Bakhoum and Mater *Int J Concr Struct Mater* (2022) 16:63
https://doi.org/10.1186/s40069-022-00553-5

International Journal of Concrete Structures and Materials

RESEARCH Open Access

Decision Analysis for the Influence of Incorporating Waste Materials on Green Concrete Properties

Emad S. Bakhoum[1,2*] and Yasser M. Mater[1]

Abstract

Concrete industry is challenged by sustainability and technical concerns. Sustainability includes minimization of raw material usage, energy consumption, and emission of greenhouse gases, while technical concerns comprise the enhancement of mechanical properties and durability such as compressive strength, resistance to chloride, acids, and elevated temperatures. Therefore, recycling of industrial waste in manufacturing of green concrete has become a robust viable alternative to disposal, due to the limited natural resources and raw materials which contribute to sustainable construction. Consequently, this research aims to develop an approach using a multicriteria decision-making algorithm based on Analytical Hierarchy Process (AHP), to select the most suitable industrial waste to achieve the desired green concrete properties. The research starts by determining the alternatives including 18 industrial wastes, and the criteria including 14 properties of concrete. After that, an experimental database for the influence of the alternatives on the criteria is established based on the literature. Then, an algorithm is developed using a python script to analyze the influence of incorporating each of the industrial waste alternative on both the mechanical and sustainable properties of concrete. Subsequently, the efficiency of the proposed algorithm is validated using three case studies that present different circumstances of concrete specifications. Based on the proposed approach, the decision-maker can assign the appropriate residual waste to be incorporated into the concrete mix according to its application in a user-friendly manner. Such approach can support both sustainable use of waste materials and enhancement of concrete properties.

Keywords: industrial waste, green concrete, analytical hierarchy process, decision-making

1 Introduction

Sustainable development related to the construction industry is concerned with providing a health-built environment, efficient resource utilization, and adopting ecological philosophy (Yang, 2005). The need for sustainable construction is due to the major amount of natural and non-renewable resources consumed in the construction industry as well as the significant impact on the environment by generating a massive amount of waste and a huge portion of emissions. Innovation in construction is essential for sustainable development in construction (Oke et al., 2017). Therefore, countries are going towards sustainable construction as one of the measures being implemented to reduce the negative impacts of the construction industry on the environment, society, and economy.

Materials present one of the key areas to contribute towards a sustainable construction future. Therefore, this research focuses on concrete which is the most common construction material used around the world (Palankar et al., 2015). Production of concrete has negative impacts on the environment. The adverse environmental impacts

Journal information: ISSN 1976-0485 / eISSN 2234-1315.

*Correspondence: ebakhoum@nu.edu.eg

[1] Civil, Infrastructure Engineering and Management Program, Faculty of Engineering and Applied Science, Nile University, Giza, Egypt
Full list of author information is available at the end of the article

of concrete are global warming, damage to topsoil, soil erosion, natural resource depletion, landscape degradation, dust, noise, wastes, emissions, and air pollution (Alqarni et al., 2020; Assi et al., 2018; Nisbet et al., 2000). Cement is the major component of concrete. It is the major producer of CO_2 and greenhouse gasses emissions in concrete. About 88% of the concrete mix emissions are related to cement. In addition, the energy of cement production is about 70% of concrete embodied energy, while transportation only accounts for nearly 7%. Cement industry emits a considerable amount of air-pollutant such as dust, sulfur dioxide (SO_2) and nitrous oxides (NO_x) from fossil fuel burning during manufacturing and transportation (Alqarni et al., 2020; Babor et al., 2009). Therefore, there is a direct relationship between the used cement content in concrete mix and the concrete's energy consumption and the CO_2 emissions.

On the other hand, concrete additives have been adopted by concrete manufacturers to improve its mechanical properties and durability such as compressive strength, resistance to chloride attacks, acids, and elevated temperatures. At the same time, reducing the consumption of cement, reducing energy costs of concrete production, and minimization of admixtures cost are challenging tasks that can be solved using different types of waste from many industries as mineral and chemical modifiers of concrete. The waste disposal problems have provided many opportunities for the construction industry to utilize waste (Akchurin et al., 2016; Prusty et al., 2016). Waste management is a challenge for researchers due to the increasing quantities of industrial waste materials including industrial by-products. Recycling and employment of industrial wastes in concrete is an economic alternative that reduces disposals and solves the problems of land-filling space and cost to achieve sustainable construction (Siddique, 2012; Siddique et al., 2018).

According to the equation: $\text{Concrete sustainability potential} = \frac{\text{Life time} \times \text{performance}}{\text{Environmental impact}}$, there are three basic methods to producing sustainable concrete (Müller et al., 2014):

1. Optimizing the environmental impact of concrete composition at equal performance and lifetime.
2. Enhancing the performance of concrete at the same environmental impact and lifetime.
3. Optimizing the lifetime of concrete at the same environmental impact and performance.

This research presents a decision analysis approach that can contribute to these three basic methods by connecting the properties of the produced sustainable concrete to the required concrete performance.

2 Research Significance and Objectives

Green concrete is a concept of integrating environmental considerations in concrete design and construction. It considers source depletion of raw materials, concrete mix design, structural design, construction, and maintenance of concrete structures (Prusty et al., 2016). Green concrete encourages sustainable and innovative use of waste materials and untraditional alternative materials in concrete. The most important benefits of green concrete are (Dash et al., 2016; Liew et al., 2017; Liu et al., 2021):

- *Technical* Improved strength, workability, durability, and reduced cracking/curing time.
- *Economic* Reduction of construction cost, maintenance cost and increasing service life.
- *Environmental* Promotes effective waste management, greenhouse gas (GHG) reduction, and resource conservation.

Therefore, most research has been going to produce green concrete for its numerous inherent benefits. The need for green concrete is increasing due to the demand for high-quality concrete products (improvement in concrete properties), economic benefits, laws, landfill space limitations, and environmental awareness and regulations including the desire to reduce greenhouse gas emissions, the need for conservation of natural resources, carbon footprint reduction. In addition, project requirements for Leadership in Energy and Environmental Design (LEED) certifications are another demand for green construction (Dash et al., 2016; Liew et al., 2017; Teixeira et al., 2016).

In both developed and developing countries, there is an increase in generated industrial waste due to the growing urbanization and industrialization. Therefore, an extensive amount of waste materials with harmful impact on the environment is generated which causes a disposal problem (Ulubeyli et al., 2016). Construction Environmental Management can effectively minimize any potential adverse environmental to avoid, minimize and mitigate construction effects on the environment (Kabir et al., 2016). Consequently, as a smart approach that can help solving those problems, the construction industry has shown considerable interest in the utilization of waste admixtures with concrete mix to produce green concrete (Dharmaraj, 2021; Shewalul, 2021). However, there are several types of industrial wastes due to the variety of industries; each of these wastes has its individual effect when incorporated into concrete.

Several researchers investigated the properties of concrete incorporating waste materials using experimental testing (Balasubramaniam & Stephen, 2022; Brekailo et al., 2022; Kabir et al., 2016). Other studies used regression analysis to predict the properties of green concrete (Naser et al., 2022; Waghmare et al., 2022). In addition to others who used machine learning techniques such as neural networks to forecast the relationship between various properties of green concrete (Mater et al., 2022; Ray et al., 2022). However, the incorporation of a certain waste into concrete should be linked with its field of application, to enhance the quality of its required features. Most of previous studies focused on the evaluation of the concrete properties after the inclusion of waste materials. In addition, there is a lack of studies that link between the use of such concrete and the concrete specifications set by designer of the concrete mix.

To this end, this research aims to develop a decision analysis approach that enables the incorporation of waste materials in concrete according to its field of application as a step towards sustainable construction. To achieve that aim, two specific objectives are stated:

a. Establishment of the database, based on literature, by reviewing and analyzing the available industrial waste additives that can be used in concrete and optimize their effect on the concrete characteristics.
b. Develop an algorithm based on analytical hierarchy process (AHP) using a python script to implement a multicriteria decision-making tool that can assist engineers in selecting the adequate waste to be used in the manufacture of concrete. The selection process aims to optimize the required concrete properties (determined by the decision-maker/designer) taking physical/mechanical properties, durability, environmental, and economic factors into consideration.

3 Establishment of the Database from Literature

The high demand for natural resources has given many opportunities for the use of waste materials in green construction. These waste materials participate strongly in green concrete for either supplementary cementitious materials (SCM) or alternative aggregates (AA). Waste materials for green concrete can be categorized as agricultural, domestic, and industrial wastes (Liew et al., 2017). The scope of this research is limited to the industrial wastes. This research starts by reviewing the various types of industrial wastes that can be incorporated into concrete mixtures, as a replacement for cement or aggregate, and their influences on the concrete properties to establish a database for the proposed approach. These waste materials can be classified into two categories: end-of-life industrial product residues, and industrial by-product residues, as presented in Table 1.

Due to the increasing of the environmental awareness related to potentially harmful effects, and the increasing of the industrial by-product's costs of landfills, the recycling of industrial wastes has become a genius alternative to disposal (Munir et al., 2017). Several studies were conducted on the incorporation of by-products in making concrete (Anitha Selvasofia et al., 2021; Saloni et al., 2021; Siddique, 2014). On the other hand, several codes and regulations considered industrial wastes in concrete. ASTM (C618-17a) covers the use of coal fly ash and raw or calcined natural pozzolan in concrete (ASTM Committee C-09 on Concrete Aggregates, 2013). Coal combustion products are used as construction materials according to European and national standards and regulations. The European standard for "fly ash for concrete" (EN 450) deals with the evaluation of fly ash for concrete (Caldas-Vieira et al., 2013). Many codes, regulations, and guidelines that deals with the use of recycled aggregates in concrete are available in different countries around the world such as India (IS 10262) (Indian Standard 10262, 2009), Germany (DIN 4226-100), UK (BS 8500-2), Spanish code on Structural Concrete (EHE-08), French standard (NF EN 206-1/CN), Italy structural code (NTC), USA American concrete institute (ACI E-701), Hong Kong, North European countries, and Australia (Barros et al., 2017; British Standards Institution, 2006; Deutsches Institut für Normung [DIN], 2002; NTC, 2008; Suchorski & David, 2007).

3.1 Industrial End-of-Life Product Residues

3.1.1 Construction and Demolition Waste (CDW)

Construction and demolition waste (CDW) includes waste generated from building materials, construction, repair, or demolition debris and rubble (Al-Ansary et al., 2004). Recycling CDW is a step towards sustainable construction because using recycled aggregate as an alternative to natural aggregate can reduce the need for new natural resources and reduce transportation and production costs. However, experimental investigations showed that using recycled aggregate in concrete mixtures reduces its strength compared to concrete with natural aggregate (Senaratne et al., 2016). Many researchers studied the utilization of CDW as concrete aggregate (Devi et al., 2021; Pliya et al., 2021; Zhu et al., 2021). Il'ina et al. concluded that the recycling of construction waste can contribute to solve ecological and economic problems because secondary rubble from concrete is cheaper than natural, since the energy consumption for its manufacture is eight times less. Therefore, the cost of produced concrete was reduced by 25% (Il'ina & Mukhina, 2016). Panizza et. al. (2018) observed that the geopolymers with CDW improved the properties of concrete even when using 50% or more replacement aggregates (Panizza et al., 2018). Shahidan et al. showed that Recycled aggregates have higher water absorption, lower

Table 1 Industrial wastes for concrete.

Category	Industry	Waste	
		Name	Abbreviations
Industrial end-of-life product residues	Construction industry		
	■ Buildings' demolition	(1) Construction and demolition waste	CDW
	■ Glass manufacturing	(2) Glass waste	GW
	■ Acrylic paints production	(3) Water-dispersible acrylic monomer	WDAM
	Automotive industry		
	■ Tires manufacturing	(4) Recycled tire rubbers	TR
Industry by-product residues	Metal industry		
	■ Silicon metal production	(5) Waste silica "silica fume"	SF
	■ Metal casting production	(6) Spent foundry sand	SFS
	■ Steel manufacturing	(7) Steel slag	SS
		(8) Ground granulated blast furnace slag	GGBS
		(9) Iron waste	IW
	■ Copper manufacturing	(10) Copper slag	CS
	Construction industry		
	■ Marble and granite mining and processing	(11) Marble waste	MW
	■ Quarries, rock mining and processing	(12) Quarry dust	QD
	■ Kaolin mining and processing	(13) Kaolin waste	KW
	■ Wastewater treatment plants	(14) Sewage sludge ash	SSA
	■ Wood manufacturing	(15) Wood ash	WA
	Thermal power plants		
	■ Coal-fired power plants	(16) Coal fly ash	FA
		(17) Coal combustion bottom ash	CCBA
	■ Burning of palm oil waste power plants	(18) Palm oil fuel ash	POFA

specific gravity, lower density, and much higher porosity compared to natural aggregates. It was observed that the optimum results for the splitting tensile strength, compressive strength, and water absorption were noticed for the 10-mm-sized aggregates. The slump value of recycled aggregate concrete (RAC) was reduced (Shahidan et al., 2017). In addition, Hassanein and Ezeldin concluded that replacing 20–30% of the natural aggregate with recycled aggregate had minor effects on the compressive strength (Hassanein & Ezeldin, 2013).

3.1.2 Glass Waste (GW)

Using recycled glass as a concrete aggregate has been an interesting area due to its benefits of water absorption and drying shrinkage (Guo et al., 2020). Lee et. al. (2011) showed that the reduction in glass particle size can reduce the alkali-silica reaction (ASR) expansion. Waste glass has been utilized as SCM in many concrete applications such as ultra-lightweight fiber reinforced concrete, glass-reinforced panels, concrete for structural repairs, fast-cured polymer concrete, architectural mortar, and self-compacting concrete (Ling et al., 2013). The benefits of using waste glass are improving the compressive strength, resistance to freezing and thawing, chloride penetration and surface scaling, and good resistance to Na_2CO_3 and H_2SO_4. The recommended optimum percentage was 5–10% for cement replacement and 7.5–25% for fine aggregate replacement. However, incorporating a high waste glass ratio may cause negative impacts such as slump and compressive strength reduction (Liew et al., 2017).

3.1.3 Water-Dispersible Acrylic Monomer (WDAM)

Akchurin et. al. (2016) reviewed the possibility of using a water-dispersible acrylic monomer (WDAM) in the waste of construction acrylic paints production to improve the concrete properties. The study showed that the maximum increase in the density was about 10%, and the maximum increase in compressive strength was 25–30% for concrete samples modified WDAM. Reduction in porosity and water absorption index was about 60% at 0.3% WDAM, and 65% at 3% WDAM (cement weight).

3.1.4 Recycled Tire Rubbers (TR)

Lower density, enhanced ductility, and better sound insulation are attractive characteristics for rubberized concrete. However, the production of concrete with rubber aggregates reduces its compressive strength which limits its use in some structural applications (Siddique & Naik, 2004). Al-Adili et. al. (2015) studied the properties of concrete by adding iron splinters (scrap) and minced rubber. The highest compressive strength was obtained (increasing about 36%) with a ratio of adding (10% iron splinter + 5% of minced rubber) admixture. Flexural strengths for this percentage were found to be the highest value (about 12%). Pelisser et. al. (2011), and Rajan et. al. (2021) noticed that at a replacement percentage of 10% sand by recycled tire rubber, that there was a reduction 14% in compressive strength compared to the conventional concrete and the concrete compositions was lighter. Ganjian et. al. (2009) indicated that using waste tire rubber up to 5% replacement did not significantly affect the concrete characteristics. Benazzouk et. al. (2007) observed that the mechanical characteristics of lightweight concrete (LWC) were accepted using a percentage of 50% of rubber. Khaloo et. al. (2008) concluded that using rubber waste produces concrete with lower unit weights. Using waste rubber > 25% was not recommended due to significant reductions in ultimate strength. Li et. al. (2004) concluded that steel belt wires in waste tires had increased the strength of rubberized concrete. Turatsinze et. al. (2007) showed that using rubber aggregates obtained from shredded non-reusable tires in cement mortar can limit their tendency for cracking.

3.2 Industrial By-product Residues

3.2.1 Waste Silica (Silica Fume SF)

Silica is generally classified as fume and known as "silica fume" (SF). It is a fine solid material generated during silicon metal production. SF has been used in many applications and acted as SCM, filler and healing agents due to its high pozzolanicity and its extreme fineness. Its benefits in concrete include improving flexural and compressive strengths, durability, and increasing pozzolanic activity (Chaitanya & Ramakrishna, 2021). In addition, it increases multi-range macro-porosity properties that allow its usage in the production of high-porosity cement foams and multi-strength lightweight concrete (LWC). The optimum percentage of SF is 10–14% when used in combination with materials such as steel fibers, nano-silica, and recycled aggregate. Using SF in concrete had some negative impacts such as reduction in long-term compressive strength, workability, and creep (Liew et al., 2017; Siddique, 2014). Hendi et. al. (2018) studied the concrete mix using glass powder and micro-silica (with high silica content). Results showed that ordinary concrete with lower superplasticizer content had better performance in HCl medium than self-consolidating concrete (SCC). Concrete with compressive strength between 32 and 34 MPa volume of permeable pores of 15.68% had the top durability performance in HCl acid medium.

3.2.2 Spent Foundry Sand (SFS)

Spent foundry sand (SFS) is a by-product waste material generated from the metal casting industry (Iqbal et al., 2021; Kavitha et al., 2021). Siddique et. al. (2018) investigated the economic and environmental advantages of using SFS in concrete as sand replacement. Green concrete containing SFS improved compressive strength up to 26% and splitting tensile strength up to 12.87%. Also, the strength and durability properties of green concrete were improved at an optimum of 15% SFS sand replacement. In addition, it achieved a reduction in CO_2 emissions and saved disposal costs.

3.2.3 Steel Slag (SS)

Steel manufacturing generates an industrial by-product called steel slag. It can be incorporated in concrete mix as cement or aggregate replacement (Devi et al., 2020; Maharishi et al., 2021; Manjunatha et al., 2021). Wang (2016) as well as Jiang et. al. (2018) found that it can be used as SCM with a satisfactory performance at a ratio of 10–20% by weight. Palankar et. al. (2015) assessed the use of steel slag coarse aggregates in geopolymer concrete as a replacement for natural aggregates with different ratios. It indicated that when using steel slag, there was a slight reduction in compressive strength and higher values of water absorption.

3.2.4 Granulated Blast Furnace Slag (GGBS)

Geopolymer concrete (GPC) and alkali-activated slag (AAS) cement can be produced by using granulated blast furnace slag (GGBS) in concrete. It was recommended that a ratio of 4:1 was the optimum for cement: GGBS at $W/C = 0.3$ and cement-to-sand ratio of 1:1.5. One of the advantages of using GGBS and fly ash is the efficiency in producing durable structures in aggressive natural environments as well as providing steel protection (Liew et al., 2017). Several researchers (Dixit, 2021; Gholampour & Ozbakkaloglu, 2017; Majhi et al., 2018; Senaratne et al., 2017) noticed that the concrete properties can be improved using silica fume, fly ash, metakaolin, and ground granulated blast slag (GGBS). It showed greater improvements in recycled aggregate concrete than natural aggregate concrete.

3.2.5 Iron Waste (IW)

Ismail and Al-Hashmi (2008) examined the feasibility of reusing waste iron in concrete as a partial replacement for sand with percentages ranging from 10 to 20% in the concrete mixtures. The results showed that the concrete mixes made with waste iron had higher compressive strengths and flexural strengths compared to traditional concrete mixtures. However, a slight decrease in the workability was observed. Satyaprakash et. al. (2019) investigated the effect of replacing fine aggregates in concrete with iron fillings to mitigate the effect of natural resource depletion due to sand mining. Results showed a substantial increase in the compressive and splitting-tensile strengths of concrete with the complete replacement of sand with iron fillings.

3.2.6 Copper Slag (CS)

Copper slag is an industrial by-product that is used as sand replacement in concrete mix (Prem et al., 2018). It was concluded that it is technically possible to use high-volume copper slag up to 100% replacement in concrete. Higher compressive and flexural strengths and an improvement in the water absorption of concrete were observed with the incorporation of copper slag. Maharishi et. al. (2021) revealed that the addition of up to 40% CS (by weight of fine aggregate) had a favorable effect on the mechanical properties of the resulting concrete. Furthermore, it increased the resistance to sulfate attack and decreased the porosity and water absorption of concrete.

3.2.7 Marble Waste (MW)

Ulubeyli et. al. (2016) studied the influence of conventional and self-compacting concrete containing waste marble on the durability of concrete. It was found that it can improve durability properties including water absorption, permeability, and resistance to chloride penetration and sulfate attack. However, there was no significant difference observed for resistance to carbonation. Rana et. al. (2016) concluded that recycled marble/granite as coarse aggregates can be used as a total replacement for natural aggregates with acceptable strength. Anitha Selvasofia et. al. (2021) revealed that up to 10% waste marble powder as a replacement for sand enhanced the mechanical properties of concrete. Moreover, increasing the ratio of MW can further increase the mechanical properties, but it would have a highly negative impact on the workability of concrete.

3.2.8 Quarry Dust (QD)

Meisuh et. al. (2018) studied the effect of using quarry dust on concrete flexural strength. It was found that the flexural strength of concrete with 25% and 100% quarry dust were, respectively, 2% and 4.3% higher compared with ordinary concrete. In addition, the optimum CRD replacement level for strength properties of concrete was 20% (Febin et al., 2019; Kumar & Ram, 2018; Ponnada et al., 2020).

3.2.9 Kaolin Waste (KW)

The kaolin mining and processing industry generates large amounts of waste (Hasan et al., 2021). Lotfy et. al. (2015) investigated the benefits of utilization of kaolin waste (KW) in concretes mix. Different KW replacement percentages 0%, 5%, 10%, 15%, 20% and 25% of Portland cement by weight were studied. It was shown that using KW had improved the compressive strength, particularly at replacement ratios of 10% and 15%. In addition, increasing KW content improved the concrete chloride ion penetration resistance.

3.2.10 Sewage Sludge Ash (SSA)

Several researchers used sewage sludge ash in concrete (Nakic, 2018; Wu et al., 2021), Nakic (2018) found that the incorporation of up to 10% SSA (by weight of cement) had minimal effect on the mechanical properties of concrete, with a slight increase in the compressive strength. Although the presence of SSA adversely affected the workability of concrete, it showed that the use of SSA in concrete could reduce greenhouse gas emissions and help conserve non-renewable natural resources. Baeza-Brotons et. al. (2014) used SSA and marble dust in concrete with percentages of 5, 10, 15, and 20% of cement as a replacement for sand. It was noticed that the density and resistance are similar in both concrete blocks containing SSA and the control sample. However, there was a significant reduction in water absorption.

3.2.11 Wood Waste Ash (WA)

Wood ash (WA) is generated as a residue through wood combustion processes (Rollakanti et al., 2021). Using WA in concrete mix can provide a solution to the waste management problem of wood ash and minimize the usage of energy extensive hydraulic cement (Chowdhury et al., 2015; Siddique, 2012). Chowdhury et. al. (2015) investigated the utilization of wood ash (WA) as a partial replacement of cement in concrete. Compared to cement, the wood ash particles are coarser and have a higher specific surface because it has porous nature and irregular shape. It was reported that increasing of wood ash ratio caused an increase in water absorption and a major decrease in strength and split tensile strength and a gradual reduction in bulk density. However, WA replacement ratio of up to 10% by cement (by weight) could produce good structural concrete.

3.2.12 Coal Fly Ash (FA)

Fly ash (FA) is a fine powder generated from gases produced by coal-fired electric power generation, and usually discarded in landfills (Kurama & Kaya, 2008). Using fly ash (FA) from coal-fired power plants can solve the waste problems and reduce overall energy use. The use of fly ash as SCM in various concrete applications has been investigated by many researchers because it contains silica. It can be replaced from 15 to 35% of the cement in concrete mixes. Fly ash increases concrete strength, improves sulfate resistance, workability, segregation, and ease of pumping of concrete, as well as decreases both permeability and water ratio required. Fly ash had negative impacts on high-volume fly ash concrete (HVFAC), such as extended setting times, slow strength development, and low early-age strength (Babor et al., 2009; Liew et al., 2017). Golewski (2017) used coal fly ash in concrete and explored the effect of the curing time on the concrete strength. Hanjitsuwan et. al. (2018) studied the strength and durability of alkali-activated fly ash (FA) mortar with calcium carbide residue with 0% to 30% (Hanjitsuwan et al., 2018). Assi et. al. (2018) used waste materials (fly ash and slag) in geopolymer concrete and concluded that Geopolymer concrete can reduce the required energy by 36% compared with Portland cement. It reflects the reduction of CO_2 emissions due to the decrease in fuel usage. The cost of geopolymer concrete and Portland cement was studied and concluded that there was a difference in the cost of about 17%.

3.2.13 Coal Combustion Bottom Ash (CCBA)

Bajare et. al. (2013) studied the economic benefit of using coal combustion bottom ash (CCBA) as cement replacement (partially) to reduce energy consumption and CO_2 emissions. It found that it was possible to decrease the concrete price by 10% and the amount of CO_2 emission by 22.9% by using grinded coal combustion bottom ash. CCBA can be used as an aggregate replacement, however, the porous surface structure of CCBA particles make it less durable and lighter than natural aggregates. Therefore, it is useful in lightweight concrete applications. Specimens with 20% cement replacement had the best results. Cerny et. al. (2017) studied the utilization of different types of fly ash for artificial sintered aggregate in order to produce lightweight high-strength concrete. Teixeira et. al. (2016) found that incorporating by-product waste of power/heat production sectors as fly ashes in concrete as cement replacement can improve the environmental performance of the concrete.

3.2.14 Palm Oil Fuel Ash (POFA)

Palm oil fuel ash (POFA) is a by-product material obtained in power plants as a result of the burning of palm oil industry waste (palm kernel shell, palm oil fiber, and palm oil husk) for the generation of electricity. Many studies (Alnahhal et al., 2021) evaluated POFA as a construction material because it has pozzolanic characteristics, and can be used as a partial replacement for cement in concrete (Hamada et al., 2018; Thomas et al., 2017). Palm oil fuel ash was used as SCM. It was reported that concrete mix with POFA had high strength, higher performance at elevated temperatures, low shrinkage, permeability, and high resistance to carbonation, chloride, sulfate, and acidic environment. However, adding POFA reduced the concrete workability and setting time because it reduces the heat of hydration. It may be used up to 20% without any considerable reduction in the workability. Using concrete with 10–30% POFA produced compressive strength higher than traditional concrete. Using POFA in concrete with a ratio of 10–20% had given higher splitting tensile strength than conventional concrete. Moreover, using POFA in lightweight foamed concrete with a ratio of 10% and 20% gives flexural tensile strengths and durability higher than conventional concrete (Hamada et al., 2018; Thomas et al., 2017). Shafigh et. al. (2016) used waste materials of oil palm shell (as coarse aggregate) and a high volume (50% and 70%) of type F fly ash (as cement replacement by mass) to make structural lightweight aggregate concrete. It was found that high-volume fly ash in oil palm shell concrete significantly reduced short-term mechanical properties. However, the use of limestone powder significantly improved the compressive strength at early and later ages.

4 Materials and Methods

4.1 Framework of the Algorithm Using AHP and Python

This research developed a multicriteria decision-making algorithm that can choose the most suitable waste material for a concrete mixture based on a database compiled from previous literature. The algorithm is implemented through python, based on Analytical Hierarchy Process (AHP), with the aim of choosing the most suitable industrial waste from a list of proposed alternatives (wastes). It maximizes the score of an alternative based on the following two main factors: first; whether the increase or decrease of a specified criterion is beneficial to concrete (according to the database from the literature). Second: the importance of this specific criterion according to the needs of the project/structural element (set by the decision-maker/concrete mix designer). The algorithm is built to include the effect of eighteen industrial wastes on fourteen reinforced concrete characteristics. Alternatives present the list of industrial wastes. Criteria present the concrete characteristics. The algorithm helps to select the alternative that optimizes the criteria. The AHP hierarchy is presented in Fig. 1.

4.2 Process Methodology

The decision-making process can be summarized in the following steps:

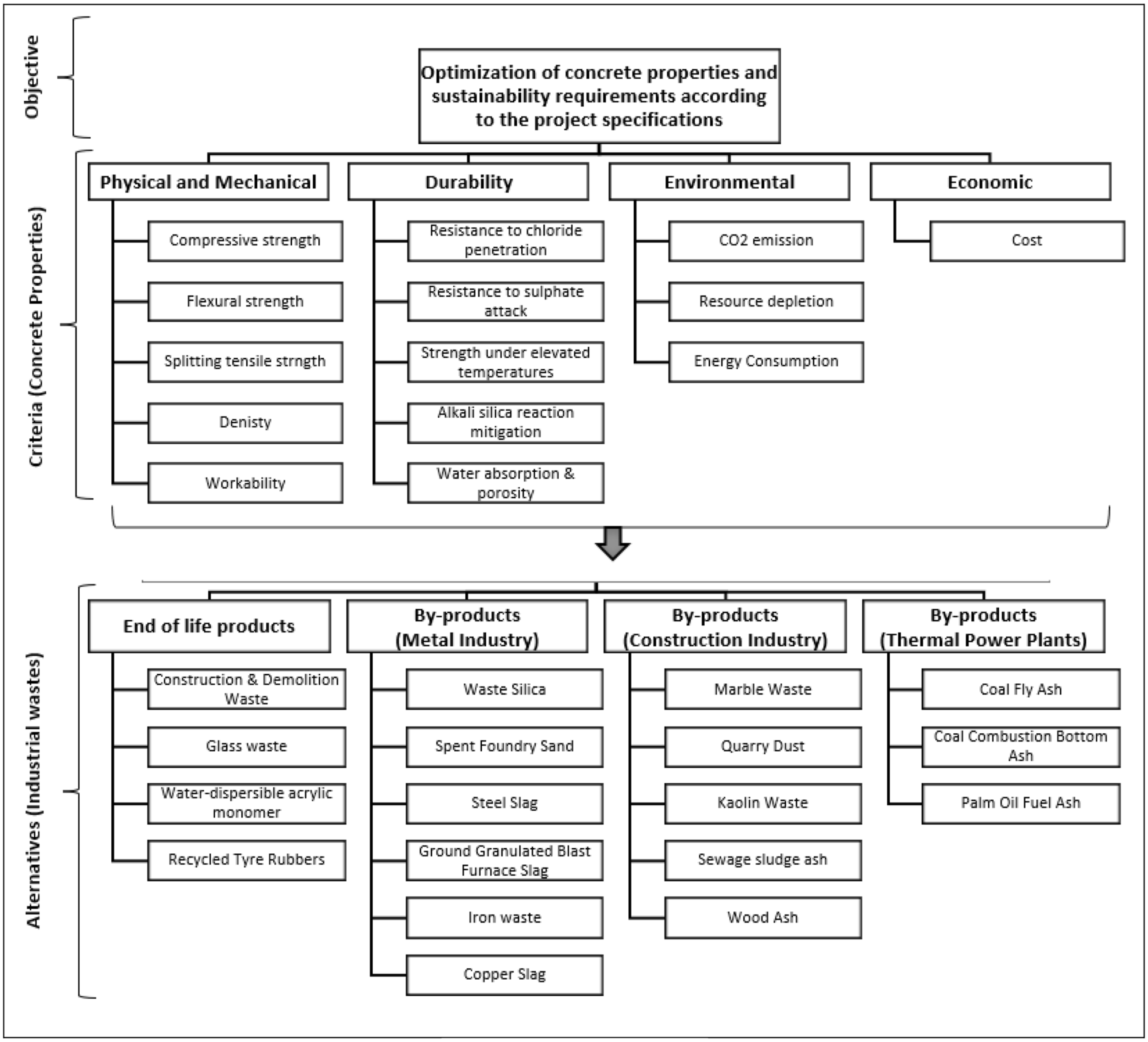

Fig. 1 AHP hierarchy.

1. Inputs to the algorithm

   a. Pairwise comparison between the criteria according to the project needs.
   b. The proposed alternatives and their effect on concrete (logic that determines whether the increase or decrease of a specific criterion is beneficial to concrete as presented in the desired outcome as presented in Table 2).

2. Validation
   The algorithm validates if the inserted data (matrix forms) are consistent with each other.

3. Score calculation
   The algorithm calculates a relative score for each alternative.
   Fig. 2 presents the flowchart of the process mechanism.

4.3 Materials Database

The criteria and alternatives and their abbreviations used in this research are presented in Table 2. The desired outcome presented in Table 2 refers to whether a specific criterion should increase or decrease to enhance the quality of the resulting concrete, while Table 3 shows the actual effect of an alternative on each of the studied criteria

Table 2 Concrete characteristics (criteria).

Properties	Criteria		Abbreviation	Desired outcome
Physical and mechanical	1	Compressive strength	Co. S	↑ up (increase)
	2	Flexural strength	Fl. S	↑ up (increase)
	3	Splitting tensile strength	S. TS	↑ up (increase)
	4	Density	D	↑ up (increase)
	5	Workability	W	↑ up (increase)
Durability	6	Resistance to chloride penetration	RCP	↑ up (increase)
	7	Resistance to sulfate attack penetration	RSAP	↑ up (increase)
	8	Strength under elevated temperatures	SUET	↑ up (increase)
	9	Alkali silica reaction mitigation	ASRM	↑ up (increase)
	10	Water absorption and porosity	WA/P	↓ down (decrease)
Environmental	11	CO_2 emission	CO_2 E	↓ down (decrease)
	12	resource depletion	RD	↓ down (decrease)
	13	Energy consumption	EC	↓ down (decrease)
Economic	14	Cost	C	↓ down (decrease)

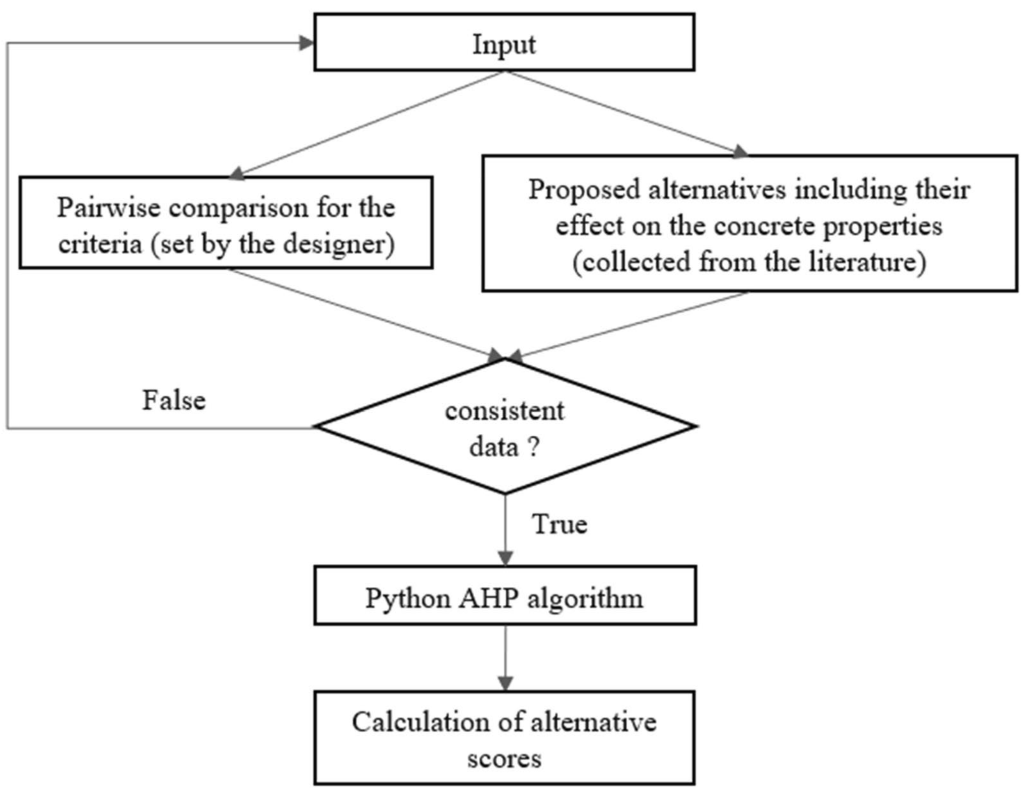

Fig. 2 Flowchart of the process.

according to the database collected in this research. It should be noted that two assumptions were made during the construction of the alternatives matrix: the first is that the effect of waste on a concrete property (criterion) was determined based on the optimum amount of that waste when it is used in concrete. The second is that if there is no data about the effect of a waste on a specified property (criterion), its effect was assumed to be neutral.

Although the exact effect (percent increase/decrease) of an industrial waste can differ from one research paper

Table 3 Database for the effect of industrial wastes on the concrete properties.

Replacement	Industrial waste	Physical and mechanical properties of concrete					Durability characteristics					Environmental factors			Economic
		Co. S	Fl. S	S. TS	D	W	RCP	RSAP	SUET	ASRM	WA/P	CO_2 E.	RD	EC	C
Aggregate	CDW	↓	↓	–	↓	↓	–	–	↓	↑	↑	–	↓	↓	↓
		Devi et. al. (2021), Il'ina and Mukhina (2016), Pliya et. al. (2021), Shahidan et. al. (2017), and Zhu et. al. (2021)													
	IW	↑	↑	↑	–	↓	–	–	–	–	–	–	–	–	↓
		Ismail and Al-Hashmi (2008), and Satyaprakash et. al. (2019)													
	TR	↓	↓	↓	↓	–	–	–	–	–	↓	–	↓	–	–
		Al-Adili et. al. (2015), Benazzouk et. al. (2007), Dharmaraj (2021), Khaloo et. al. (2008), Pelisser et. al. (2011), Rajan et. al. (2021), Shewalul (2021), and Siddique and Naik (2004)													
	SFS	↑	–	↑	–	↓	–	–	–	–	–	↓	–	–	↓
		Iqbal et. al. (2021), Kavitha et. al. (2021), and Siddique et. al. (2018)													
	MW	↑	↑	↑	↓	↓	↑	↑	–	↑	↑	–	–	–	–
		Rana et. al. (2016), Anitha Selvasofia et. al. (2021), and Ulubeyli et. al. (2016)													
	QD	↑	↑	↑	–	↓	–	–	–	–	↓	–	–	–	↓
		Febin et. al. (2019), Meisuh et. al. (2018), Nasier, (2021), and Ponnada et. al. (2020)													
	CCBA	↓	↓	–	–	–	–	–	–	–	–	↓	–	↓	↓
		Bajare et. al. (2013), and Kurama and Kaya (2008)													
	SS	↓	–	–	–	↓	↑	–	–	–	↑	–	–	–	–
		Devi et. al. (2020), and Palankar et. al. (2015)													
	CS	↑	↑	↑	↑	–	–	↑	–	–	↓	–	↓	–	↓
		Maharishi et. al. (2021), Manjunatha et. al. (2021), and Prem et. al. (2018)													
Cement	WDAM	↑	↑	–	↑	–	↑	–	–	–	↓	↓	–	↓	–
		Akchurin et. al. (2016), and Liu et. al. (2021)													
	SF	↑	↑	–	↑	↓	↑	↑	↑	↑	–	↓	↓	↓	–
		Chaitanya and Ramakrishna (2021), Liew et. al. (2017), and Siddique (2014)													
	KW	↑	↑	↑	–	↑	↑	↑	–	–	–	–	–	↓	–
		Hasan et. al. (2021), and Lotfy et. al. (2015)													
	FA	↑	↑	–	–	↑	↑	↑	↑	↑	–	–	↓	↓	–
		Babor et. al. (2009), Dharmaraj, (2021), and Liew et. al. (2017)													
	POFA	↑	↑	↑	–	↓	↑	↑	↑	–	–	↓	–	↓	↓
		Alnahhal et. al. (2021), Hamada et. al. (2018), and Thomas et. al. (2017)													
	WA	↑	↑	↑	–	↓	–	–	–	–	↑	↓	–	↓	–
		Chowdhury et. al. (2015), Dixit (2021), and Rollakanti et. al. (2021)													
	GGBS	↓	↓	↓	↓	↑	↑	↑	↑	↑	↓	↓	–	–	–
		Chabi et. al. (2018), Gholampour and Ozbakkaloglu (2017), and Majhi et. al. (2018)													
	GW	↑	–	–	–	↑	↓	↑	↑	↑	↓	↓	–	↓	–
		Chabi et. al. (2018), and Guo et. al. (2020)													
Both	SSA	↑	–	–	–	↓	–	–	–	–	↓	↓	↓	–	↓
		Baeza-Brotons et. al. (2014), Nakic (2018), and Wu et. al. (2021)													

[↑] refers to increasing value, [↓] refers to a decreasing value, [–] refers to a neutral value.

to another, it was found that most of the literature agreed on whether a specific waste had an increasing/decreasing effect on each specific criterion. Therefore, each alternative was assumed to either; increase, decrease, or keep a specified criterion as neutral. Such effect was given a numbering value as follows: increasing = 2, decreasing = 0.5, neutral = 1, which means that increasing and decreasing values were assigned two reciprocal values. Changing those two proposed values had a minor effect on the results, which will be explained in the sensitivity analysis process.

5 Application and Validation

5.1 Case Studies

The proposed algorithm is applied on three case studies representing three concrete elements to validate and analyze the results from the algorithm. The priority of each criterion was assumed as shown in Table 4 for each structural element. These priorities were set according to the following.

5.1.1 Case 1: RC Column

The first case study was implemented to represent the required concrete characteristics of a reinforced concrete column; therefore, the compressive strength was given the highest possible value. After which comes the workability as concrete columns require a considerable amount of workability during concrete placement. Other durability factors were given less value since concrete columns inside of buildings are protected by concrete surface finishing. Finally, the environmental and economical values were given the least priority since concrete columns have the least volume with respect to the volume of other structural members of a reinforced concrete (RC) building.

5.1.2 Case 2: RC Slab

The second case study was developed to demonstrate the case of a reinforced concrete slab; therefore, the flexural and splitting tensile strengths were given the highest priority, followed by the compressive strength as it known to be the most important property in reinforced concrete structural members. Environmental and economic factors were also given the second priority due to the large concrete volume required to pour concrete slabs within a project with respect to the other structural members of the same RC building. Finally, durability factors were given a lesser priority as concrete slabs are protected by the flooring and surface finishing works.

Table 4 Priority of each criterion.

Concrete characteristics		Priority		
		Case 1	Case 2	Case 3
1	Compressive strength	9	5	3
2	Flexural strength	3	9	3
3	Splitting tensile strength	3	9	3
4	Density	3	3	3
5	Workability	5	3	5
6	Resistance to chloride penetration	3	3	5
7	Resistance to sulfate attack penetration	3	3	5
8	Strength under elevated temperatures	3	3	5
9	Alkali silica reaction mitigation	3	3	5
10	Water absorption and porosity	3	3	5
11	CO_2 emission	1	5	9
12	Resource depletion	1	5	9
13	Energy consumption	1	5	9
14	Cost	1	5	9

5.1.3 Case 3: Concrete Block Pavements

Finally, the third case study was implemented to represent non-structural concrete members, such as concrete block pavements. The highest priority was given to the environmental and economic factors, followed by the durability of concrete, because such members may not be surface finished, and they may be subjected to extreme weather conditions. Finally, the least priority was given to physical and mechanical properties of concrete since it is a non-structural member.

5.2 Results and Analysis

The results of the three case studies are presented in Fig. 3, and they were compatible with the priorities set in the algorithm. In addition, they were compatible with the results of previous research from the literature. For example, the best industrial waste to use in a concrete column (case 1) was found to be fly ash, since it is known to increase both the compressive strength and workability, as reported in experimental studies (Gadag et al., 2022; Rao et al., 2022), while the industrial waste with the least score is CDW as it is known to have an adverse effect on both the compressive strength and workability because of its higher water absorption owing to the presence of adhered cement mortar (Devi et al., 2021).

Results of case 2 showed that palm oil fuel ash and copper slag have the highest scores because they have a positive impact on the flexural and splitting tensile strengths, while the worst alternative was found to be traditional/modifier rubber because of its negative effect on both properties. Finally, silica fume and fly ash had the highest potential to be used in non-structural concrete elements as in case 3, because they can greatly enhance the concrete durability, while the worst alternative in this case was the steel slag because it is reported to increase the porosity and water absorption of concrete, which in turn decreases the durability.

5.3 Sensitivity Analysis for the Reciprocal Values

To validate the proposed methodology for the decision-making tool presented in this research, the reciprocal increase and decrease values were changed by other numerical values and the effect was studied on case 1. The average difference between two consecutive scores is plotted against various reciprocal values in Fig. 4. An amplification effect was noticed when the gap between the reciprocal values increased, such effect boosted the influence of increasing/decreasing criteria with respect to criteria having neutral values, which means that the sensitivity of the decision-making system in the

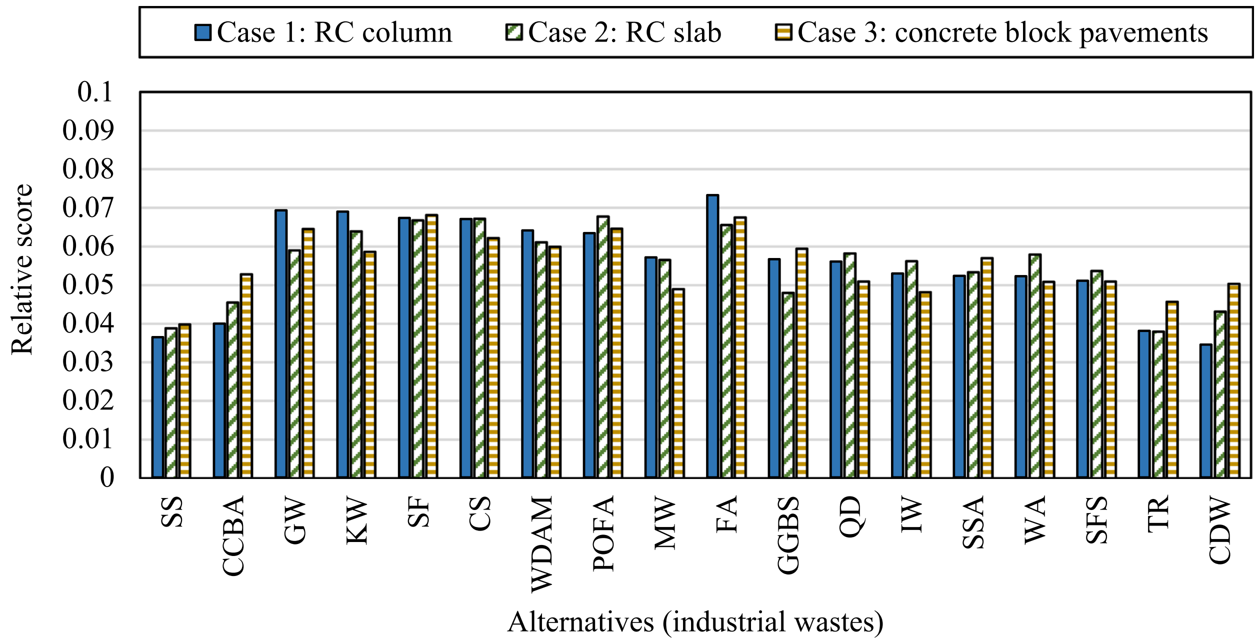

Fig. 3 Relative scores for the different industrial wastes.

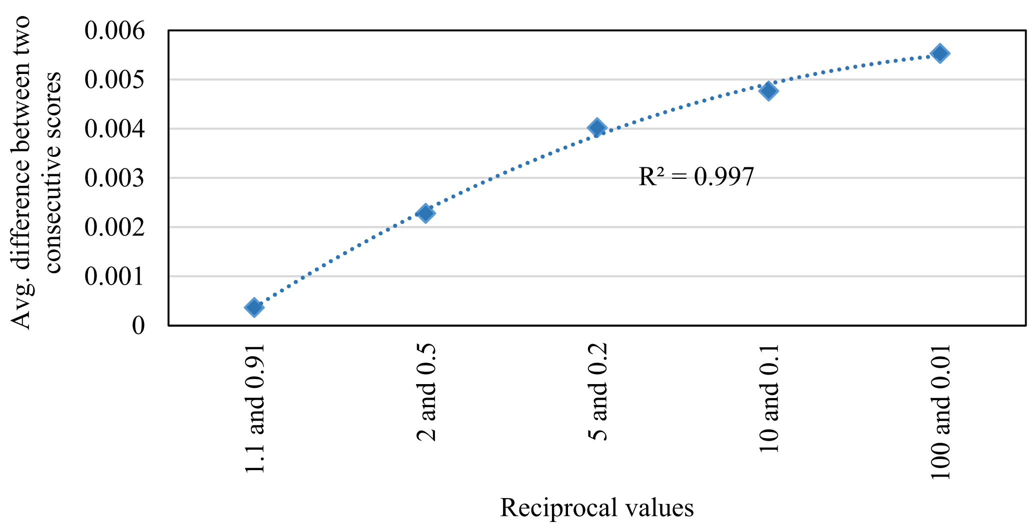

Fig. 4 Avg. difference between consecutive scores when using other reciprocal values.

proposed methodology can be adjusted to account for the significance of the influence of any waste material on a specific concrete property.

Table 5 shows the ordering of the alternatives according to the proposed criteria in case 1, the obtained results were in good agreement with the experimental database. However, some changes to the ordering were noticed due to the previously illustrated amplification effect.

6 Conclusions and Recommendations

Natural and raw materials are limited on our planet. Moreover, huge amounts of waste are generated due to mining, processing, and industrial activities. Therefore, this research considered the reuse and recycling of wastes to provide alternatives to raw materials in construction to preserve natural resources, reduce the waste in landfills, save energy, reduce cost, and improve public health. Utilizing waste materials as alternatives for

Table 5 Order of alternatives using different reciprocal values.

Industrial waste	1.1 and 0.91	2 and 0.5	5 and 0.2	10 and 0.1	100 and 0.01
FA	1	1	1	1	1
KW	2	3	4	4	5
CS	3	5	5	5	6
GW	4	2	2	2	3
SF	5	4	3	3	2
WDAM	6	6	8	8	8
POFA	7	7	7	7	7
QD	8	10	10	10	10
MW	9	8	9	9	9
IS	10	11	12	12	13
SSA	11	12	13	13	12
WA	12	13	11	11	11
SFS	13	14	14	14	14
GGBS	14	9	6	6	4
CCBA	15	15	16	17	18
TR	16	16	15	16	16
SS	17	17	18	18	17
CDW	18	18	17	15	15

cement or aggregates in green concrete is presented as one of the most sustainable and innovative methods due to its environmental and economic advantages. However, the performance of green concrete should be optimized to maximize these advantages.

This research starts by presenting a classification and explanation of the different wastes that can be used in concrete. The influence of each waste on the produced concrete is reviewed from the points of physical/mechanical properties; durability; environmental impact; and economic effectiveness. According to the analysis of these effects, the decision-maker has to choose the best residue that can achieve the objectives. Therefore, an efficient algorithm—implemented using python—is proposed to optimize the utilization of wastes in green concrete. Based on AHP the algorithm can calculate a score for each waste material from a database of waste alternatives. The score depends on both the effect of each waste on every property of the concrete (in the database), and the required concrete specifications (set by the designer). Three case studies were proposed to test and validate the efficiency of the proposed algorithm. The three case studies aim to present different circumstances where different concrete specifications are required. The results were compatible with the priorities set for each case study. Furthermore, they show high compatibility with experimental results of previous research from the literature.

Since there is no waste material that can be used to enhance all the concrete properties altogether, the adoption of the proposed methodology in the production of green concrete promotes both the sustainability and mechanical properties of concrete. However, building a larger database incorporating more waste materials and more concrete properties can significantly enhance the decision-making process. Also, further research is still required to implement a qualitative and quantitative approach for data collection and analysis to achieve more precise input and output from the proposed methodology.

Acknowledgements
The authors would like to express their gratitude to Nile University (NU) for supporting this research.

Author contributions
ESB contributed to conceptualization, literature review, methodology, investigation, validation, writing, reviewing, and editing. YMM contributed to literature review, methodology, investigation, validation, software and coding, writing, reviewing, and editing. Both authors read and approved the final manuscript.

Authors' information
ESB: Associate Professor in Construction Engineering and management, Civil, Infrastructure Engineering and Management Program, Faculty of Engineering and Applied Science, Nile University, Giza, Egypt (postal code 12677). ORCID No. https://orcid.org/0000-0002-8368-529X.
YMM: Instructor, Civil, Infrastructure Engineering and Management Program, Faculty of Engineering and Applied Science, Nile University, Giza, Egypt (postal code 12677). ORCID No. https://orcid.org/0000-0002-4182-2591.

Funding
Open access funding provided by The Science, Technology & Innovation Funding Authority (STDF) in cooperation with The Egyptian Knowledge Bank (EKB). The authors received no financial support for the research, authorship, and/or publication of this article.

Availability of data and materials

The datasets used and/or analyzed during the current study are available from the corresponding author on reasonable request.

Declarations

Competing interests

The authors declare that they have no competing interests.

Author details

[1]Civil, Infrastructure Engineering and Management Program, Faculty of Engineering and Applied Science, Nile University, Giza, Egypt. [2]Civil Engineering Department, National Research Centre, Giza, Egypt.

Received: 13 May 2022 Accepted: 24 July 2022
Published online: 01 November 2022

References

Akchurin, T. K., Tukhareli, A. V., & Cherednichenko, T. F. (2016). Effective concrete modified by complex additive based on waste products of construction acrylic paints. *2nd International Conference on Industrial Engineering (Icie-2016), 150*, 1468–1473. https://doi.org/10.1016/j.proeng.2016.07.083

Al-Adili, A., Al-Ameer, O. A., & Raheem, E. (2015). Investigation of incorporation of two waste admixtures effect on some properties of concrete. *International Conference on Technologies and Materials for Renewable Energy, Environment and Sustainability—TMREES, 15*(74), 652–662. https://doi.org/10.1016/j.egypro.2015.07.801

Al-Ansary, M. S., El-Haggar, S. M., & Taha, M. A. (2004). *Sustainable guidelines for managing demolition waste in Egypt.* Paper presented at the proceedings of the international RILEM conference on the use of recycled materials in building and structures, Barcelona.

Alnahhal, A. M., Alengaram, U. J., Yusoff, S., Singh, R., Radwan, M. K. H., & Deboucha, W. (2021). Synthesis of sustainable lightweight foamed concrete using palm oil fuel ash as a cement replacement material. *Journal of Building Engineering, 35*, 102047. https://doi.org/10.1016/j.jobe.2020.102047

Alqarni, A. S., Albidah, A. S., Alaskar, A. M., & Abadel, A. A. (2020). The effect of coarse aggregate characteristics on the shear behavior of reinforced concrete slender beams. *Construction and Building Materials, 264*, 120189.

Anitha Selvsofia, S. D., Dinesh, A., & Babu, S. (2021). Investigation of waste marble powder in the development of sustainable concrete. *Materials Today: Proceedings, 44*, 4223–4226.

Assi, L., Carter, K., Deaver, E., Anay, R., & Ziehl, P. (2018). Sustainable concrete: Building a greener future. *Journal of Cleaner Production, 198*, 1641–1651. https://doi.org/10.1016/j.jclepro.2018.07.123

ASTM Committee C-09 on Concrete Aggregates. (2013). *Standard specification for coal fly ash and raw or calcined natural pozzolan for use in concrete*. ASTM international.

Babor, D., Plian, D., & Judele, L. (2009). Environmental impact of concrete. *Buletinul Institutului Politehnic Din Lasi. Sectia Constructii, Arhitectura, 55*(4), 27.

Baeza-Brotons, F., Garces, P., Paya, J., & Saval, J. M. (2014). Portland cement systems with addition of sewage sludge ash. Application in concretes for the manufacture of blocks. *Journal of Cleaner Production, 82*, 112–124. https://doi.org/10.1016/j.jclepro.2014.06.072

Bajare, D., Bumanis, G., & Upeniece, L. (2013). Coal combustion bottom ash as microfiller with pozzolanic properties for traditional concrete. *Modern Building Materials, Structures and Techniques, 57*, 149–158. https://doi.org/10.1016/j.proeng.2013.04.022

Balasubramaniam, T., & Stephen, S. J. (2022). Influence of industrial wastes on the mechanical and durability characteristics of high strength concrete. *Construction and Building Materials, 317*, 126202.

Barros, J. A., Ferrara, L., & Martinelli, E. (2017). Recent advances on green concrete for structural purposes. *The Contribution of the Eu-fp7 Project Encore*. https://doi.org/10.1007/978-3-319-56797-6

Benazzouk, A., Douzane, O., Langlet, T., Mezreb, K., Roucoult, J. M., & Quéneudec, M. (2007). Physico-mechanical properties and water absorption of cement composite containing shredded rubber wastes. *Cement & Concrete Composites, 29*(10), 732–740. https://doi.org/10.1016/j.cemconcomp.2007.07.001

Brekailo, F., Pereira, E., Pereira, E., Farias, M. M., & Medeiros-Junior, R. A. (2022). Red ceramic and concrete waste as replacement of Portland cement: Microstructure aspect of eco-mortar in external sulfate attack. *Cleaner Materials, 3*, 100034.

British Standards Institution. (2006). *Concrete--complementary British Standard to BS EN 206-1: Specification for constituent materials and concrete*. BSI.

Caldas-Vieira, F., Feuerborn, H.-J., & Saraber, A. (2013). *European product standards-update on status and changes with relevance to CCPs.* Paper presented at the world of coal ash (WOCA) conference. Lexington, KY, USA.

Cerny, V., Kocianova, M., & Drochytka, R. (2017). Possibilities of lightweight high strength concrete production from sintered fly ash aggregate. *18th International Conference on Rehabilitation and Reconstruction of Buildings (Crrb), 195*, 9–16. https://doi.org/10.1016/j.proeng.2017.04.517

Chabi, E., Lecomte, A., Adjovi, E. C., Dieye, A., & Merlin, A. (2018). Mix design method for plant aggregates concrete: Example of the rice husk. *Construction and Building Materials, 174*, 233–243. https://doi.org/10.1016/j.conbuildmat.2018.04.097

Chaitanya, M., & Ramakrishna, G. (2021). Enhancing the mechanical properties of pervious recycled aggregate concrete using silica fumes. *Materials Today: Proceedings, 46*, 634–637. https://doi.org/10.1016/j.matpr.2020.11.549

Chowdhury, S., Mishra, M., & Suganya, O. (2015). The incorporation of wood waste ash as a partial cement replacement material for making structural grade concrete: An overview. *Ain Shams Engineering Journal, 6*(2), 429–437. https://doi.org/10.1016/j.asej.2014.11.005

Dash, M. K., Patro, S. K., & Rath, A. K. (2016). Sustainable use of industrial-waste as partial replacement of fine aggregate for preparation of concrete—A review. *International Journal of Sustainable Built Environment, 5*(2), 484–516.

Devi, S. V., Gausikan, R., Chithambaranathan, S., & Jeffrey, J. W. (2021). Utilization of recycled aggregate of construction and demolition waste as a sustainable material. *Materials Today: Proceedings, 45*, 6649–6654. https://doi.org/10.1016/j.matpr.2020.12.013

Devi, V. S., Kumar, M. M., Iswarya, N., & Gnanavel, B. K. (2020). Durability of steel slag concrete under various exposure conditions. *Materials Today: Proceedings, 22*, 2764–2771.

Dharmaraj, R. (2021). Experimental study on strength and durability properties of iron scrap with flyash based concrete. *Materials Today: Proceedings, 37*, 1041–1045. https://doi.org/10.1016/j.matpr.2020.06.290

Deutsches Institut für Normung (DIN). (2002). DIN 4226-100: 2002-2: Aggregates for mortar and concrete. *Part 100: recycled aggregates*.

Dixit, A. (2021). A study on the physical and chemical parameters of industrial by-products ashes useful in making sustainable concrete. *Materials Today: Proceedings, 43*, 42–50. https://doi.org/10.1016/j.matpr.2020.11.203

Febin, G. K., Abhirami, A., Vineetha, A. K., Manisha, V., Ramkrishnan, R., Sathyan, D., & Mini, K. M. (2019). Strength and durability properties of quarry dust powder incorporated concrete blocks. *Construction and Building Materials, 228*, 116793. https://doi.org/10.1016/j.conbuildmat.2019.116793

Gadag, P. R., Ghorpade, V. G., & Rao, H. S. (2022). Evaluation of strength parameters of ultra-fine flyash and nanosilica incorporated high-performance concrete. *Materials Today: Proceedings, 49*, 2288–2296.

Ganjian, E., Khorami, M., & Maghsoudi, A. A. (2009). Scrap-tyre-rubber replacement for aggregate and filler in concrete. *Construction and Building Materials, 23*(5), 1828–1836. https://doi.org/10.1016/j.conbuildmat.2008.09.020

Gholampour, A., & Ozbakkaloglu, T. (2017). Performance of sustainable concretes containing very high volume Class-F fly ash and ground granulated blast furnace slag. *Journal of Cleaner Production, 162*, 1407–1417. https://doi.org/10.1016/j.jclepro.2017.06.087

Golewski, G. L. (2017). Improvement of fracture toughness of green concrete as a result of addition of coal fly ash. Characterization of fly ash microstructure. *Materials Characterization, 134*, 335–346. https://doi.org/10.1016/j.matchar.2017.11.008

Guo, P. W., Meng, W. N., Nassif, H., Gou, H. Y., & Bao, Y. (2020). New perspectives on recycling waste glass in manufacturing concrete for sustainable civil infrastructure. *Construction and Building Materials, 257*, 119579. https://doi.org/10.1016/j.conbuildmat.2020.119579

Hamada, H. M., Jokhio, G. A., Yahaya, F. M., Humada, A. M., & Gul, Y. (2018). The present state of the use of palm oil fuel ash (POFA) in concrete.

Construction and Building Materials, 175, 26–40. https://doi.org/10.1016/j.conbuildmat.2018.03.227

Hanjitsuwan, S., Phoo-ngernkham, T., Li, L. Y., Damrongwiriyanupap, N., & Chindaprasirt, P. (2018). Strength development and durability of alkali-activated fly ash mortar with calcium carbide residue as additive. *Construction and Building Materials, 162*, 714–723. https://doi.org/10.1016/j.conbuildmat.2017.12.034

Hasan, M. F., Hassan, M. A., & Lateef, K. H. (2021). Effect of MK and SF on the concrete mechanical properties. *Materials Today: Proceedings, 42*, 2914–2919. https://doi.org/10.1016/j.matpr.2020.12.751

Hassanein, O. F., & Ezeldin, A. S. (2013). Concrete recycling in Egypt for construction applications: A technical and financial feasibility model. *International Journal of Mechanical and Industrial Engineering, 7*(12), 902–907.

Hendi, A., Behravan, A., Mostofinejad, D., Sedaghatdoost, A., & Amini, M. (2018). A step towards green concrete: Effect of waste silica powder usage under HCl attack. *Journal of Cleaner Production, 188*, 278–289. https://doi.org/10.1016/j.jclepro.2018.03.288

Il'ina, L., & Mukhina, I. (2016). Estimation of the applicability for the filler produced by recycling of concrete and reinforced concrete used in heavy concrete. *Procedia Engineering, 150*, 1525–1530.

Indian Standard 10262. (2009). *Concrete mix proportioning-guidelines*. Indian Standard Code.

Iqbal, M. F., Javed, M. F., Rauf, M., Azim, I., Ashraf, M., Yang, J., & Liu, Q. F. (2021). Sustainable utilization of foundry waste: Forecasting mechanical properties of foundry sand based concrete using multi-expression programming. *Science of the Total Environment, 780*, 146524. https://doi.org/10.1016/j.scitotenv.2021.146524

Ismail, Z. Z., & Al-Hashmi, E. A. (2008). Reuse of waste iron as a partial replacement of sand in concrete. *Waste Management, 28*(11), 2048–2053. https://doi.org/10.1016/j.wasman.2007.07.009

Jiang, Y., Ling, T. C., Shi, C. J., & Pan, S. Y. (2018). Characteristics of steel slags and their use in cement and concrete—A review. *Resources Conservation and Recycling, 136*, 187–197. https://doi.org/10.1016/j.resconrec.2018.04.023

Kabir, S., Al-Shayeb, A., & Khan, I. M. (2016). Recycled construction debris as concrete aggregate for sustainable construction materials. *ICSDEC 2016—Integrating Data Science Construction and Sustainability, 145*, 1518–1525. https://doi.org/10.1016/j.proeng.2016.04.191

Kavitha, O. R., Shyamala, G., & Akshana, V. (2021). Study of sustainable concrete property containing waste foundry sand. *Materials Today: Proceedings, 39*, 855–860. https://doi.org/10.1016/j.matpr.2020.10.359

Khaloo, A. R., Dehestani, M., & Rahmatabadi, P. (2008). Mechanical properties of concrete containing a high volume of tire-rubber particles. *Waste Management, 28*(12), 2472–2482. https://doi.org/10.1016/j.wasman.2008.01.015

Kumar, N. V. S., & Ram, K. S. S. (2018). Experimental study on properties of concrete containing crushed rock dust as a partial replacement of cement. *Materials Today: Proceedings, 5*(2), 7240–7246.

Kurama, H., & Kaya, M. (2008). Usage of coal combustion bottom ash in concrete mixture. *Construction and Building Materials, 22*(9), 1922–1928. https://doi.org/10.1016/j.conbuildmat.2007.07.008

Lee, G., Ling, T. C., Wong, Y. L., & Poon, C. S. (2011). Effects of crushed glass cullet sizes, casting methods and pozzolanic materials on ASR of concrete blocks. *Construction and Building Materials, 25*(5), 2611–2618. https://doi.org/10.1016/j.conbuildmat.2010.12.008

Li, G. Q., Stubblefield, M. A., Garrick, G., Eggers, J., Abadie, C., & Huang, B. S. (2004). Development of waste tire modified concrete. *Cement and Concrete Research, 34*(12), 2283–2289. https://doi.org/10.1016/j.cemconres.2004.04.013

Liew, K. M., Sojobi, A. O., & Zhang, L. W. (2017). Green concrete: Prospects and challenges. *Construction and Building Materials, 156*, 1063–1095. https://doi.org/10.1016/j.conbuildmat.2017.09.008

Ling, T. C., Poon, C. S., & Wong, H. W. (2013). Management and recycling of waste glass in concrete products: Current situations in Hong Kong. *Resources Conservation and Recycling, 70*, 25–31. https://doi.org/10.1016/j.resconrec.2012.10.006

Liu, Q., Lu, Z. Y., Liang, X. X., Liang, R., Li, Z. J., & Sun, G. X. (2021). High flexural strength and durability of concrete reinforced by in situ polymerization of acrylic acid and 1-acrylamido-2-methylpropanesulfonic acid. *Construction and Building Materials, 292*, 123428. https://doi.org/10.1016/j.conbuildmat.2021.123428

Lotfy, A., Karahan, O., Ozbay, E., Hossain, K. M. A., & Lachemi, M. (2015). Effect of kaolin waste content on the properties of normal-weight concretes. *Construction and Building Materials, 83*, 102–107. https://doi.org/10.1016/j.conbuildmat.2015.03.002

Maharishi, A., Singh, S. P., Gupta, L. K., & Shehnazdeep. (2021). Strength and durability studies on slag cement concrete made with copper slag as fine aggregates. *Materials Today: Proceedings, 38*, 2639–2648. https://doi.org/10.1016/j.matpr.2020.08.232

Majhi, R. K., Nayak, A. N., & Mukharjee, B. B. (2018). Development of sustainable concrete using recycled coarse aggregate and ground granulated blast furnace slag. *Construction and Building Materials, 159*, 417–430. https://doi.org/10.1016/j.conbuildmat.2017.10.118

Manjunatha, M., Reshma, T., Balaji, K., Bharath, A., & Tangadagi, R. B. (2021). The sustainable use of waste copper slag in concrete: An experimental research. *Materials Today: Proceedings, 47*, 3645–3653.

Mater, Y., Kamel, M., Karam, A., & Bakhoum, E. (2022). ANN-Python prediction model for the compressive strength of green concrete. *Construction Innovation*. https://doi.org/10.1108/CI-08-2021-0145

Meisuh, B. K., Kankam, C. K., & Buabin, T. K. (2018). Effect of quarry rock dust on the flexural strength of concrete. *Case Studies in Construction Materials, 8*, 16–22. https://doi.org/10.1016/j.cscm.2017.12.002

Müller, H. S., Breiner, R., Moffatt, J. S., & Haist, M. (2014). Design and properties of sustainable concrete. *Procedia Engineering, 95*, 290–304.

Munir, M. J., Kazmi, S. M. S., & Wu, Y. F. (2017). Efficiency of waste marble powder in controlling alkali-silica reaction of concrete: A sustainable approach. *Construction and Building Materials, 154*, 590–599. https://doi.org/10.1016/j.conbuildmat.2017.08.002

Nakic, D. (2018). Environmental evaluation of concrete with sewage sludge ash based on LCA. *Sustainable Production and Consumption, 16*, 193–201. https://doi.org/10.1016/j.spc.2018.08.003

Naser, A. H., Badr, A. H., Henedy, S. N., Ostrowski, K. A., & Imran, H. (2022). Application of multivariate adaptive regression splines (MARS) approach in prediction of compressive strength of eco-friendly concrete. *Case Studies in Construction Materials, 17*, e01262.

Nasier, S. (2021). Utilization of recycled form of concrete, E-wastes, glass, quarry rock dust and waste marble powder as reliable construction materials. *Materials Today: Proceedings, 45*, 3231–3234. https://doi.org/10.1016/j.matpr.2020.12.381

Nisbet, M. A., VanGeem, M. G., Gajda, J., & Marceau, M. (2000). Environmental life cycle inventory of portland cement concrete. *PCA R&D Serial, 28*.

NTC, L. G. (2008). Norme tecniche per le costruzioni. *Gazzetta Ufficiale della Repubblica Italiana, 29(30)*.

Oke, A. E., Aigbavboa, C. O., & Semenya, K. (2017). Energy savings and sustainable construction: Examining the advantages of nanotechnology. *Proceedings of the 9th International Conference on Applied Energy, 142*, 3839–3843. https://doi.org/10.1016/j.egypro.2017.12.285

Palankar, N., Shankar, A. R., & Mithun, B. (2015). Studies on eco-friendly concrete incorporating industrial waste as aggregates. *International Journal of Sustainable Built Environment, 4*(2), 378–390.

Panizza, M., Natali, M., Garbin, E., Tamburini, S., & Secco, M. (2018). Assessment of geopolymers with construction and demolition waste (CDW) aggregates as a building material. *Construction and Building Materials, 181*, 119–133. https://doi.org/10.1016/j.conbuildmat.2018.06.018

Pelisser, F., Zavarise, N., Longo, T. A., & Bernardin, A. M. (2011). Concrete made with recycled tire rubber: Effect of alkaline activation and silica fume addition. *Journal of Cleaner Production, 19*(6–7), 757–763. https://doi.org/10.1016/j.jclepro.2010.11.014

Pliya, P., Hajiloo, H., Romagnosi, S., Cree, D., Sarhat, S., & Green, M. F. (2021). The compressive behaviour of natural and recycled aggregate concrete during and after exposure to elevated temperatures. *Journal of Building Engineering, 38*, 102214. https://doi.org/10.1016/j.jobe.2021.102214

Ponnada, S., Cheela, V. S., & Raju, S. G. (2020). Investigation on mechanical properties of composite concrete containing untreated sea sand and quarry dust for 100% replacement of fine aggregate. *Materials Today: Proceedings, 32*, 989–996.

Prem, P. R., Verma, M., & Ambily, P. S. (2018). Sustainable cleaner production of concrete with high volume copper slag. *Journal of Cleaner Production, 193*, 43–58. https://doi.org/10.1016/j.jclepro.2018.04.245

Prusty, J. K., Patro, S. K., & Basarkar, S. (2016). Concrete using agro-waste as fine aggregate for sustainable built environment—A review. *International Journal of Sustainable Built Environment, 5*(2), 312–333.
Rajan, R. G., Sakthieswaran, N., & Babu, O. G. (2021). Experimental investigation of sustainable concrete by partial replacement of fine aggregate with treated waste tyre rubber by acidic nature. *Materials Today: Proceedings, 37*, 1019–1022. https://doi.org/10.1016/j.matpr.2020.06.279
Rana, A., Kalla, P., Verma, H. K., & Mohnot, J. K. (2016). Recycling of dimensional stone waste in concrete: A review. *Journal of Cleaner Production, 135*, 312–331. https://doi.org/10.1016/j.jclepro.2016.06.126
Rao, B. K., Reddy, M. A. K., & Rao, A. V. (2022). Effect of flyash as cement replacement material and pore filling material in concrete. *Materials Today: Proceedings, 52*, 1775–1780.
Ray, S., Haque, M., Ahmed, T., Mita, A. F., Saikat, M. H., & Alom, M. M. (2022). Predicting the strength of concrete made with stone dust and nylon fiber using artificial neural network. *Heliyon, 8*(3), e09129.
Rollakanti, C. R., Prasad, C. V. S. R., Poloju, K. K., Al Muharbi, N. M. J., & Arun, Y. V. (2021). An experimental investigation on mechanical properties of concrete by partial replacement of cement with wood ash and fine sea shell powder. *Materials Today: Proceedings, 43*, 1325–1330. https://doi.org/10.1016/j.matpr.2020.09.164
Saloni, P., Lim, Y. Y., Pham, T. M., Jatin, & Kumar, J. (2021). Sustainable alkali activated concrete with fly ash and waste marble aggregates: Strength and durability studies. *Construction and Building Materials, 283*, 122795. https://doi.org/10.1016/j.conbuildmat.2021.122795
Satyaprakash, Helmand, P., & Saini, S. (2019). Mechanical properties of concrete in presence of Iron filings as complete replacement of fine aggregates. *Materials Today: Proceedings, 15*, 536–545. https://doi.org/10.1016/j.matpr.2019.04.118
Senaratne, S., Lambrousis, G., Mirza, O., Tam, V. W. Y., & Kang, W. H. (2017). Recycled concrete in structural applications for sustainable construction practices in Australia. *International High-Performance Built Environment Conference—A Sustainable Built Environment Conference 2016 Series (Sbe16), Ihbe 2016, 180*, 751–758. https://doi.org/10.1016/j.proeng.2017.04.235
Shafigh, P., Nomeli, M. A., Alengaram, U. J., Bin Mahmud, H., & Jumaat, M. Z. (2016). Engineering properties of lightweight aggregate concrete containing limestone powder and high volume fly ash. *Journal of Cleaner Production, 135*, 148–157. https://doi.org/10.1016/j.jclepro.2016.06.082
Shahidan, S., Azmi, M. A. M., Kupusamy, K., Zuki, S. S. M., & Ali, N. (2017). Utilizing construction and demolition (C&D) waste as recycled aggregates (RA) in concrete. *Procedia Engineering, 174*, 1028–1035.
Shewalul, Y. W. (2021). Experimental study of the effect of waste steel scrap as reinforcing material on the mechanical properties of concrete. *Case Studies in Construction Materials, 14*, e00490. https://doi.org/10.1016/j.cscm.2021.e00490
Siddique, R. (2012). Utilization of wood ash in concrete manufacturing. *Resources Conservation and Recycling, 67*, 27–33. https://doi.org/10.1016/j.resconrec.2012.07.004
Siddique, R. (2014). Utilization of industrial by-products in concrete. *2nd International Conference on Sustainable Civil Engineering Structures and Construction Materials, 95*, 335–347. https://doi.org/10.1016/j.proeng.2014.12.192
Siddique, R., & Naik, T. R. (2004). Properties of concrete containing scrap-tire rubber—An overview. *Waste Management, 24*(6), 563–569. https://doi.org/10.1016/j.wasman.2004.01.006
Siddique, R., Singh, G., & Singh, M. (2018). Recycle option for metallurgical by-product (spent foundry sand) in green concrete for sustainable construction. *Journal of Cleaner Production, 172*, 1111–1120. https://doi.org/10.1016/j.jclepro.2017.10.255
Suchorski, & David, M. (2007). Aggregates for concrete, ACI education bulletin E1-07, ACI committee E-701, materials for concrete construction. August.
Teixeira, E. R., Mateus, R., Camoes, A. F., Braganca, L., & Branco, F. G. (2016). Comparative environmental life-cycle analysis of concretes using biomass and coal fly ashes as partial cement replacement material. *Journal of Cleaner Production, 112*, 2221–2230. https://doi.org/10.1016/j.jclepro.2015.09.124
Thomas, B. S., Kumar, S., & Arel, H. S. (2017). Sustainable concrete containing palm oil fuel ash as a supplementary cementitious material—A review. *Renewable & Sustainable Energy Reviews, 80*, 550–561. https://doi.org/10.1016/j.rser.2017.05.128
Turatsinze, A., Bonnet, S., & Granju, J. L. (2007). Potential of rubber aggregates to modify properties of cement based-mortars: Improvement in cracking shrinkage resistance. *Construction and Building Materials, 21*(1), 176–181. https://doi.org/10.1016/j.conbuildmat.2005.06.036
Ulubeyli, G. C., Bilir, T., & Artir, R. (2016). Durability properties of concrete produced by marble waste as aggregate or mineral additives. *World Multidisciplinary Civil Engineering-Architecture-Urban Planning Symposium 2016, WMCAUS 2016, 161*, 543–548. https://doi.org/10.1016/j.proeng.2016.08.689
Waghmare, S., Katdare, A., & Patil, N. (2022). Studies on application of multiple regression analysis for prediction of split tensile strength of concrete with zeolite. *Materials Today: Proceedings, 59*, 1148–1154.
Wang, G. C. (2016). *The utilization of slag in civil infrastructure construction*. Woodhead Publishing.
Wu, Z. X., Jiang, Y. M., Guo, W. X., Jin, J. X., Wu, M. J., Shen, D. S., & Long, Y. Y. (2021). The long-term performance of concrete amended with municipal sewage sludge incineration ash. *Environmental Technology & Innovation, 23*, 101574. https://doi.org/10.1016/j.eti.2021.101574
Yang, J. (2005). Introduction—Bridging the gaps in smart and sustainable built environments. In J. Yang, P. S. Brandon, & A. C. Sidwell (Eds.), *Smart & sustainable built environments*. Blackwell Publishing Ltd.
Zhu, Y. F., Zahedi, A., Sanchez, L. F. M., Fournier, B., & Beauchemin, S. (2021). Overall assessment of alkali-silica reaction affected recycled concrete aggregate mixtures derived from construction and demolition waste. *Cement and Concrete Research, 142*, 106350. https://doi.org/10.1016/j.cemconres.2020.106350

Publisher's Note