples, the compressive strength of PCC1 (51 MPa), PCCR2 (35.85 MPa), PCC3 (38.6 MPa), PCC4 (34.87 MPa) and PCC5 (35.85 MPa) demonstrates the variability of strength due to the type of aggregate used. In contrast, AAC samples show superior results with AAC1 (61.57 MPa), AAC2 (48.57 MPa), AAC3 (56.99 MPa), AAC4 (41.33 MPa) and AAC5 (55.09 MPa). It can be found that the rate of decline in strength for PCCRA and AACRA is due to the incorporation of CRAs, similar to earlier studies (Hu et al., 2019; Khan et al., 2023). The reason for this is the high porosity and water absorption of CRAs, which undergo chemical reactions and experience a decrease in PCC2, AAC2, PCC4 and AAC4 strength. However, the significantly higher strength in AAC3 and AAC5, which use PCAs, suggests that the alkali activation mechanism benefits from the increased bond strength provided by pre-treated aggregates (Khan et al., 2024).

The current study additionally examined the impact of the NCA, CRAs, and PCRAs on the percentage of change in 28 days strength of PCC and AAC mixtures. As shown in Fig. 5, the strength of PCC1, PCC2, PCC3, PCC4, and PCC5 gradually decreases. The strength was reduced by 17.16%, 26.19%, 32.27%, 15.63% and 34.93%, respectively, corresponding to AAC1, AAC2, AAC3, AAC4 and AAC5. For example, the compressive strengths of PCC combinations with 60% and 100% PCRAs instead of NCA were 7.67% and 2.81% higher, respectively, than those of PCC combinations with similar combinations of CRAs. The results indicate that samples with PCRAs exhibit minimal variations in strength compared to NCA. Furthermore, the highest increase was 53.66% for AAC5.

4.2 Ultrasonic Pulse Velocity (UPV)

The UPV test is a widely accepted non-descriptive method to assess the concrete's quality, homogeneity, and integrity. The test indirectly evaluates the material's internal structure by measuring the speed at which an ultrasonic pulse travels through the concrete. Various researchers have validated the UPV test, emphasizing its reliability in assessing concrete's mechanical properties and durability (Rao et al., 2018; Shirvani et al., 2023). The UPV test results for different AAC and PCC samples containing NCA, CRAs, and PCRs are illustrated in Fig. 6. The test results indicate that as the content of CRAs and PCRAs increases, the UPV values show a corresponding decrease. This decline in UPV can be attributed to several factors directly related to the material characteristics of CRAs and PCRAs, such as increased porosity, the presence of microcracks, and reduced aggregate density. The UPV test results closely align with the compressive strength data presented in Fig. 5. This relationship is expected, as UPV provides insight into the material's internal compactness and homogeneity, critical factors influencing compressive strength. Higher UPV values generally indicate denser, less porous concrete, leading to improved compressive strength. Conversely, lower UPV values reflect a higher presence of voids and microcracks, contributing to reduced strength. For the 28-day cured samples, the UPV values are PCC1 (4.81 km/s), PCC2 (4.57 km/s), PCC3 (4.62 km/s), PCC4 (4.22 km/s) and PCC5 (4.7 km/s). In comparison, the AAC samples exhibited slightly higher UPV values, including AAC1 (4.91 km/s), AAC2 (4.72 km/s), AAC3 (4.82 km/s), AAC4 (4.22 km/s) and AAC5 (4.71 km/s). The PCC5 and AAC5 mixtures exhibited inferior performance to the other mixtures, primarily because of the reduced

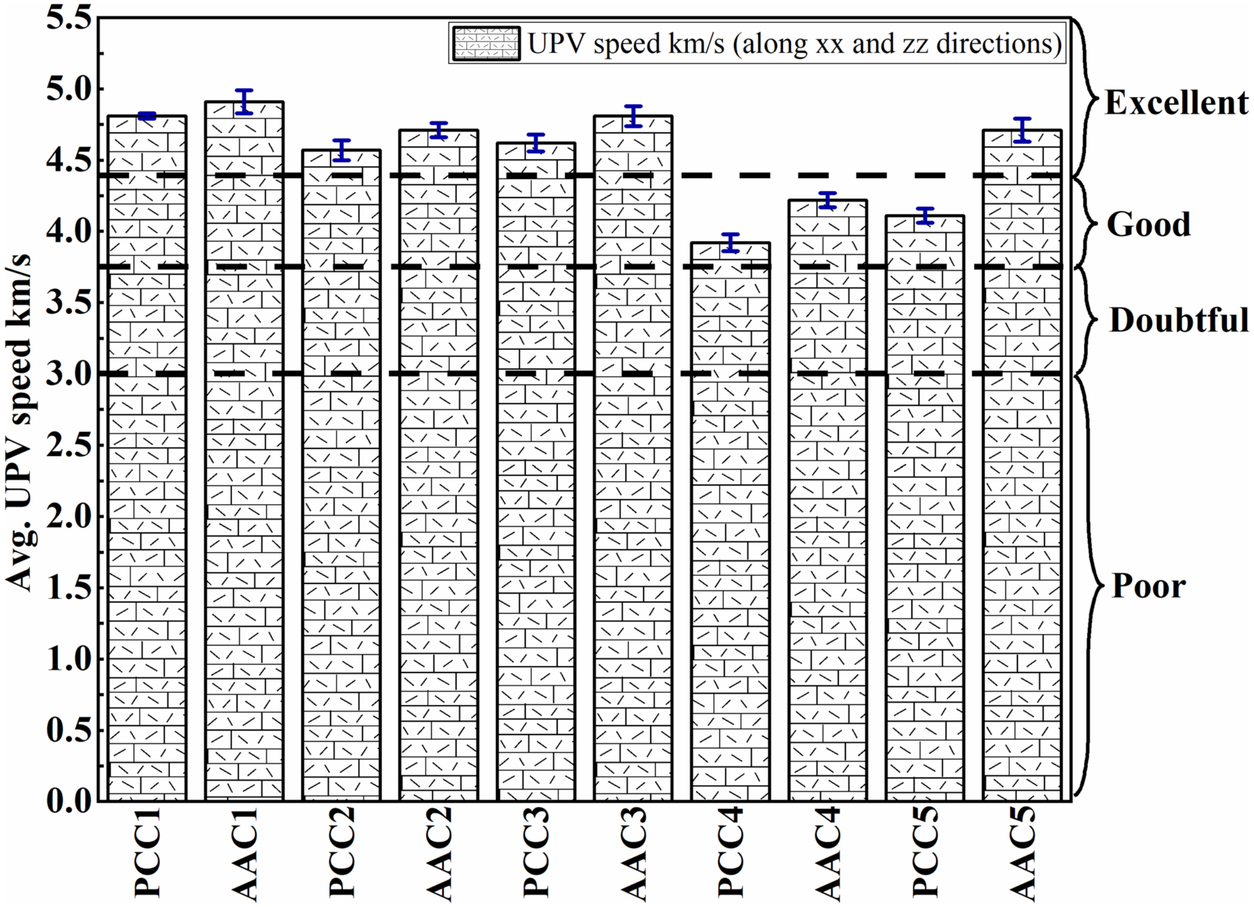


Fig. 6 UPV test of PCC and AAC specimens

density of the CRAs. Based on the UPV classification guidelines provided in IS 516 Part 5 (IS:516 Part-5, Sec-1, Hardened concrete - Methods of test & Bur., 2021), the UPV values obtained for all the tested samples fall within the range of 3.92 km/s to 4.91 km/s, classifying them as good-quality concrete. However, it is essential to note that while the UPV values classify these samples as good, the recycling plant-based CRAs are only ideal for use in high-performance PCC and ACC applications with pre-treatment. The lower UPV values of these samples indicate reduced potential for strength and durability, which would negatively affect the long-term performance of the concrete in structural applications. This is demonstrated in Fig. 6. However, pre-treated CRAs (i.e., PCRAs) in the AAC and PCC mixture impact its performance. While it is not as effective as PCC and AAC with 100% NCA, it still performs better than recycling plant-based CRAs, as shown in Fig. 5.

4.3 Environmental Impact Assessment

PCC is a heterogeneous mixture containing OPC, RS, NCA, SP, CRAs and PCRAs. AAC consists of RS, NCA, FA, GGBFS, CRAs, NaOH, Na_2SiO_3, AEA, and PCRAs. Figs. 7 and 8 present the CO_2 emission and EE consumption associated with 1 m^3 of PCC and AAC, with a clear distinction between the EI of the two concrete types. The comparison highlights AAC's significantly lower EE and CO_2 emission compared to PCC. Results indicate a reduction of 67.34% in EE and 59.92% in CO_2 emission compared to PCC1. This difference is primarily due to the absence of OPC in AAC, which a major source of both EE consumption and greenhouse gas emissions in traditional concrete production. In contrast, the high EE and CO_2 emission of PCC1 are predominantly attributed to the production of OPC, which contributes 91.68% of the total EE and 95.3% of the CO_2 emission for PCC1, as shown in Figs. 9 and 10. The production process of OPC entails the calcination of limestone, a highly energy-intensive procedure that results in the emission of substantial quantities of CO_2. For AAC1, Na_2SiO_3 and NaOH are the largest contributors to the EI, with Na_2SiO_3 accounting for 34.55% of the total EE and 46.82% of the CO_2 emission. Combined, Na_2SiO_3 and NaOH contribute 46.59% of the total EE and 52.48% of the CO_2 emission of AAC1.

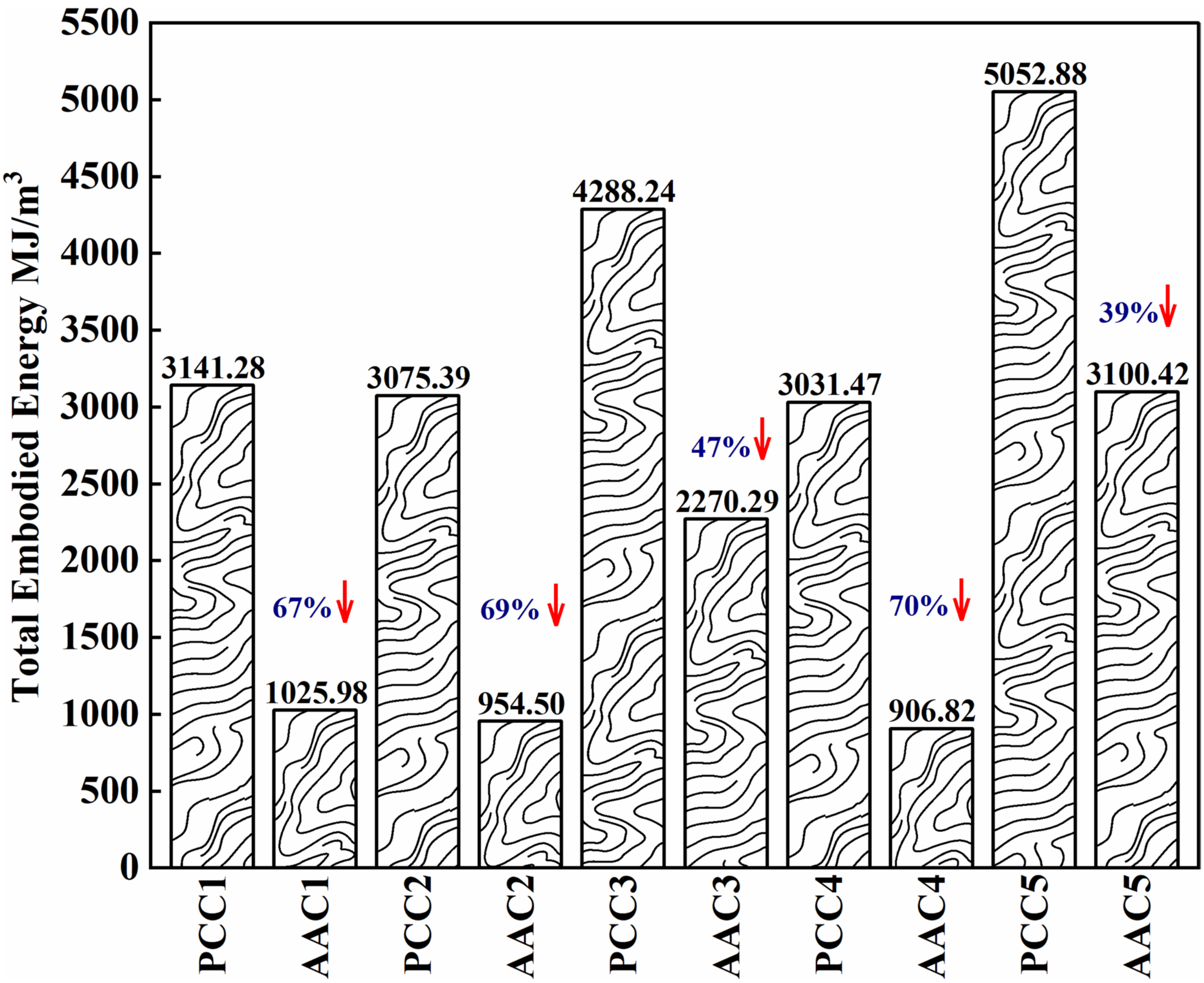


Fig. 7 Total EE of PCC and AAC specimens

While these alkali activators are crucial for the geopolymerization process, they are also associated with high energy and emission costs due to their industrial production processes. The binding materials for AAC (FA and GGBFS) contribute 30.58% of the total EE and 37.42% of the CO_2 emission for AAC1. Despite their contribution, these materials are considered environmentally favorable compared to OPC, as they are industrial by-products and their use in AAC reduces the need for virgin materials. The effect of NCA and RS on the EE and CO_2 emission of PCC1 and AAC1 is minimal, in line with previous research (Gao et al., 2021; Liang et al., 2023; Salami et al., 2023). These materials are less energy-intensive to produce and transport compared to OPC.

The total EE and CO_2 emission of AAC2 and PCC2 are presented in Figs. 7 and 8. A clear distinction emerges between the two mixtures. It can be seen from the figures that AAC2 results in 68.96% lower EE and 60.73% lower CO_2 emission compared to PCC2, reinforcing the environmental advantages of AAC over traditional PCC mixtures. Similar to ACC1, the primary reason for AAC2's reduced environmental footprint lies in the absence of OPC, which is known for its high energy demands and emissions during production. Sodium silicate (Na_2SiO_3) is responsible for 37.14% of the total EE and 48.36% the CO_2 emission for AAC2, as shown in Figs. 9 and 10. While sodium silicate is essential for the alkali activation process in AAC, its production is energy-intensive and emits significant amounts of CO_2. Together, FA and GGBFS contribute to 32.87% of the total EE and 38.65% of the CO_2 emission of AAC2. Despite their contribution, FA and GGBFS are considered environmentally favorable compared to OPC, as they are industrial by-products and serve as alternatives to virgin materials. OPC remains the dominant factor affecting the EI of PCC2, similar to findings

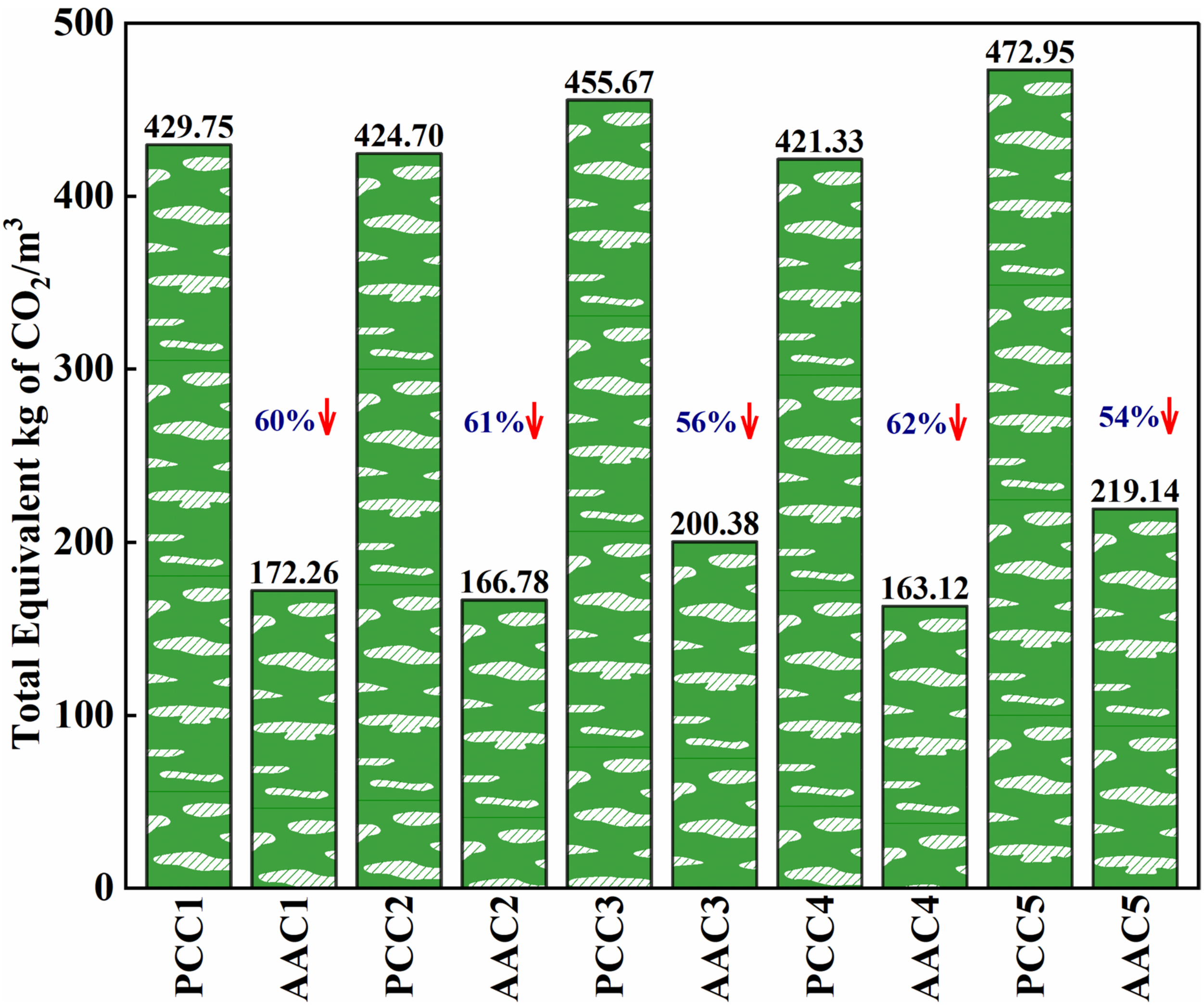


Fig. 8 The CO_2 emission of PCC and AAC specimens

for PCC1. In the case of PCC2, OPC is responsible for the bulk of both EE and CO_2 emission as shown in Figs. 9 and 10. It underscores the need to find sustainable alternatives or supplementary cementitious materials to reduce the EI of traditional PCC mixtures. The contribution of aggregates, including NCA and CRAs, to the total EE and CO_2 emission is negligible for both AAC2 and PCC2. This is consistent with previous findings (Gopalakrishna & Pasla, 2024) that showed the EI of aggregates is relatively low compared to binders like OPC, FA, and GGBFS. The use of admixtures such as superplasticizer (SP) and air-entraining agent (AEA) is minimal in both mixtures due to the low water/binder ratio used in the mix designs. For PCC2, SP contributes 2.13% of the EE and 1% of the CO_2 emission, while AEA accounts for 4.06% of the EE and 0.84% of the CO_2 emission in AAC2 (Figs. 9 and 10). Though small, these contributions are notable, especially for AAC mixtures.

The EIA of pre-treated CRAs with CP and MP in PCC3 and AAC3 highlights their significant impact on both EE and CO_2 emission. PCC3 and AAC3 have resulted in higher EE and CO_2 emissions than the other mixtures due to incorporating CP and MP during the pre-treatment process of CRAs. Despite the increase in energy and emissions from the pre-treatment, OPC remains the major contributor to the EE and CO_2 emissions in PCC specimens. This is consistent with the environmental profiles of other PCC mixtures that utilize NCA, CRAs, and PCRAs. Figs. 7 and 8 present the EE and CO_2 emission analysis of PCC3 and AAC3. The EE of AAC3 is 47.06% lower, and its CO_2 emission are 56.02% less when compared to PCC3, demonstrating the inherent sustainability benefits of AAC mixtures while using pre-treated

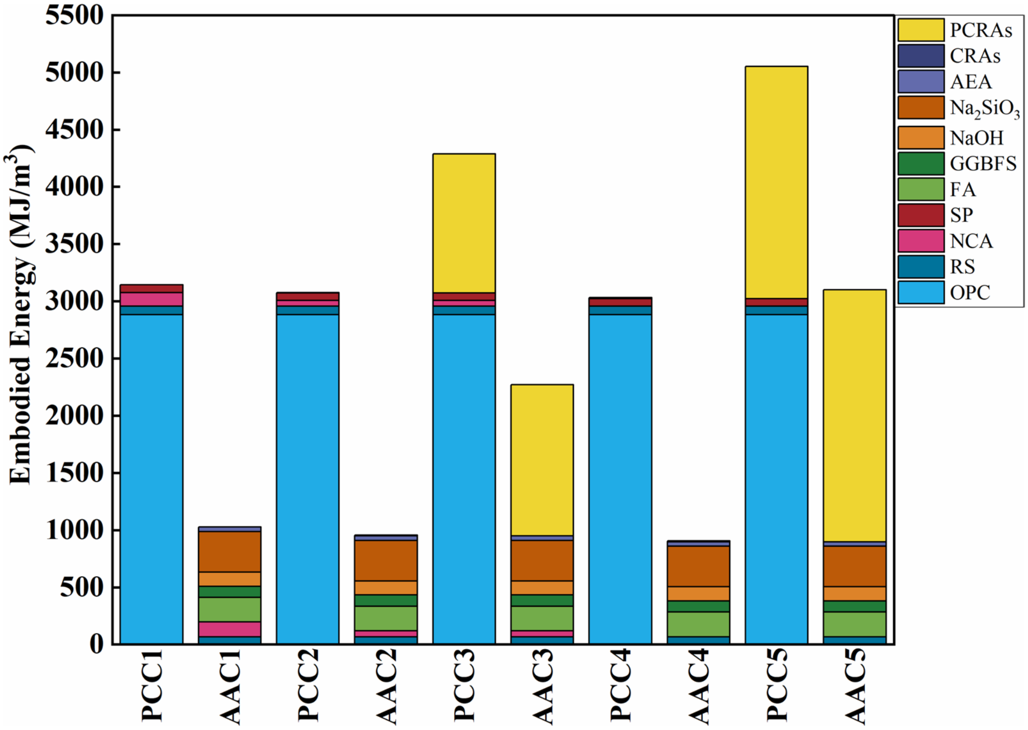


Fig. 9 The material breakdown percentage of EE for various AAC and PCC specimens

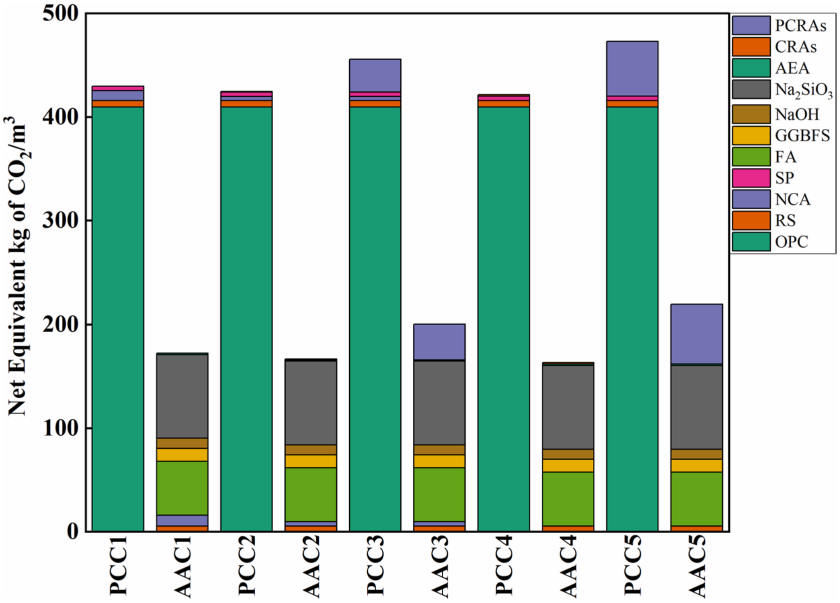


Fig. 10 The material breakdown percentage of CO_2 emission for various AAC and PCC specimens

CRAs. AAC mixtures, which use alkali-activated materials, generally have less EI than traditional cement-based PCC mixtures. However, the use of PCRAs in AAC3 does lead to increased energy consumption and CO_2 emission compared to untreated CRAs, underlining the environmental cost associated with the pre-treatment process. For PCC3, the combination of CP and MP for pre-treating CRAs contributes 28.41% of the total EE and 6.97% of the total CO_2 emission, as shown in Figs. 9 and 10. For AAC3, the same pre-treatment processes

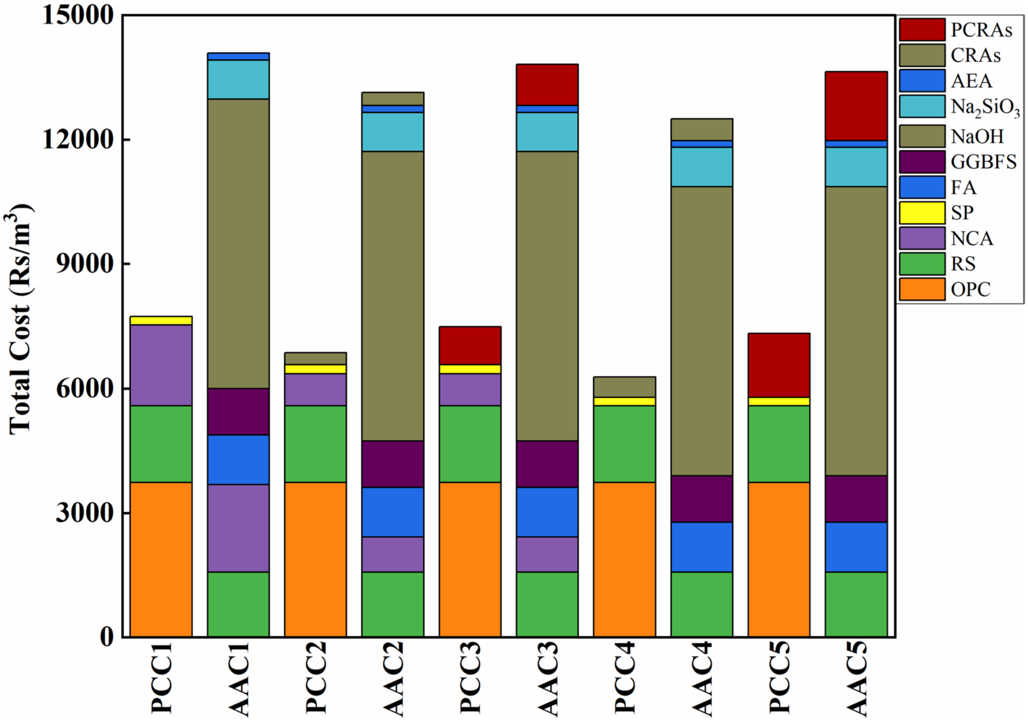


Fig. 11 Cost analysis breakdown of AAC and PCC specimens

contribute significantly more to EE and CO_2 emission, accounting for 58.21% and 17.19%, respectively. This suggests that the pre-treatment of CRAs has a much more significant influence on AAC mixtures, likely due to the overall lower EI of AAC mixtures without OPC.

Figs. 7 and 8 present the EE and CO_2 emission analysis of PCC4 and AAC4. The AAC4 exhibits a 70.09% reduction in EE and a 61.28% reduction in CO_2 emission compared to PCC4. This reduction is attributed to the use of 100% CRAs in both AAC4 and PCC4. However, AAC's alkali-activated mixture design proves to be more environmentally efficient that the Portland cement-based PCC. In the case of AAC5, the mixture achieves 38.64% lower EE and 53.66% less CO_2 emission compared to PCC5. Both AAC5 and PCC5 use 100% PCRAs. While PCRAs contribute to better mechanical performance than untreated CRAs, their pre-treatment process adds additional energy consumption. Despite the higher EI due to pre-treatment, AAC5 still performs better than PCC5, demonstrating the general trend that AAC mixtures result in less energy use and CO_2 emission than PCC, even when using treated aggregates.

4.4 Cost Analysis

Fig. 11 visually compares the material cost for 1 m^3 of AAC and PCC with various aggregate options (NCA, CRAs and PCRAs). The analysis reveals that the cost to produce 1 m^3 of AAC1 is 14,085 Rs/m^3, while PCC1 costs 7734 Rs/m^3. The higher cost of AAC is primarily attributed to NaOH, which is a significant part of the alkaline activator in AAC mixtures. However, there is potential to reduce this cost by substituting NaOH with other alkaline materials. It was observed that fly ash (FA) is less expensive than GGBFS, and CRAs are more economical than NCAs. For instance, replacing NCA with 60% CRA in PCC2 and AAC2 resulted in cost savings of 11.31% and 6.73%, respectively, compared to PCC1 and AAC1. Similarly, PCC4 and AAC4, which use 100% CRAs, show 18.85% and 11.23% cost savings, respectively. The cost incurred towards the pre-treatment process of PCRAs has greatly influenced the overall cost of concrete made with varying percentage replacements. For instance, PCC3 and AAC3 with 60% of PCRAs replacing NCA, has resulted in a cost decrease of 3.19% and 1.89%, respectively, compared to PCC1 and AAC1. The cost decrease is even higher for PCC5 and AAC5, where 100% PCRAs lead to a cost drive of 5.31% and 3.16%, respectively. The results show that PCRAs have a marginally lesser cost

Table 5 Total cost analysis of ACC and PCC specimens

S. no.	Materials	Total cost	
		Rs/m^3	US \$/m^3 (converted as per the conversion rates prevalent on 20.01.2025)
1	PCC1	7734.7	89.45
2	AAC1	14,085.31	162.89
3	PCC2	6859.9	79.33
4	AAC2	13,136.24	151.91
5	PCC3	7488.46	86.60
6	AAC3	13,818.17	159.80
7	PCC4	6276.7	72.59
8	AAC4	12,503.53	144.60
9	PCC5	7324.3	84.70
10	AAC5	13,640.07	157.74

than the NCA, while CRAs have the lowest price compared to NCAs and PCRAs.

In terms of EIA, PCC mixtures have a larger carbon footprint than AAC mixtures of comparable compressive strength. Among the various coarse aggregates, PCRAs contribute more to the EI than CRAs due to the involved pre-treatment process. The study also demonstrated that substituting CRAs for NCA in PCC and AAC mixtures leads to the most favorable balance between cost-effectiveness and environmental benefits. While PCC proves to be an economical option to AAC in terms of production cost, the AAC offers better environmental sustainability and strength (Miyan et al., 2024). Table 5 summarizes the cost of 1 m^3 of AAC and PCC with various coarse aggregates.

4.4.1 SEM Analysis

The microstructure of AAC and PCC powdered materials was investigated using a high-resolution SEM (APEROS, FEI). The various AAC and PCC powdered samples were first attached to the surface of conductive tape. Then, a layer of gold was applied to the firmly powdered samples using a sputter-coating process. The coated samples were then transferred to the microscope. Fig. 12 shows the surface morphology of AAC and PCC specimens with various coarse aggregates. Fig. 12 displays small cracks, floccule products with surface pores, and rod-like products in the AAC2, PCC2, AAC4, and PCC4 samples with 60% and 100% CRAs. This implies that old adhered cement paste connected to CRAs would reduce their mechanical performance (Alyousef et al., 2018). Meanwhile, the samples with PCRAs (i.e., AAC3, PCC3, AAC5, and PCC5) and NCA (i.e., AAC1 and PCC1) exhibit denser structures with no visible cracks or pores. This suggests that PCRAs enhance strength compared to untreated CRAs (El-Hassan & Elkholy, 2021; Fang & Zhang, 2020). Sodium calcium alumino-silicate hydrate (N-C)-A-S-H gels are the randomly dispersed spherical-shaped products found in AAC samples that improve compressive strength compared to PCC samples (Humad et al., 2019). It is evident from the pictures that C-S-H gel and CH crystals make up the majority of the hydration products of all PCC samples. CH crystals and loosely scattered C-S-H gel are seen in the PCC2 microstructure, along with a few microcracks separating the hydration products. The microstructure of the PCC4 has been antiquated with the addition of 100% CRAs (Yan et al., 2024).

5 Conclusions

This investigation evaluated AAC and PCC mixtures incorporating NCA, CRAs, and PCRAs to develop eco-friendly concrete with enhanced mechanical properties and lower EE consumption and CO_2 emission compared to traditional PCC mixtures. The UPV test and cost analysis were also evaluated for all the mixtures. The following conclusions were drawn:

- The AAC3 and AAC5 mixtures exhibited compressive strengths of 57 MPa and 55.09 MPa, respectively, surpassing the target strength of 48.25 MPa. The compressive strength of AAC3 was 47.64% higher than PCC3, and AAC5 was 53.66% higher than PCC5, demonstrating superior strength performance with AAC mixtures.
- AAC2 and AAC4 mixtures exhibited substantial reductions in energy consumption, by 68.96% and 70.09%, and CO_2 emission, by 60.73% and 61.28%, respectively, compared to all other mix combinations. However, compressive strength was seriously affected by the untreated CRAs in PCC compared to AAC due to the presence of voids, which decreased the density of the mix.
- The AAC1, AAC2, AAC3, AAC4 and AAC5 combinations exhibited reduced energy consumption by 67.34%, 68.96%, 47.06%, 70.09% and 38.64%, respectively, and CO_2 emission by 59.92%, 60.73%, 56.02%, 61.28% and 53.66%, respectively, compared to PCC1, PCC2, PCC3, PCC4 and PCC5.
- The findings indicate that, depending on the components in the mixtures, AAC may be superior to PCC in terms of EE and CO_2 emission. At the same time, the effect of aggregates (i.e., RS, NCA and CRAs), SP and AEA are minimal on EE and CO_2 emission.
- In PCC mixtures, OPC was the primary contributor to EE and CO_2 emission, accounting for 57% to 91.68% of EE and 86.58% to 97.19% of CO_2 emissions. This highlights the substantial environmental burden of OPC in concrete mixtures. In AAC mixtures, while NaOH and

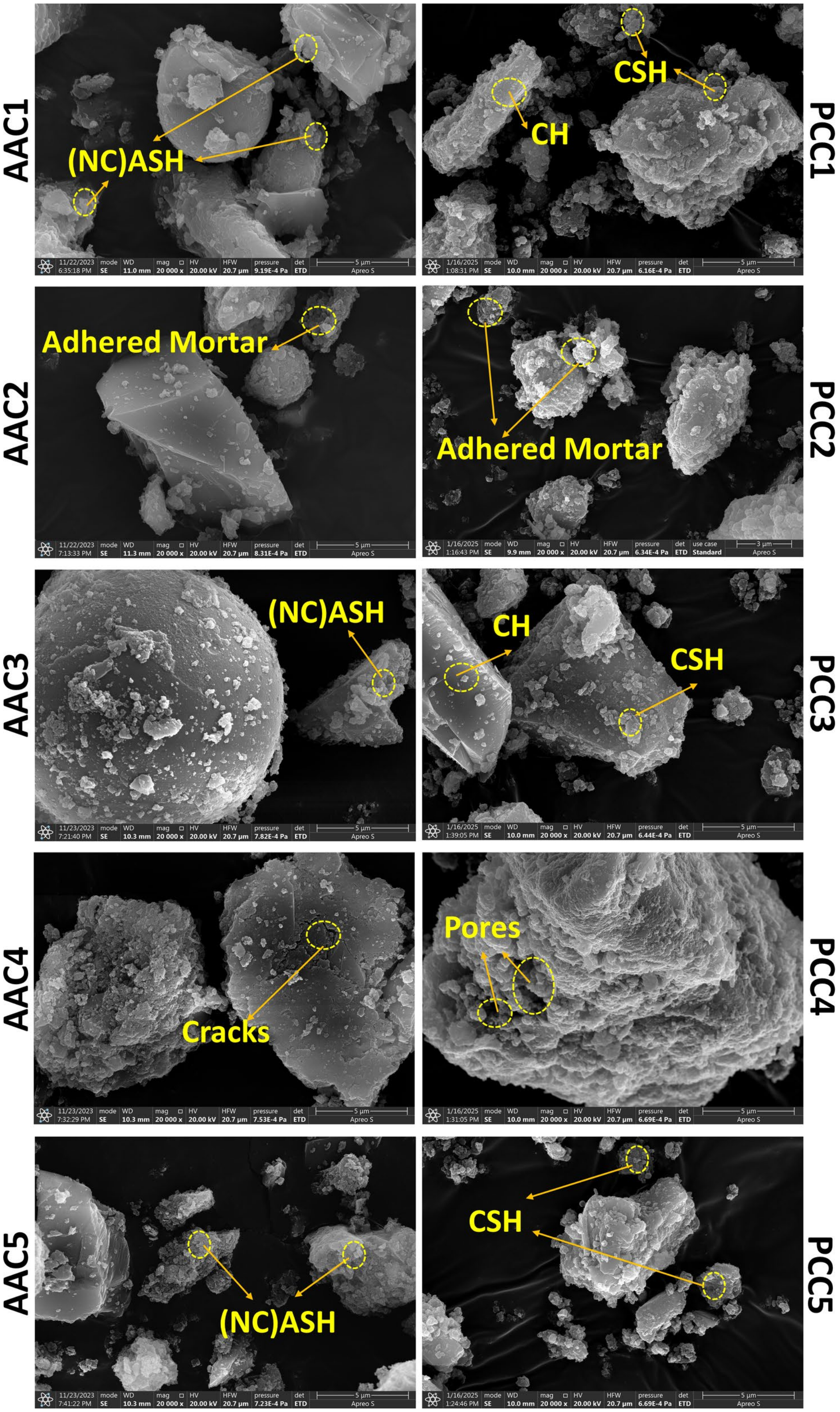


Fig. 12 SEM analysis of AAC and PCC specimens

Na_2SiO_3 contributed significantly to EE and CO_2 emissions, they resulted in lower overall emissions than OPC. The pre-treatment of CRAs using CP and MP added to the EI of both AAC and PCC mixtures, but their contribution to EE and CO_2 emission was lower than OPC. Despite increasing EE and CO_2 emission in treated CRAs, AAC mixtures with pre-treated aggregates (AAC3, AAC5) still demonstrated substantial environmental benefits over PCC mixtures.

- The results show that the cost of AAC1 is at least 82% higher than PCC1. The usage of NaOH in the alkaline activator is the primary cause of the increase in the price of AAC; the incorporation of CRAs and PCRAs reduced production costs in AAC and PCC compared to NCAs.
- According to the findings of SEM, (NC)ASH gel is the hydration product of AAC while CSH gel is the hydration product of PCC with different proportions of coarse aggregates.

6 Recommendations

Based on the findings, AAC has proven to be more effective than PCC in terms of strength and EIA. Nevertheless, the EE and CO_2 emission statistics for various coarse aggregates were obtained from pre-existing literature instead of being calculated directly in this research. Future research should perform a comprehensive LCA to evaluate EE consumption and CO_2 emission more accurately. Using specialized software such as OpenLCA, SimaPro, Mobius, and Sphera would allow for a more robust assessment and validation of the current findings. This analysis should consider all stages of the concrete's life cycle, from raw material extraction to production, use, and disposal, to ensure a holistic evaluation of EIs. Variations in mixture design may lead to different environmental outcomes, and further scrutiny is needed to optimize sustainable concrete mixtures. The current study does not account for the EE and CO_2 emission related to the transportation of materials. Future studies should incorporate these transportation-related factors, as they can significantly influence the overall EI, especially when considering recycled aggregates and regional material sourcing.

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Author contributions
MD Ikramullah Khan contributed to conceptualization, methodology, validation, formal analysis, investigation, data curation, writing original draft, visualization; V. Vinayaka Ram: contributed to conceptualization, resources, review and editing, visualization, supervision; Vipulkumar Ishvarbhai Patel: contributed to conceptualization, resources, review and editing, visualization, supervision. All the authors read and approved the final manuscript.

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Availability of data and materials
The datasets used and/or analyzed during the current investigation are available from the corresponding author upon reasonable request.

Declarations

Competing interests
The authors unequivocally state that they do not have any known financial or personal affiliations that could have impacted the research conducted in this study.

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References

Abbas, A., Fathifazl, G., Fournier, B., Isgor, O. B., Zavadil, R., Razaqpur, A. G., & Foo, S. (2009). Quantification of the residual mortar content in recycled concrete aggregates by image analysis. *Materials Characterization, 60*, 716–728. https://doi.org/10.1016/j.matchar.2009.01.010

Adamu, M., Alanazi, H., Ibrahim, Y. E., & Abdellatief, M. (2024). Mechanical, microstructural characteristics and sustainability analysis of concrete incorporating date palm ash and eggshell powder as ternary blends cementitious materials. *Construction and Building Materials, 411*, 134753. https://doi.org/10.1016/j.conbuildmat.2023.134753

Ahmad, I., Shokouhian, M., Cheng, H., & Radlińska, A. (2024). Enhancement of mechanical properties and freeze-thaw durability of recycled aggregate concrete using aggregate pretreatment Iran. *Journal of Science and Technology*. https://doi.org/10.1007/s40996-024-01672-7

Alsalman, A., Assi, L. N., Kareem, R. S., Carter, K., & Ziehl, P. (2021). Energy and CO2 emission assessments of alkali-activated concrete and ordinary Portland cement concrete: A comparative analysis of different grades of concrete. *Cleaner Environmental Systems., 3*, 100047. https://doi.org/10.1016/j.cesys.2021.100047

Althaus, M. Chudacoff, R. Hischier, N. Jungbluth, M. Osses, A. Primas, S. Hellweg (2007) Life cycle inventories of chemicals. ecoinvent report No.8, v2.0., Final Rep. Ecoinvent Data 1–957. http://scholar.google.com/scholar?hl=en&btnG=Search&q=intitle:Life+Cycle+Inventories+of+Chemicals#0.

Alyousef, R., Benjeddou, O., Khadimallah, M. A., Mohamed, A. M., & Soussi, C. (2018). Study of the Effects of Marble Powder Amount on the Self-Compacting Concretes Properties by Microstructure Analysis on Cement-Marble Powder Pastes. *Adv. Civ. Eng.* https://doi.org/10.1155/2018/6018613

Arora, S., Singh, B., & Bhardwaj, B. (2019). Strength performance of recycled aggregate concretes containing mineral admixtures and their performance prediction through various modeling techniques. *Journal of Building Engineering, 24*, 100741. https://doi.org/10.1016/j.jobe.2019.100741

Astm C618–19, Standard Specification for Coal Fly Ash and Raw or Calcined Natural Pozzolan for Use, Annu. B. ASTM Stand. (2019) 1, 3–6. https://doi.org/10.1520/C0618-19.2.

Bakharev, T., Sanjayan, J. G., & Cheng, Y. B. (2003). Resistance of alkali-activated slag concrete to acid attack. *Cement and Concrete Research, 33*, 1607–1611. https://doi.org/10.1016/S0008-8846(03)00125-X

Bhawan, B. Shah, Z. Marg, Product manual for ordinary Portland cement according to is 269 : 2015 List of Test Equipment, (2018) 1–14.

Çevik, A., Alzeebaree, R., Humur, G., Niş, A., & Gülşan, M. E. (2018). Effect of nano-silica on the chemical durability and mechanical performance of fly ash based geopolymer concrete. *Ceramics International, 44*, 12253–12264. https://doi.org/10.1016/j.ceramint.2018.04.009

Colangelo, F., & Cioffi, R. (2017). Mechanical properties and durability of mortar containing fine fraction of demolition wastes produced by selective demolition in South Italy. *Composites Part b Engineering, 115*, 43–50. https://doi.org/10.1016/j.compositesb.2016.10.045

de Azevedo, A. R. G., Marvila, M. T., Rocha, H. A., Cruz, L. R., & Vieira, C. M. F. (2020). Use of glass polishing waste in the development of ecological ceramic roof tiles by the geopolymerization process. *International Journal of Applied Ceramic Technology, 17*, 2649–2658. https://doi.org/10.1111/ijac.13585

de Juan, M. S., & Gutiérrez, P. A. (2009). Study on the influence of attached mortar content on the properties of recycled concrete aggregate. *Construction and Building Materials, 23*, 872–877. https://doi.org/10.1016/j.conbuildmat.2008.04.012

Duxson, P., Fernández-Jiménez, A., Provis, J. L., Lukey, G. C., Palomo, A., & Van Deventer, J. S. J. (2007b). Geopolymer technology: The current state of the art. *Journal of Materials Science, 42*, 2917–2933. https://doi.org/10.1007/s10853-006-0637-z

Duxson, P., Provis, J. L., Lukey, G. C., & van Deventer, J. S. J. (2007a). The role of inorganic polymer technology in the development of "green concrete." *Cement and Concrete Research, 37*, 1590–1597. https://doi.org/10.1016/j.cemconres.2007.08.018

El-Hassan, H., & Elkholy, S. (2021). Enhancing the performance of Alkali-Activated Slag-Fly ash blended concrete through hybrid steel fiber reinforcement. *Construction and Building Materials, 311*, 125313. https://doi.org/10.1016/j.conbuildmat.2021.125313

Fang, G., & Zhang, M. (2020). The evolution of interfacial transition zone in alkali-activated fly ash-slag concrete. *Cement and Concrete Research, 129*, 105963. https://doi.org/10.1016/j.cemconres.2019.105963

Fathifazl, G., Razaqpur, A. G., & Marinković, S. (2010). Recycled concrete as aggregate for structural concrete production. *Sustainability, 2*, 1204–1225.

Gao, X., Yao, X., Yang, T., Zhou, S., Wei, H., & Zhang, Z. (2021). Calcium carbide residue as auxiliary activator for one-part sodium carbonate-activated slag cements: Compressive strength, phase assemblage and environmental benefits. *Construction and Building Materials, 308*, 125015. https://doi.org/10.1016/j.conbuildmat.2021.125015

González-Fonteboa, B., Martínez-Abella, F., Eiras-López, J., & Seara-Paz, S. (2011). Effect of recycled coarse aggregate on damage of recycled concrete. *Materials and Structures, 44*, 1759–1771. https://doi.org/10.1617/s11527-011-9736-7

Gopalakrishna, B., & Dinakar, P. (2024a). The evaluation of the life cycle and corrosion properties of recycled aggregate geopolymer concrete incorporating fly ash and GGBS. *Journal of Building Engineering, 94*, 109977. https://doi.org/10.1016/j.jobe.2024.109977

Gopalakrishna, B., & Dinakar, P. (2024b). Life cycle assessment (LCA) and the influence of alkaline activator content on mechanical and microstructural properties of geopolymer mortar. *Journal of Engineering Research*. https://doi.org/10.1016/j.jer.2024.01.010

Gopalakrishna, B., & Pasla, D. (2024). Durability performance of recycled aggregate geopolymer concrete incorporating fly ash and ground granulated blast furnace slag. *Journal of Materials in Civil Engineering*. https://doi.org/10.1061/jmcee7.mteng-17067

Gupta, S., Agrawal, H., & Chaudhary, S. (2023). Thermo-mechanical treatment as an upcycling strategy for mixed recycled aggregate. *Construction and Building Materials, 398*, 132471. https://doi.org/10.1016/j.conbuildmat.2023.132471

Habert, G., D'Espinose De Lacaillerie, J. B., Lanta, E., & Roussel, N. (2010). Environmental evaluation for cement substitution with geopolymers, 2nd. *International Conference on Sustainable Construction., 1*, 1607–1615.

Habert, G., D'Espinose De Lacaillerie, J. B., & Roussel, N. (2011). An environmental evaluation of geopolymer based concrete production: Reviewing current research trends. *Journal of Cleaner Production, 19*, 1229–1238. https://doi.org/10.1016/j.jclepro.2011.03.012

Hammond, G. P., & Jones, C. I. (2008). Embodied energy and carbon in construction materials. *Proceedings of the Institution of Civil Engineers: Energy, 161*, 87–98. https://doi.org/10.1680/ener.2008.161.2.87

Hu, Y., Tang, Z., Li, W., Li, Y., & Tam, V. W. Y. (2019). Physical-mechanical properties of fly ash/GGBFS geopolymer composites with recycled aggregates. *Construction and Building Materials, 226*, 139–151. https://doi.org/10.1016/j.conbuildmat.2019.07.211

Humad, A. M., Kothari, A., Provis, J. L., & Cwirzen, A. (2019). The effect of blast furnace slag/fly ash ratio on setting, strength, and shrinkage of alkali-activated pastes and concretes. *Front. Mater., 6*, 1–10. https://doi.org/10.3389/fmats.2019.00009

I. 10262, Indian standard, Concrete mix Proportioning – Guidelines (Second Revision), Bis. (2019) 1–42.

I.B. und U. e. V. (IBU), Environmental production declaration, Concrete admixtures - Air entrainers, Eur. Fed. Concr. Admixtures Assoc. Ltd. (2021) EPD-EFC-20150086-IAG1-EN.

Ibrahim, M., Alimi, W., Assaggaf, R., Salami, B. A., & Oladapo, E. A. (2023). An overview of factors influencing the properties of concrete incorporating construction and demolition wastes. *Construction and Building Materials, 367*, 130307. https://doi.org/10.1016/j.conbuildmat.2023.130307

Ikramullah-Khan, M. D., Abdy-Sayyed, M. A., Swamy-Yadav, G., & Haripriya-Varma, S. (2020). The impact of fly ash and structural fiber on the mechanical properties of concrete. *Materials Today., 39*, 508–512. https://doi.org/10.1016/j.matpr.2020.08.242

Institut Bauen und Umwelt e.V. (IBU), EPD-EFC-20210198-IBG1-EN Environmental Product Declaration Concrete admixtures - Plasticizer and superplasticizer. 2021., Eur. Fed. Concr. Admixtures Assoc. Ltd. (2021) EPD-EFC-20210198-IBG1-EN. https://ibu-epd.com/veroeffentlichte-epds/.

International Finance Corporation, India Construction Materials Database of Embodied Energy and Global Warming Potential METHODOLOGY REPORT, (2017) 1–100. https://edgebuildings.com/wp-content/uploads/2022/04/IFC-India-Construction-Materials-Database-Methodology-Report.pdf.

IS 2386- Part III, Method of Test for aggregate for concrete. Part III- Specific gravity, density, voids, absorption and bulking, Bur. Indian Stand. New Delhi. (1963) (Reaffirmed 2002).

IS 456:2000, Concrete, Plain and Reinforced, in: Bur. Indian Stand. Delhi, 2000: pp. 1–114.

IS 269, Requirements of Ordinary Portland Cement, Bur. Indian Stand. New Delhi, India. (2015).

IS 9103 : 2020, Product Manual for Concrete Admixtures, Bur. Indian Stand. New Delhi. (2020) 1–9

IS:516 Part-1/Sec-1, Hardened concrete - Methods of test, Bur. Indian Stand. IS 516–2021, New Delhi, India. 54 (2021) 1–20. www.standardsbis.in.

IS:516 Part-5/Sec-1, Hardened concrete - Methods of test, Bur. Indian Stand. IS 516–2021, New Delhi, India. 54 (2021) 1–20. www.standardsbis.in.

Ismail, S., & Ramli, M. (2013). Engineering properties of treated recycled concrete aggregate (RCA) for structural applications. *Construction and Building Materials, 44*, 464–476. https://doi.org/10.1016/j.conbuildmat.2013.03.014

Jurado-Contreras, S., Bonet-Martínez, E., Sánchez-Soto, P. J., Gencel, O., & Eliche-Quesada, D. (2022). Synthesis and characterization of alkali-activated materials containing biomass fly ash and metakaolin: Effect of the soluble salt content of the residue. *Archives of Civil and Mechanical Engineering, 22*, 1–21. https://doi.org/10.1007/s43452-022-00444-2

Katz, A. (2004). Treatments for the improvement of recycled aggregate. *Journal of Materials in Civil Engineering, 16*, 597–603. https://doi.org/10.1061/(asce)0899-1561(2004)16:6(597)

Khan, M. I., Abdy-Sayyed, M. A., & Ali, M. M. A. (2021). Examination of cement concrete containing micro silica and sugarcane bagasse ash subjected to sulphate and chloride attack. *Materials Today, 39*, 558–562. https://doi.org/10.1016/j.matpr.2020.08.468

Khan, M. D. I., Ram, V. V., & Patel, V. I. (2023). Influence of pretreatment methods for coarse recycled aggregates on the performance of alkali-activated concrete. *Arabian Journal Science Engineering, 1*, 1–19. https://doi.org/10.1007/s13369-023-08436-x

Khan, M. I., Ram, V. V., & Patel, V. I. (2024). Durability performance of alkali-activated concrete with pre-treated coarse recycled aggregates for pavements. *Scientific Reports, 14*, 1. https://doi.org/10.1038/s41598-024-64506-6

Khan, M. I., Ram, V. V., & Patel, V. I. (2025). Unveiling the potential of pretreated recycled aggregates and alkali-activated binders in the development of pavement-quality concrete. *Journal of Materials in Civil Engineering, 37*, 1–16. https://doi.org/10.1061/JMCEE7.MTENG-18660

Kim, Y., Hanif, A., Kazmi, S. M. S., Munir, M. J., & Park, C. (2018). Properties enhancement of recycled aggregate concrete through pretreatment of coarse aggregates—comparative assessment of assorted techniques. *Journal of Cleaner Production, 191*, 339–349. https://doi.org/10.1016/j.jclepro.2018.04.192

Kou, S. C., & Poon, C. S. (2015). Effect of the quality of parent concrete on the properties of high performance recycled aggregate concrete. *Construction and Building Materials, 77*, 501–508. https://doi.org/10.1016/j.conbuildmat.2014.12.035

Kumar, R. (2017). Influence of recycled coarse aggregate derived from construction and demolition waste (CDW) on abrasion resistance of pavement concrete. *Construction and Building Materials, 142*, 248–255. https://doi.org/10.1016/j.conbuildmat.2017.03.077

Liang, G., Yao, W., & Wei, Y. (2023). A green ultra-high performance geopolymer concrete containing recycled fine aggregate: Mechanical properties, freeze-thaw resistance and microstructure. *Science of the Total Environment, 895*, 165090. https://doi.org/10.1016/j.scitotenv.2023.165090

Lu, B., Shi, C., & Hou, G. (2018). Strength and microstructure of CO2 cured low-calcium clinker. *Construction and Building Materials, 188*, 417–423. https://doi.org/10.1016/j.conbuildmat.2018.08.134

Manjunatha, M., Seth, D., & Balaji, K. V. G. D. (2021). Role of engineered fibers on fresh and mechanical properties of concrete prepared with GGBS and PVC waste powder - An experimental study. *Materials Today, 47*, 3683–3693. https://doi.org/10.1016/j.matpr.2021.01.605

Mesgari, S., Akbarnezhad, A., & Xiao, J. Z. (2020). Recycled geopolymer aggregates as coarse aggregates for Portland cement concrete and geopolymer concrete: Effects on mechanical properties. *Construction and Building Materials, 236*, 117571. https://doi.org/10.1016/j.conbuildmat.2019.117571

Miyan, N., Omur, T., Amed, B., Özkan, H., Aydın, R., & Kabay, N. (2024). Recycled waste concrete and metakaolin based alkali-activated paste: Characterization, optimization, and life cycle assessment. *Construction and Building Materials*. https://doi.org/10.1016/j.conbuildmat.2024.135233

Mohamed, O. A., Al-Khattab, R., & Al-Hawat, W. (2022). Effect of relative GGBS/fly contents and alkaline solution concentration on compressive strength development of geopolymer mortars subjected to sulfuric acid. *Scientific Reports., 12*, 1–13. https://doi.org/10.1038/s41598-022-09682-z

Niş, A., & Altundal, M. B. (2023). Durability performance of alkali-activated concretes exposed to sulfuric acid attack. *Review La Construction, 22*, 16–35. https://doi.org/10.7764/RDLC.22.1.16

Nuaklong, P., Sata, V., & Chindaprasirt, P. (2018). Properties of metakaolin-high calcium fly ash geopolymer concrete containing recycled aggregate from crushed concrete specimens. *Construction and Building Materials, 161*, 365–373. https://doi.org/10.1016/j.conbuildmat.2017.11.152

Purushothaman, R., Amirthavalli, R. R., & Karan, L. (2015). Influence of treatment methods on the strength and performance characteristics of recycled aggregate concrete. *Journal of Materials in Civil Engineering, 27*, 04014168. https://doi.org/10.1061/(asce)mt.1943-5533.0001128

Rafeet, A., Vinai, R., Soutsos, M., & Sha, W. (2019). Effects of slag substitution on physical and mechanical properties of fly ash-based alkali activated binders (AABs). *Cement and Concrete Research, 122*, 118–135. https://doi.org/10.1016/j.cemconres.2019.05.003

Rao, K. J., Keerthi, K., & Vasam, S. (2018). Acid resistance of quaternary blended recycled aggregate concrete, Case Stud. *Construction Materials, 8*, 423–433. https://doi.org/10.1016/j.cscm.2018.03.005

Roychowdhury, A., Somvanshi, A., & Verma, A. (2020). Another brick off the wall: Improving construction and demolition waste management in Indian cities. *Centre for Science and Environment., 1*, 1–149.

Salami, B. A., Ibrahim, M., Al-Osta, M. A., Nasir, M., Ali, M. R., Bahraq, A. A., & Wasiu, A. (2023). Engineered and green natural pozzolan-nano silica-based alkali-activated concrete: Shrinkage characteristics and life cycle assessment. *Environmental Science and Pollution Research, 30*, 17840–17853. https://doi.org/10.1007/s11356-022-23424-8

Salas, D. A., Ramirez, A. D., Ulloa, N., Baykara, H., & Boero, A. J. (2018). Life cycle assessment of geopolymer concrete. *Construction and Building Materials, 190*, 170–177. https://doi.org/10.1016/j.conbuildmat.2018.09.123

Sasanipour, H., & Aslani, F. (2020). Durability properties evaluation of self-compacting concrete prepared with waste fine and coarse recycled concrete aggregates. *Construction and Building Materials, 236*, 117540. https://doi.org/10.1016/j.conbuildmat.2019.117540

Sasanipour, H., Aslani, F., & Taherinezhad, J. (2021). Chloride ion permeability improvement of recycled aggregate concrete using pretreated recycled aggregates by silica fume slurry. *Construction and Building Materials, 270*, 121498. https://doi.org/10.1016/j.conbuildmat.2020.121498

Shen, W., Cao, L., Li, Q., Zhang, W., Wang, G., & Li, C. (2015). Quantifying CO2 emissions from China's cement industry. *Renewable and Sustainable Energy Reviews, 50*, 1004–1012. https://doi.org/10.1016/j.rser.2015.05.031

Shima, H., Tateyashiki, H., Matsuhashi, R., & Yoshida, Y. (2005). An advanced concrete recycling technology and its applicability assessment through input-output analysis. *Journal of Advanced Concrete Technology., 3*, 53–67. https://doi.org/10.3151/jact.3.53

Shirvani, M. A., Khodaparast, A., Herozi, M. R., Mousavi, R., Fallah-Valukolaee, S., Ghorbanzadeh, A., & Nematzadeh, M. (2023). Pre- and post-heating mechanical properties of concrete containing recycled fine aggregate as partial replacement of natural sand and nano-silica as partial replacement of cement: Experiments and predictions. *Archives of Civil and Mechanical Engineering, 23*, 219. https://doi.org/10.1007/s43452-023-00760-1

Silva, S., Evangelista, L., & de Brito, J. (2021). Durability and shrinkage performance of concrete made with coarse multi-recycled concrete aggregates. *Construction and Building Materials, 272*, 121645. https://doi.org/10.1016/j.conbuildmat.2020.121645

Sui, Y., & Mueller, A. (2012). Development of thermo-mechanical treatment for recycling of used concrete. *Materials and Structures, 45*, 1487–1495. https://doi.org/10.1617/s11527-012-9852-z

Tammam, Y., Uysal, M., Canpolat, O., & Kuranlı, Ö. F. (2023). Effect of waste filler materials and recycled waste aggregates on the production of geopolymer composites. *Arabian Journal for Science and Engineering, 48*, 4823–4840. https://doi.org/10.1007/s13369-022-07230-5

Tayeh, B. A., Hamada, H. M., Almeshal, I., & Bakar, B. H. A. (2022). Durability and mechanical properties of cement concrete comprising pozzolanic materials with alkali-activated binder: A comprehensive review. *Case Stud. Constr. Mater., 17*, e01429. https://doi.org/10.1016/j.cscm.2022.e01429

B. Tempest, O. Sanusi, J. Gergely, V. Ogunro, D. Weggel, Compressive strength and embodied energy optimization of fly ash based geopolymer concrete, 3rd World Coal Ash, WOCA Conf. - Proc. (2009) 1–17.

The Sustainable Development Goals Report, 2023. https://unstats.un.org/sdgs/report/2023/.

Thwe, E., Khatiwada, D., & Gasparatos, A. (2021). Life cycle assessment of a cement plant in Naypyitaw, Myanmar. *Cleaner Environmental Systems., 2*, 100007. https://doi.org/10.1016/j.cesys.2020.100007

Turner, L. K., & Collins, F. G. (2013). Carbon dioxide equivalent (CO2-e) emissions: A comparison between geopolymer and OPC cement concrete. *Construction and Building Materials, 43*, 125–130. https://doi.org/10.1016/j.conbuildmat.2013.01.023

Valencia-Saavedra, W., Robayo-Salazar, R., & de Gutiérrez, R. M. (2021). Alkali-activated hybrid cements based on fly ash and construction and demolition wastes using sodium sulfate and sodium carbonate. *Molecules, 26*, 1. https://doi.org/10.3390/molecules26247572

Wang, B., Yan, L., Fu, Q., & Kasal, B. (2021). A comprehensive review on recycled aggregate and recycled aggregate concrete. *Resources Conservation and Recycling, 171*, 105565. https://doi.org/10.1016/j.resconrec.2021.105565

Yan, P., Chen, B., Zhu, M., & Meng, X. (2024). Study on mechanical properties and microstructure of green ultra-high performance concrete prepared by recycling waste glass powder. *Journal of Building Engineering, 82*, 108206. https://doi.org/10.1016/j.jobe.2023.108206

Zhang, M., Liu, X., & Kong, L. (2023). Evaluation of carbon and economic benefits of producing recycled aggregates from construction and demolition waste. *Journal of Cleaner Production, 425*, 138946. https://doi.org/10.1016/j.jclepro.2023.138946

Publisher's Note

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