Doctoral Dissertation

By

Maysam M. Shmlls

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Life-Cycle Assessment and Multi-Criteria Decision-Making of Two-Generation High-Performance Recycled Aggregate Concrete

Doctoral Dissertation

Supervisors

Dr. Dávid Bozsaky PhD

Dr. Tamás Horváth PhD

Doctoral School of Multidisciplinary Engineering Sciences

DECLARATION OF AUTHENTICITY

I declare that the contents and the work described in this thesis were performed at Széchenyi István University, Faculty of Architecture, Civil Engineering and Transport Sciences. I declare that every source of data contained in this dissertation is either original to me or has been appropriately adapted from other sources.

SUMMARY

The research presented in this thesis is about the production of high-performance concrete (HPC) and the comprehensive analysis of its life cycle. The investigated HPCs were made by combining recycled concrete aggregate (RCA) or multi-recycled concrete aggregate (MRCA) as a partial replacement for natural aggregate (NA) and/or two supplementary cementitious materials (SCMs), fly ash and silica fume, as cement replacements. Early on, by reviewing the literature, it was determined that the RCA and MRCA's replacement ranges were, respectively, 30% and 70% of NA by mass. The ratios for FA and SF of cement were 12% and 20% by mass, respectively. HPCs were evaluated in terms of fresh, mechanical, and water absorption properties. Flow table test was conducted to assess the fresh state. Testing was done on mechanical characteristics (compressive, flexural, and splitting tensile strength). These mechanical properties were evaluated at ages 28, 90, and 180 days. Furthermore, at 90 days of age, a water absorption test was also conducted. Long-term testing yielded comparable results, implying that the influence of FA and SF may grow strength of recycled aggregate concretes over time. Nevertheless, HPC revealed that it is one of the optimal solutions for unitizing materials.

The construction industry must integrate several factors from diverse scientific domains to meet sustainable criteria. Yet, the majority of research studies primarily discuss isolated parameters like functional or environmental performance, albeit to a limited extent. Therefore, this work discusses evaluation for other concrete aspects such as the human health, ecosystem quality, climate change, resources, and cost analysis. By utilizing multi-criteria decision making (MCDM) techniques could lead to such sustainable concrete, which is a field of research that includes evaluating the positives and negatives of many options in a circumstance or research area that includes ordinary life, social sciences, engineering, medicine, and a variety of other topics. MCDM can consider a set of criteria to help choose the optimal option from a different alternative. Therefore, the basic role of these techniques is to involve aspects of sustainability into the design of building materials by establishing a set of criteria. The life cycle assessment (LCA) plus five MCDM techniques have been used in this work, namely, TOPSIS, VIKOR, EDAS, WSM, and WPM, to select the best mixture concrete between all types regardless of the generation of concrete. Where the output of LCA was considered as an input for MCDM. The results demonstrated that, when compared to regular concrete or the first generation of recycled concrete, the second generation of recycled concrete can provide a better alternative, achieving acceptable technical performance with less environmental impact and cost.

ÖSSZEFOGLALÓ

A disszertációban bemutatott kutatás a Nagy teljesítményű beton (HPC) előállításának és életciklusának átfogó elemzését tartalmazza. A vizsgált nagyszilárdságú betonokban a természetes adalékanyagot (NA) részben újrahasznosított beton adalékanyaggal (RCA) vagy többszörösen újrahasznosított beton adalékanyaggal (MRCA), és két cementhelyettesítő anyaggal (CSM), pernyével (FA) és szilikaporral (SF) kombináltam. A szakirodalom áttekintésével megállapítottam, hogy ideális esetben az újrahasznosított és az többszörösen újrahasznosított adalékanyag helyettesítési mennyisége a normál adalékanyag 30, illetve 70 tömegszázalékát teszi ki, a pernye és a szilikapor cementhez viszonyított tömegaránya pedig 12% és 20%. A nagyszilárdságú betonokat először friss betonként, majd mechanikai és vízfelvételi tulajdonságai alapján értékeltem. A friss állapot konzisztenciájának meghatározásához terülésvizsgálatot végeztem. A mechanikai jellemzők vizsgálata is megtörtént (nyomó-, hajlító- és hasító-húzószilárdság) 28, 90 és 180 napos korban. 90 napos korban vízfelvételvizsgálatot is végeztem. A hosszútávú tesztek eredményeit kiértékelve bizonyítottam, hogy a pernye és a szilikapor megerősítheti az újrahasznosított adalékanyaggal készülő betont. A különböző kísérleti receptúrák alapján készült betonok vizsgálatai kimutatták, hogy a betonkeverék összetétele optimalizálható.

Az építőiparban számos tényezőt kell együttesen figyelembe vennünk különböző tudományterületekről annak érdekében, hogy megfeleljünk a fenntarthatósági kritériumoknak. A kutatások többsége azonban elsősorban olyan elszigetelt paramétereket tárgyal, mint a funkcionális vagy a környezeti teljesítmény egyes szempontjai. Ezért ez a munka más konkrét szempontok, mint például az emberi egészség biztosítása, az ökoszisztéma minősége, az éghajlatváltozáshoz való hozzájárulás, az erőforrásokkal történő gazdálkodás és a költséghatékonyság értékelését is tárgyalja. A többkritériumos döntéshozatal (MCDM) alkalmazása segítségünkre lehet a fenntartható betonreceptúrák kiválasztásában. Ez a módszer lehetőséget ad számos opció előnyeinek és hátrányainak összevetésére. Az MCDM alkalmazásával figyelembe vehetünk egy sor olyan feltételt, amelyek segíthetnek kiválasztani az optimális megoldást a különböző alternatívák közül. Ennek következtében az MCDM alkalmas arra is, hogy a fenntarthatósági szempontokat beépítsük az építőanyagok tervezésébe egy sor egyéb követelmény meghatározásával. Kutatásom során az életciklus-értékelés (LCA) mellett öt MCDM módszert is felhasználtam (TOPSIS, VIKOR, EDAS, WSM és WPM) annak érdekében, hogy kiválaszthassam a legjobb betonkeveréket a kísérletekben vizsgált receptúrák közül. E folyamatban az életciklus-elemzés eredményei az MCDM számítások bemenő

adataivá váltak. Az eredmények azt mutatták, hogy a hagyományos betonhoz vagy az újrahasznosított beton első generációjához képest az újrahasznosított beton második generációja még jobb alternatívát kínálhat, elfogadható műszaki teljesítményt érhet el kevesebb környezeti hatással és költséggel.

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DEDICATION

To my parents: Samira Shmisa and Mohammed Shmlls, my sister Ansam Shmlls and her family (Ali Naisie, Tala Naisie, Timaa Naisie, Bana Naisie and Rashid Naisie), my Love: Areej Alloush, her family (Abdulla Alloush, Sabah Aziza, Nadeen Alloush, Jafar Alloush), and big thanks to my aunt: Dr. Afaf Shmlls.

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LIST OF ABBREVIATION

AA	Aquatic Acidification
ACI	American Concrete Institute
AE	Aquatic Ecotoxicity
AEU	Aquatic Eutrophication
CA	Carcinogens
CC	Control Concrete
EDAS	Evaluation based on Distance from Average Solution
FA	Fly Ash
GHG	Green House Gas
GWP	Global Warming Potential
HPC	High-Performance Concrete
HSC	High-Strength Concrete
HSMRAC	High-Strength Multi-Recycled Aggregate Concrete
HSRAC	High-Strength Recycled Aggregate Concrete
IR	Ionizing Radiation
ITZ	Interfacial Transition Zone
LCA	Life Cycle Assessment
LO	Land Occupation
MCDM	Multi-Criteria Decision Making
ME	Mineral Extraction
MRCA	Multi-Recycled Concrete Aggregate
NA	Natural Aggregate
NCA	Non-Carcinogens
NRE	Non-Renewable Energy
NRMCA	National Ready Mixed Concrete Association
OLD	Ozone Layer Depletion
PO	Photochemical Oxidation
RAC	Recycled Aggregate Concrete
RCA	Recycled Concrete Aggregate
RCC	Relative Closeness Coefficient
RI	Respiratory Inorganics
SCMs	Supplementary Cementitious Materials

SF	Silica Fume
SCHPC	Self-Compacting High-Performance Concrete
TAN	Terrestrial Acidification / Nitrification
TE	Terrestrial Ecotoxicity
TOPSIS	Technique for Order of Preference by Similarity to Ideal Solution
VIKOR	VIseKriterijumska Optimizacija i kompromisno Resenje technique
w/c	water-to-cement ratio
WPM	Weighted Product Model
WSM	Weighted Sum Model

LIST OF SYMBOLS

A	Alternative
AS_i	Appraisal score
AV_j	Average solutions matrix
CO_2	Carbon dioxide
12S	Concrete with 12% silica fume
20F	Concrete with 20% fly ash
20F-12S	Concrete with 20% fly ash and 12% silica fume
R30	Concrete with 30% recycled concrete aggregate
R70	Concrete with 70% recycled concrete aggregate
RR30/30	Concrete with 30% multi recycled concrete aggregate (crushed concrete R30)
RR70/30	Concrete with 30% multi recycled concrete aggregate (crushed concrete R70)
RR30/70	Concrete with 70% multi recycled concrete aggregate (crushed concrete R30)
RR70/70	Concrete with 70% multi recycled concrete aggregate (crushed concrete R70)
W	Criteria weights matrix
C_j	Criterion
X	Decision matrix
MPt	Dimensionless units
Ki	Factor to compute the weighted values (entropy method)
Z_i	Normalized matrix (entropy method)
F3	Plastic class of concrete consistency
A^+, A^-	Positive and negative ideal solution of TOPSIS technique
SPi, SNi	Positive and negative normalize values
D^+, D^-	Positive and negative separation matrixes of TOPSIS technique
PDA, NDA	The matrixes of positive distance from average and negative distance from average are calculated at this phase based on the kind of criterion

LIST OF DIMENSIONS

mm	millimetre
m	metre
km	kilometre
MPa	megapascal
N/mm^2	newton per square millimetre
kg/m^3	kilogram per cubic metre
g/cm^3	gram per cubic centimetre
MJ/kg	megajoule per kilogram
°C	degree Celsius
%	percentage
Ft/kg	forint per kilogram
MPt	dimensionless units

CHAPTER 1: Introduction

This chapter discusses the background of the topic area, as well as the study's purpose and objective (through its specified scope and limitations).

1.1 Challenges

Current society faces a huge challenge related to the generations of a large volume of waste and consumption of natural resources at a high rate. One of the sectors, where waste management and resource saving are most important, is the construction sector. While the huge volume of building rubble and demolition waste grows quickly because of frequent building destruction. Applying sustainability concepts and minimizing buildings' environmental impact during the construction, use, maintenance, and end-of-life phases must be highlighted. Thus, the integration between life cycle assessment (LCA) and multi-criteria decision making (MCDM) would be essential for succeeding in the construction field with low environmental impact, as considering several criteria is required. The building processes and procedures are a collection of many functions, requirements, and activities that involve a variety of elements and factors that must be considered. Whereas over 20 billion tons of natural materials are used to produce concrete yearly, which is primarily made of cement, aggregate, and water [1]. Cement consumption has reached 4400 million tonnes, and globally, it is responsible for more than 5% of yearly CO_2 emissions [2, 3]. Aggregates, which make up the majority of concrete as a portion, account for two-thirds of the weight of the concrete [4]. Up to 48.3 billion tonnes of aggregates are used annually in concrete production, due to the high demand for buildings, thus, much meaning should be placed on its high recycling potential.

The substitute materials of concrete components are one of the essential cost-effective methods that reduce the environmental impact and CO_2 emissions generated from concrete production. For instance, replacing natural aggregate (NA) and/or cement with recycled concrete aggregate (RCA) and supplementary cementitious materials (SCMs), respectively. Inclusion and considering current knowledge and literature on the use of RCA as an alternative for NA and both fly ash (FA) and silica fume (SF) as SCMs in concrete production indicates that the majority of research concentrated on the experimental testing and evaluation [5, 6, 7, 8, 9, 10, 11]. However, relatively few studies have been conducted on the LCA of recycled aggregate concrete (RAC) [12, 13, 14, 15]. Additionally, LCA of multi recycled aggregate concrete using SCMs is not evaluated in the literature review, which is considered a novel scientific finding in this work.

The CO_2 emissions from cement, FA, SF, and RCA, respectively, are 0.7666 kg, 0.0196 kg, 0.0024 kg, and 0.0177 kg for each 1 kilogram, according to [16, 17], stated that if FA and SF are utilized in place of cement, there is unquestionably a significant decrease in CO_2 emissions. Additionally, substituting RCA in place of NA in a single mixture will result in a double reduction in CO_2 emissions. Every time, a new RAC is used in construction, whether in the production of precast concrete or monolithic concrete, will eventually reach the end of its operational life or maybe be destructed intentionally. Some examples are the rejected precast concrete globally produced with RCA or RAC buildings that were destructed due to wars or natural disasters. The primary aim of the study [18] was to investigate the use of the larger particle portion of aggregates, involving the examination of various replacement levels for the coarse portion of aggregates. The study also explored the potential benefits of altering concrete mix compositions with RCA. The research findings indicated that concrete mixes incorporating RCA demonstrated performance levels that closely resembled those of the control concrete across most attributes. While some performance degradation was observed, it was generally not as significant as initially anticipated. This can be attributed to the high quality of RCA and the effectiveness of the superplasticizer used in the mix. These factors combined to enhance the overall performance of the concrete across all the parameters tested.

Continuously, when RAC is crushed, a multi-recycled concrete aggregate (MRCA) is produced, along with a considerable amount of new recycled materials. The usage of MRCA will bring about fresh advantages for 1) lowering CO_2 emissions, 2) using fewer raw resources, and 3) reducing the price of concrete generally. Noticeably, as it was mentioned before there have not been many investigations on MRCA properties and LCA of using it to produce a second generation of recycling concrete, which can be called multi-recycled aggregate concrete (MRAC) especially when it is cured with SCMs.

Analytically, and because of the considerable volumes of carbon dioxide emissions created during the pyro-processing and calcination of cement processes, LCA assists to lower the environmental load and energy consumption necessary to produce ordinary portland cement. Assessment of the environmental profile of various materials requires specific tools like Sima Pro, Open LCA, or GaBi software [19], that can be employed to assist the life cycle for any process or product, where a variety of environmental impact assessment techniques can be applied to quantify environmental impact indicators in line with [20]. The used standard was ISO 14040:2006, which outlines the principles and framework for LCA [19], covering key aspects such as

- Defining the goal and scope of the LCA.

- Conducting the life cycle inventory analysis phase.

- Performing the life cycle impact assessment phase

- Interpreting the life cycle results, reporting, and undergoing critical review.

The standard also addresses the limitations of LCA, the interconnectedness of different LCA phases, and conditions for making value choices and incorporating optional elements. Most analyses are particularly concerned with the "Lifetime" phases, and they take into account the majority of the environmental categories of acidification, abiotic depletion, global warming potential, eutrophication potential, photochemical ozone creation potential, and non-renewable primary energy resources.

However, an interpretation of LCA analysis results represents another substantial task. Specifically, the interconnection with other material parameters such as mechanical performance or investment costs poses another issue that should be considered and serve as a complex decision-support technique. A type of additional integrated sustainability evaluation is MCDM. It is an analytical assessment and decision-support strategy for resolving complicated situations with a high level of uncertainty, competing aims, many interests and viewpoints, various types of data and information, and accounting for detailed and dynamic biophysical and economic systems. The MCDM techniques can offer answers to increasingly complicated energy management issues and global warming problems. However, the single criteria decision framework has been drastically amended because of increasing environmental awareness in the 1980s. The current emphasis on global environmental protection pushes MCDM techniques to aid in conserving energy and reducing environmental impact. In addition, they have been widely used in sociological, commercial, agricultural, ecological, and biological sectors [21, 22, 23, 24, 25, 26, 27, 28]. For instance, MCDM-based system of experts was created to address the connections between climate change and adaptation strategies in terms of managing water resources [21]. Several processes that were vulnerable to climate change were examined and pre-screened through a thorough literature review, expert consultation, and statistical analysis. Comprehensive explanations and incorporation into the created system were provided for adaptation policies to impacts of temperature increase, and changes in precipitation pattern. Additional example in the sociology [22], it presents a case study centred around determining optimal positions for support canters within a military logistics system, focusing on minimizing the count of locations while maximizing their overall quality. The objective is to ensure that the support canters encompass all predetermined canters that require assistance. Furthermore, each supported centre must be within a critical distance of only one of the established support canters.

Meeting the sustainable criteria relevant to the construction sector integrates several aspects covering various scientific fields. However, most research papers cover mostly isolated parameters such as functional, environmental performance in a narrow extent. The multi-life cycle and cost-effectiveness of the second generation of recycling concrete (MRAC) have not found assessed in the literature. This research is an analysis that enables the optimization building materials design including the selection of the most practical choice among two generations of recycling concrete while compromising the technical, environmental intensity, and financial factors. This work proposes a comprehensive framework for performance-based design applications that are inexpensive, sustainable, and effective by employing the LCA's acquired data as input in five MCDM techniques, namely, TOPSIS, EDAS, VIKOR, WSM, and WPM, to progress concrete, fulfilling all specific requirements in the actual construction projects. Beside that the study also considered the issue of handling the material after the end of its first life cycle and defines, as one of the first thesis describing this issue in such a complete concept, the possible impacts of multigenerational resource management.

1.2 Significance of research

Economic growth needs to be carried out in a way that is harmonious with the earth's ecology, and engineering products' sustainability is now required rather than a choice. High-performance concrete (HPC) is a new generation of concrete based on the idea of replacing cement with other components. Consequently, it processes great strength and better water absorption, making it a highly advanced type of concrete. By substituting a particular proportion of this concrete's components with SCMs, where sustainable and financial value may be added. Additionally, a green version of the material could be created.

Figure 1. Destroyed place in Syria [23]

1.3 Special case

It is extremely important to study RCA and MRCA in the Middle East because there are constant wars in many regions, like Syria and the Gaza Strip, where a lot of debris was left behind by the destroyed structures. The Gaza Strip is expected to contain two million tons of concrete rubble after the 2014 conflict, and there are currently no estimates on the scale of the tremendous devastation in Syria, as represented in Figure 1.

1.4 Objectives and goals

This dissertation's primary objective was to improve HPC by examining the effects of employing RCA or MRCA as a partial substitute for NA and other materials as SCMs on its fresh and hardened properties. The motivation behind developing HPC was to reduce the environmental effect of concrete while increasing its performance and service life. The second objective was to select the ideal mixtures from all the alternatives. These main goals were accomplished by the following aims:

1) To improve the proportioning and process of the HPC mixture in order to achieve concrete strength class (C55/67).
2) To determine the maximum replacement possibility of cement by FA and SF.
3) To define the minimal dosage of superplasticizer and the potential replacement quantity for RCA/MRAC in the HPC's workability.

4) To study the possibility of multiple utilisations of MRAC in real construction.
5) To assess the environmental impact of end-of-life concrete as a replacement for coarse aggregate in the multi-life cycle dimension using LCA analysis.
6) To choose the best alternative among all mixtures using five MCDM, and to compare the results obtained from all the used techniques.

CHAPTER 2: Literature review

In this chapter, an introduction to aggregate's importance and the concrete area is provided, along with details on its characteristics, potential applications, and capacity to incorporate additive materials. Additionally, the ways in generating RAC and MRAC are discussed. This chapter also covers LCA and MCDM literature review.

2.1 Importance of aggregate

The landmark announcement of sustainable development at the Rio Summit in 1992 [24] marked a pivotal moment in global consciousness, drawing significant attention to the pressing need for environmental stewardship and resource preservation. This watershed event catalysed a profound shift in mindset, prompting widespread acknowledgment of the exponential population growth witnessed throughout the past century and the imminent challenges posed by rapid urbanization in developing nations. As nations grappled with the implications of unchecked expansion and consumption, there emerged a heightened sense of responsibility toward safeguarding the planet's finite resources for future generations. This newfound awareness permeated various sectors, none more so than the construction industry, which found itself at the forefront of efforts to reconcile progress with sustainability. In response to the imperative of sustainable development, the construction sector embarked on a journey of introspection, recognizing the need for fundamental changes in its practices. Central to this transformation was a concerted focus on waste management and resource utilization, as stakeholders sought innovative ways to minimize environmental impact without compromising progress. Despite these efforts, the industry continues to confront a mounting challenge in the form of demolition waste and construction debris. The relentless pace of development, coupled with heightened levels of destruction and building activities, has contributed to a surge in waste generation, posing a formidable obstacle to the realization of sustainable goals.

Addressing this issue demands a multifaceted approach, one that encompasses not only technological innovation and regulatory intervention but also a cultural shift in attitudes toward resource consumption and waste management. From the adoption of circular economy principles to the promotion of sustainable design practices, stakeholders must collaborate across disciplines and borders to chart a path toward a more sustainable future.

Indeed, the imperative of sustainable development remains as urgent today as it was in 1992, if not more so. As we confront the dual challenges of population growth and urbanization, the imperative to preserve and protect our planet for generations to come has never been clearer. In the crucible of this shared responsibility lies the promise of a future where progress and sustainability are not mutually exclusive, but rather complementary pillars upon which to build a thriving global community. On a global scale, the adoption of modern techniques and sustainable procedures by the construction manufactures to minimize the negative impacts on the environment has been emphasized, as these industries utilize huge quantities of natural resources and release significant amounts of carbon emissions. As a result, and because aggregate is one of the most often used materials, much meaning should be placed on its high recycling potential. Thus, utilizing RCA in the concrete mixture is a practical way to maximize this potential. Additionally, some countries are having trouble obtaining this raw material because domestic sources do not supply it in sufficient quantities or of sufficient quality for the ongoing projects. Figure 2 shows the crushed stone and gravel import between 2020-2021 [25].

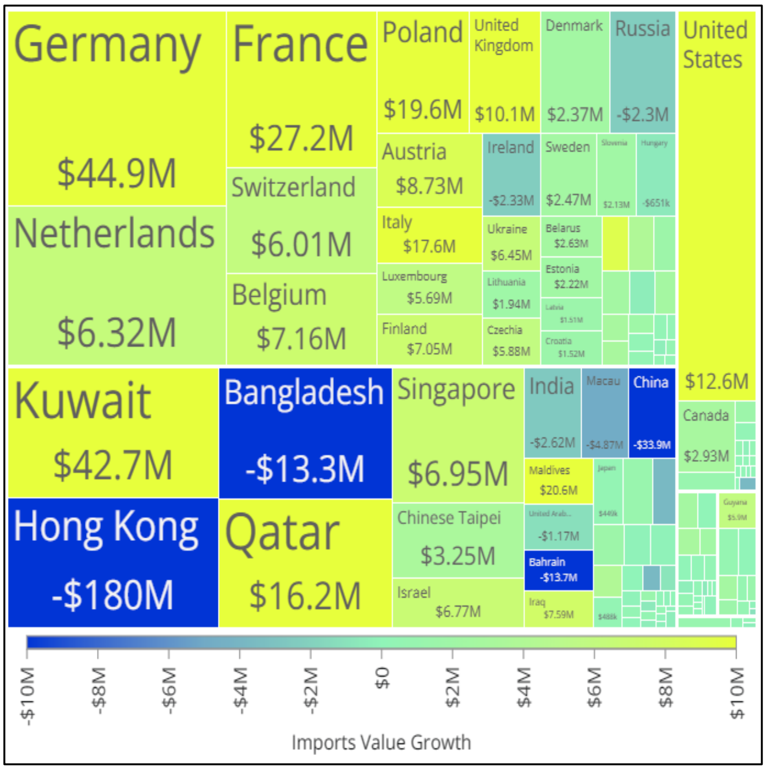


Figure 2. Crushed stone and gravel import between 2020-2021 [25]

Consequently, the adoption of sustainable practices not only holds the potential to curb the depletion of natural resources but also promises a substantial reduction in the volume of materials destined for landfills. This paradigm shift towards sustainability has ushered in a revaluation of conventional construction materials and methodologies, paving the way for innovative approaches such as the incorporation of RCA in concrete production. Extensive research has consistently underscored the viability and efficacy of utilizing RCA, particularly in enhancing the mechanical properties of RAC [26]. The utilization of RCA marks a departure from the traditional reliance on Natural Aggregates (NA), a practice rooted in the construction industry's history, notably originating in England during World War II for pavement construction. Through rigorous studies on recycling demolition waste, it has been firmly established that RCA holds immense potential for broader applications beyond pavement construction, thereby catalysing a paradigm shift in the utilization of demolition waste and the integration of RCA into various concrete formulations. However, in pursuit of further enhancing the properties of RAC, researchers have advocated for the incorporation of Supplementary Cementitious Materials (SCMs) as cement replacements [27]. Studies conducted by Meyer [28], exploring the effects of SCMs on concrete incorporating RCA, have highlighted the considerable improvements achievable across all properties of such concrete formulations. This synergy between RCA and SCMs represents a significant leap forward in sustainable concrete production, offering a pathway towards more resilient and environmentally responsible construction practices.

2.2 The use of supplementary cementitious materials

2.2.1 Fly ash (FA)

It a byproduct of coal combustion, has emerged as a versatile material with a myriad of applications across various industries [29]. Fly ash has a porosity is 20%, while the water absorption is 5% by weight. Comprising predominantly of tiny carbon-burned particles, it possesses unique properties that make it highly sought after for use in construction, agriculture, and even environmental remediation efforts. However, while FA offers tremendous potential, its quality and effectiveness are contingent upon stringent processing procedures.

Recognizing the need to standardize the utilization of FA, the British Standards have outlined a comprehensive set of criteria and procedures governing its processing [30]. These guidelines serve as a roadmap for maximizing the quality and efficacy of FA, ensuring that it meets the requisite standards for diverse applications. Central to these processing procedures is the categorization of FA, which involves classifying it based on various parameters such as particle size, chemical composition, and mineral content. This initial step lays the foundation for subsequent processing stages, facilitating the efficient utilization of FA in targeted applications.

Once categorized, the collection and sieving of FA are undertaken to remove impurities and ensure uniformity of particle size distribution. This not only enhances the physical properties of FA but also improves its compatibility with other materials in composite formulations.

Drying is another critical step in the processing of FA, as it eliminates moisture content and enhances its handling characteristics. This is particularly important in applications where moisture sensitivity can impact performance, such as in the production of concrete and cementitious materials.

Investigations on FA with RCA have been carried out in order to decrease this effect on the strength of RAC, as a substitute for cement, S.C. Kou et al. [31] tested RAC with various quantities of FA and discovered that 25% FA is the ideal ratio to create high strength recycled concrete. Moreover, the mechanical and other properties of concrete have improved by adding FA as a partial substitute for cement, according to [32]. For the purpose of examining the effects of substituting RCA for NA and using three SCMs materials in place of cement, more than 700 samples have been evaluated in this study [33]. FA, together with the other two materials has been used in place of cement. The same water to binder ratio was used to create all formulations, and specimens were made for assessing compressive strength, water absorption, water permeability, chloride migration coefficient, and freeze/thaw resistance. However, they incorporated two ratios of waste FA (15% and 30%) into various admixtures with various replacement amounts of RCA for long-term testing. One of the most noteworthy findings of the study was that the greatest increase in compressive strength occurred when the FA content was 15% and the replacement of NA with RCA was at 50% of NA. This suggests that this particular combination of FA and RCA led to significant improvements in compressive strength, particularly at the 90 and 270-day curing ages. Different physical and mechanical characteristics of RCA were examined in this study [34]. RAC reduces the cost of making concrete up to 30%. Many researchers studied the ability of RAC with different replacement amount of NA. These studies usually confirmed the reduction of the compressive and tensile strength [35]. However, some of them found the opposite results [36]. In order to decrease this effect on the strength of RAC, some researchers used cement replacement materials such as FA, waste cellular concrete or waste perlite powder to modify the strength of RAC.

The effective use of resources, especially in the building sector, is a result of the desire to minimize CO_2 emissions. The effort to employ eco-friendly materials, like RCA, is a prime example. P. Chindaprasirt et al. [37] discusses the varieties of RCA and the characteristics of RAC in both the fresh and hardened phases. They found that after exposure to elevated temperature, the properties of concrete were affected and the residual mechanical properties became enhanced, and the explosive spalling of concrete decreased. In this study [38], the examination of the residual mechanical performance of concrete made with RCA exposed to high temperatures. Four concrete compositions were tested, including one with NA and three with varying levels of NA replacement (20%, 50%, and 100%) by RCA. After subjecting these specimens to temperatures of 400 °C, 600 °C, and 800 °C for one hour, the results showed altered concrete properties, improved remaining mechanical qualities, and reduced risk of explosive spalling. The incorporation of pulverized FA and the slag in two separate admixtures showed an important effect to save the residual mechanical properties, to reduce the exterior cracks and to decrease the possibility of spalling after the concrete's exposure to high temperature [39].

2.2.2 Silica fume (SF)

It a valuable by-product of processing basic silicone or silicone alloys in electric arc furnaces, is generated when high-purity quartz undergoes transformation into silicone at temperatures exceeding 2000°C. The silica fume porosity and water absorption are less 1%. This process also yields silica smoke at lower temperatures. SF finds significant application in enhancing portland cement concrete, contributing to improvements in compressive strength, splitting strength, and other mechanical properties through pozzolanic interactions with free calcium hydroxide [40]. However, the addition of SF to concrete mixtures can impact workability over time due to its high surface area, which leads to water absorption and slump loss. Despite this challenge, carefully controlled incorporation of SF offers a sustainable solution for reducing cement content, lowering carbon emissions, and improving overall performance and durability in concrete production. Thus, SF represents a versatile and environmentally friendly material with promising applications in modern construction practices.

Researchers investigated the effects of SF on RAC strength. This study [41] examined the laboratory performance of both NA and RCA with the incorporation of mineral admixtures like FA and SF. Various properties were assessed, including strength, shrinkage, chloride penetration, and pulse velocity. Interestingly, the replacement ratio of RCA had no effect on the SF needed for strength improvement; 10% SF was found sufficient to enhance RAC strength. Similarly, the authors in this research [42], they focused on investigating the characteristics of RAC. The study involved conducting experimental work to analyse how the inclusion of RCA affects both the workability and the mechanical properties of RAC. Additionally, the study explored the impact of using SF as a replacement material for cement on the performance of RAC. SF was incorporated at four different levels (5%, 10%, 15%, and 20%). In total, six different mixes were prepared: four RAC mixes containing these varying SF contents, one RAC mix without SF (100% RCA), and one mix with NA serving as a reference. the findings showed that SF might be used at contents of 10–20% of cement mass to give RAC with mechanical performance comparable to concrete containing only NA. Figure 3. shows the difference colour and shape of FA and SF supplement materials.

Figure 3. Fly ash (left) and silica fume (right) supplement materials [43]

2.3 Types of concrete

2.3.1 High-performance concrete (HPC)

According to the American Concrete Institute's (ACI) delineation of HPC [44], this specialized form of concrete necessitates meeting stringent criteria encompassing a unique blend of performance attributes and uniformity standards, often beyond the reach of conventional constituents and standard mixing practices. One of the prominent challenges associated with HPC lies in its inherent limitations concerning flowability and filling capacity, primarily attributed to its low water-to-cement ratio (w/c). However, innovative solutions such as the incorporation of superplasticizers and SCMs have emerged as effective measures to ameliorate these deficiencies. The evolution of HPC can be traced back to the concerted efforts of researchers striving to address the shortcomings of conventional concrete formulations. Through systematic modifications to the composition of concrete constituents, refinement of mixing techniques, and optimization of transportation procedures, the concept of HPC gradually took shape. Central to these advancements was the emphasis on enhancing the interfacial transition zone—a critical region where the hydrated cement pastes interfaces with aggregates. By fortifying this zone, researchers sought to improve the overall performance and durability of concrete structures, thereby expanding the realm of possibilities in construction engineering and infrastructure development.

2.3.2 Self-compacting high-performance concrete (SCHPC)

It represents a groundbreaking advancement in concrete technology, characterized by its remarkable flowability and ability to seamlessly fill formwork and encapsulate reinforcement without the need for mechanical consolidation. This distinctive form of concrete boasts a unique composition engineered to deliver unparalleled flow characteristics, strength, transportation efficiency, and long-term durability, thereby ensuring the fulfilment of stringent service life requirements even under challenging material load exposure conditions. What truly distinguishes SCHPC from its counterparts is its exceptional performance throughout both the fresh and hardened stages, a feat made possible through the precise incorporation of specific components, including superplasticizers and SCMs, in conjunction with traditional elements like aggregates, sand, cement, and water [45].

However, the composition of SCHPC deviates from that of conventional control concrete in several key aspects. Notably, self-compacting mixtures necessitate higher volumes of binder, fine aggregate (with a particle size of 4 mm), powders (comprising cement and SCMs), and superplasticizers, compared to conventional formulations. Conversely, the water-to-cement ratio (w/c) and coarse aggregate content are typically lower in self-compacting mixtures. For achieving optimal performance in self-compacting high-strength concrete, it is recommended to maintain the w/c ratio within the narrow range of 0.2 to 0.4, a critical parameter that significantly influences the final properties and characteristics of the concrete mixture. This meticulous balance of ingredients underscores the precision and sophistication inherent in SCHPC production, paving the way for the realization of structurally robust and aesthetically pleasing concrete structures across a diverse array of construction applications.

2.3.3 High strength concrete (HSC)

It can be traced back to pioneering research conducted in the field of ceramic materials during the late 1950s and early 1960s. Within the realm of polycrystalline ceramics, investigations revealed a fundamental relationship between particle size reduction and enhanced material strength [46]. This pivotal discovery found its theoretical underpinning in Griffith's theory, a cornerstone principle elucidating the fracture behavior of brittle materials containing internal flaws. According to Griffith's theory, the strength of a material is expected to increase as both pore and particle sizes diminish, following a square root relationship.

Building upon this theoretical framework, researchers soon identified a parallel correlation between microstructure and strength in cement pastes characterized by densely packed cement particles and an exceptionally low water-to-cement ratio (w/c) [47]. However, it wasn't until the early 1970s that the advent of novel and highly efficient dispersing agents revolutionized the process of suspending minuscule cement particles in water, paving the way for significant advancements in concrete technology.

The evolution of concrete composition has been further propelled by the widespread adoption of SCMs and reactive fillers, contributing to the formulation of increasingly intricate concrete mixtures governed by the interplay of these constituent elements. Moreover, the integration of various processed concrete materials, cutting-edge admixtures, and sophisticated manufacturing techniques has further diversified the landscape of concrete characteristics.

Consequently, conventional metrics such as the water-to-cement ratio, once considered sacrosanct in evaluating concrete quality, have gradually lost their simplistic relevance in light of these multifaceted developments. The contemporary discourse surrounding concrete characteristics has transcended simplistic descriptors, reflecting the intricate interplay of diverse factors shaping the physical properties and performance of modern concrete formulations.

HSC is applied in several construction fields. Early on, HSC was primarily used for offshore constructions, high-rise buildings, and bridgework. The value and advantages of using HSC varied slightly across the various project participants. However, the most significant factors for the clients were longer service life, decreased concrete volume and costs, decreased construction time, and increased space and comfort in high-rise structures. Improvements in qualities including compressive strength, E-modulus, durability, quick final creep achievement, and decreased dead load were crucial to the designer. Fast-track construction and less expensive options were significant to the contractor. Additionally, from an environmental perspective, cost savings on cement and aggregate as well as an extended service life led to more sustainability in the construction field [48].

In parallel with extensive efforts in offshore concrete structure construction, considerable research was dedicated to advancing HSC. Notably, during the early 1990s, significant progress was achieved in concrete production. This included the development of concrete formulations using high-quality natural rock aggregates and lightweight aggregates. These lightweight aggregates exhibited a fresh concrete density of 1865 kg/m^3 and impressive compressive strengths of up to 198.6 MPa [49]. This groundbreaking research opened avenues for innovative applications, including the utilization of HSC in industrial structures, highway road surfaces, and hydraulic buildings.

2.4 Concrete and sustainability

The discourse on sustainability has intensified within the construction industry, driven by growing awareness of the significant environmental repercussions associated with building material production, construction processes, and structural utilization [50]. Achieving the status of environmentally friendly or "green" concrete necessitates meeting specific criteria. This includes minimizing carbon emissions throughout the concrete lifecycle, optimizing natural resource utilization, actively reducing waste generation, enhancing durability and longevity, and conducting comprehensive environmental impact assessments. By adhering to these criteria, concrete producers and construction practitioners can contribute to sustainable construction practices, mitigating environmental impact and fostering the development of resilient, environmentally responsible built environments. Reduced CO_2; concrete that exhibits lower carbon dioxide emissions throughout its lifecycle, including the production of raw materials, manufacturing, transportation, construction, and eventual demolition or recycling.

1) Efficient use of resources; concrete that optimizes the use of natural resources, such as aggregates and water, while minimizing waste generation.
2) Recycled content; concrete that incorporates recycled materials, such as RCA or MRCA, to reduce the demand for virgin resources.
3) Energy efficiency; concrete that contributes to energy conservation through measures like improved insulation properties or reduced energy consumption during the production process.
4) Durability and longevity; concrete structures that have extended service life, reducing the need for frequent repairs or minimizing resource consumption over time.

By meeting these sustainability criteria, concrete can be regarded as environmentally friendly and contribute to more sustainable practices in the construction industry.

2.5 High performance recycled aggregate concrete (HPRAC)

In the realm of hardened concrete, the influence of NA or substitutions for cement emerges as a pivotal factor, capable of yielding strengths equal to or even surpassing those of conventional control concrete (CC). HPC has now come to signify concrete boasting a specified compressive strength of C55/67 or greater [51], underscoring the pivotal role of strength attainment in modern concrete production and construction practices.

A cornerstone of sustainability within the concrete production sector lies in the pursuit of high-strength concrete formulations. Recognizing this imperative, numerous investigations have been undertaken to explore the feasibility of producing RAC with varying degrees of RCA substitution, leveraging a diverse array of admixtures or SCMs to enhance mechanical properties [52]. Table 1 provides a comprehensive overview of the breadth and depth of research endeavours focused on RAC, shedding light on the multifaceted approaches and strategies employed in the quest for sustainable and resilient concrete solutions.

Table 1. Overview of research studies of RAC

Reference	**Replacement rate of aggregate by RCA (%)**	**The used ratio of SCMs with RAC (%)**	**Effect of SCMs on properties of RAC**
Corinaldesi et al. (2009) [52]	100	(15) SF, (30) FA	Concrete properties were assessed using compressive strength and other mechanical properties. The main finding from the first round of experiments in this study indicates that FA or SF may be added to RAC to increase its compressive strength such that it is on par with or even surpasses that of CC.
Sasanipour et al. (2019) [53]	25, 50, 75, 100	(8) SF	The compressive strength of concrete built with RCA reduced due to their porosity and excessive water absorption. Concrete’s workability and additional properties were enhanced by SF. Moreover, replacing 25% of the RCA had no noticeable impact on electrical resistivity.
Pedro et al. (2018) [54]	0, 50, 100	(0, 5, 10) SF, (10) FA	The adoption of a mixing method created by the authors that reduced the previously experienced dispersion issues related to this product allowed for the integration of identified SF, which in turn helped to improve concrete’s performance.
Kou and Poon (2006) [55]	20, 50, 100	(0, 25, 35) FA	According to the findings, the concrete’s compressive strengths decreased as the RCA and FA contents increased. The concrete’s overall porosity and typical porosity diameter increased as the RCA content did.
Reddy et al. (2016) [56]	0, 25, 50, 75, 100	(0, 5, 10) SF	RAC will be produced and evaluated by its physical and mechanical properties with the addition of SF. These strength findings are matched with the result of CC. By employing 5% of SF, the target strength is reached.

Sunayana et al. (2017) [57] investigated the impact of substituting cement with up to 30% FA in RAC. The results revealed that 20% FA enhanced the compressive strength of RAC when compared to the CC or RAC with 30% FA. However, Corinaldesi et al. (2009) [52] substituted cement by using either 15% or 30% FA ratios. Based on the findings of the experiments, adding FA to RAC improves the pore structure by reducing the volume of macro pores, which improves mechanical properties such as compressive, splitting tensile, and flexural strengths. However, the influence of RCA in HPC has been studied by Limbachiya et al. (2000) [58] using concrete specimens derived from precast components with compressive strengths varying between 50 and 70 N/mm^2. According to the results, 30% of RCA may be utilized to generate concrete with strength and other properties that are comparable to those of CC. A. Fernando et al. (2002) [59] have examined HSRAC's mechanical properties and attempted to discover the effect of RCA on the strength of the concrete. The important finding from this study is that HSRAC could be produced from RAC obtained from even lower concrete grades. Additionally, it is possible to create ecologically friendly and commercially sustainable choices by applying a simple treatment procedure and adding SCMs as mineral admixture materials instead of cement.

2.6 High performance multi recycled aggregate concrete (HPMRAC)

Ultimately, the structures built by HSRAC are almost certainly going to be demolished once again like those buildings which built from mainly NA, either because of a particular incident or for other reasons, such as ongoing conflicts and natural disasters in certain places [60]. Roughly 850 million tons of concrete demolition rubble are expected to be recycled annually in European nations, and about 200 million tons are expected in China. The situation is similar in Middle Eastern nations like Syria and the Gaza Strip, where continuous wars left a massive amount of rubble from destroyed buildings. There are no current estimates of the magnitude of the immense destruction in Syria, that occurred after the war in 2014, which was anticipated to produce a million tons of concrete rubble. As a result, MRCA will be built from the resulting trash and rubble. Thus, MRCA will be used in the production of MRAC. The importance of the use of MRCA to make new concrete has been emphasized by researchers, yet only a few studies have investigated MRAC in the long-term test. M. Abed et al. (2020) [61] tested MRCA and their effected on the fresh, physical, mechanical, and microstructural properties of MRAC at the age 28 and 90 days, to support the cradle-to-cradle theory of concrete, it was shown that using up to 50% MRCA did not significantly change the properties of fresh concrete, but it could enhance the mechanical and microstructural properties of MRAC. By using up to 100% MRCA. Huda and Alam (2014) [62] have examined the hardened properties of MRAC and their behaviour at different ages up to 120 days. As evidence of the beneficial effects of MRCA, they found that the compressive strength was slightly reduced, and that MRAC could outperform the required strength by at least 25% replacement. A summary of studies that investigated the experimental properties of MRAC is presented in Table 2, however, the long-term properties of MRAC were not found investigated.

Table 2. Overview of research studied MRAC

References	**days**	**MRCA (%)**	**FA (%)**	**SF (%)**	**Comments**
Abed et al. (2020) [61]	28, 90	25, 50	-	-	The results demonstrate better mechanical and microstructural qualities.
Huda and Alam (2014) [62]	3, 7, 28, 56, 120	100	20	-	The compressive strength was reported to be marginally reduced by up to 100% replacement, however, MRAC could perform at least 25% better than the required strength.
Marie and Quiasrawi (2012) [63]	28	5, 10, 15, 20	-	-	Compared to RCA, the MRAC performed much better. Additionally, it is demonstrated that repeated recycling helps to preserve the sustainability of the ecosystem and natural resources.
Silva et al. (2021) [64]	7, 28, 56	25, 100	-	-	The performance of the regenerated coarse aggregates decreases after three recycling cycles due to a decrease in the quality of their properties.
Thomas and Brito (2020) [65]	28	25, 100	-	-	This study reveals that there is a limit to how many times concrete can be recycled.
Abreu et al. (2020) [66]	7, 28, 56	25, 100	-	-	The quality of coarse aggregates decreases as the number of times they are recycled increases, which has an impact on how well concrete performs mechanically.
Salesa et al. (2017) [67]	2, 7, 28, 90	100	-	-	High-quality concrete may be produced using MRAC from the precast concrete industry, and waste recycling helps to reduce the environmental effect.
Brito et al. (2006) [68]	28	100	-	-	The findings show that, for compressive strength and workability, concrete formed from MRAC, and RAC almost have the same properties. The authors demonstrated that recycling cycles have no limits.
P. Zhu et al. (2019) [69]	28	100	22	5.6	After three generations, it is possible to use RCA for structural concrete. Furthermore, as recycle cycles rise, RCA's qualities eventually decrease.

However, to qualify recycled concrete aggregate and multi-recycled concrete aggregate produced from high-performance concrete, several steps can be taken. Firstly, comprehensive testing of physical properties such as particle size distribution, scanning electron microscope analysis of RAC/MRCA is crucial. Chemical composition analysis to identify any harmful substances is essential for environmental and safety considerations. Performance testing under real-world conditions and compliance with relevant industry standards are vital steps to ensure the quality and suitability of these aggregates for construction applications. One example of a city utilizing recycled aggregate concrete in real applications is Los Angeles, California, USA.

2.7 Main properties of HPC using RCA, MRCA

2.7.1 Fresh properties

The workability of fresh concrete suffers when RRCA or MRCA is utilized without accounting for its water absorption capacity. Compared to concrete made with NA, RAC or MRAC) experiences more significant slump loss [70]. This difference in behavior can mainly be attributed to the characteristics of RCA/MRCA, including dimensions, quality, shape, and water content, which have a substantial impact on the properties of fresh concrete. Additionally, according to the American Concrete Institute (ACI), fresh properties or workability refer to the characteristics of freshly mixed concrete or mortar that affect its ease of mixing, placing, consolidating, and finishing to achieve a uniform state. Workability is a crucial property that sets apart HPC, and for concrete to meet HPC standards, a low water-to-cement (w/c) ratio is essential to enhance its strength. Therefore, to enhance the fresh properties of RAC/MRAC, the use of a superplasticizer is recommended. Some studies have proposed the use of RCA or MRCA under completely dry external conditions to improve workability, especially when dealing with high w/c ratios [71]. In practical scenarios, RCA or MRCA often retains some residual moisture, which is common in real-world applications. Consequently, utilizing RCA/MRCA under conditions where it maintains partial moisture content, such as air-dry conditions, presents a more realistic simulation and enhances the overall reliability of the study outcomes. When it comes to designing HPC, careful consideration of various properties during the design phase is paramount. These properties encompass a range of factors, including the concrete's ability to effectively fill up spaces (filling ability), its capacity to flow smoothly (passing ability), its viscosity or thickness, and its resistance to segregation or separating into different components. Attending to these critical aspects ensures that the concrete meets the necessary performance criteria and delivers the desired results, making informed decisions during the design process crucial for achieving optimal outcomes in HPC production and application.

2.7.2 Mechanical properties

Compressive strength, flexural strength, and splitting tensile strength are top mechanical properties used to comprehensively evaluate the behavior and performance of HPC. These properties offer valuable insights into the material's robustness and its ability to withstand diverse types of loads encountered in real-world applications. According to the specifications outlined by the American Concrete Institute (ACI), HPC typically mandates a minimum specified compressive strength of class (C55/67), indicative of its high-strength characteristics. Flexural strength assessment provides crucial information regarding the concrete's ability to resist forces that induce bending or deformation, which is particularly significant in structural elements subject to bending stresses. Similarly, the splitting tensile strength of HPC is a critical parameter that assesses its resistance to cracking or splitting forces acting perpendicular to the applied load. This property is often determined through a test involving a cylindrical specimen subjected to diametrical compression until failure occurs, providing valuable insights into the material's durability and structural integrity. Together, these mechanical properties serve as essential benchmarks for evaluating the performance and quality of HPC in diverse engineering applications. When RCA or MRCA are added to concrete along with SCMs, it can impact the strength and other properties of the concrete, either making them better or worse. This outcome depends on a few things, like what the materials are made of and how much RCA/MRCA is used. There are many factors that matter, such as how much water is used compared to the amount of cement, the qualities of the RCA/MRCA, the characteristics of the old mortar and concrete in the RCA/MRCA [71], how the materials are mixed together, how much cement is used at the beginning, what kind of other additives are included, and if plasticizers are used. All of these things together affect how the concrete with RCA/MRCA will turn out [72]. In short, there are different ways to make concrete with RCA/MRCA stronger, but it's important to think about all these factors carefully.

Additionally, Higher quality aggregates tend to enhance the strengths of HPC, while also contributing to its durability. Some points should be taken in consideration 1) Choosing the correct ratio of supplementary materials and -2) Making the aggregate tests (such as water absorption test of aggregate, sieve analysis process) can improve the strength of HPC concrete.

2.7.3 Water absorption property

In broad terms, durability, as defined by the American Concrete Institute (ACI), encompasses a material's ability to resist various forms of deterioration, including weathering, chemical attacks, abrasion, and other environmental factors that may impact its performance. This aspect holds crucial significance during the initial design phase, where the selection of appropriate materials is paramount to ensuring a prolonged and dependable structural service life [73]. Water absorption characteristics are influenced by multiple factors, such as the properties of concrete components and the techniques and ratios employed during mixing in the construction process. The presence of water in concrete introduces stability challenges, ultimately diminishing the performance of concrete products. The total volume of penetrable pores, typically assessed through the water absorption by immersion test, serves as an indicator of the overall accessible pore volume within the concrete. However, it's noteworthy that this test doesn't precisely predict concrete permeability [74]. Furthermore, it's observed that the water absorption of RAC/MRAC surpasses that of CC, a phenomenon influenced by various factors including the geometric shape, physical characteristics, size, and replacement ratio of RCA/MRCA, along with the properties of the mortar.

2.8 Life Cycle Assessment (LCA)

Over the past three decades, the landscape of environmental sustainability has undergone profound transformations, with significant advancements witnessed in the domain of LCA. This evolution stems from the pressing need for sustainable development practices that prioritize environmental stewardship alongside economic viability. LCA has emerged as a powerful tool, offering a comprehensive framework for evaluating, analysing, comparing, and enhancing products with regards to their environmental impact across their entire life cycle. The 1990s marked a pivotal period characterized by a surge in scientific inquiry and collaborative endeavours aimed at refining LCA methodologies. Central to this development was the active engagement of the ISO, which, since 1994, has played a central role in steering the course of LCA evolution. Through concerted efforts that brought together LCA specialists, consumers, and scientists, ISO facilitated the continual refinement and consolidation of LCA frameworks, ontologies, and techniques. The collaborative ethos fostered by ISO's leadership has been instrumental in shaping the course of LCA, propelling it towards greater robustness, standardization, and applicability across diverse industries and sectors [75][76]. Furthermore, LCA has proven to be a valuable tool in addressing the interests of local decision-makers, particularly in the long-term assessment of RCA utilization. Findings from LCA may be utilized as signs for the impacts of resource conservation, waste disposal, and concrete recycling technologies on the environment. In Serbia, Marinkovi et al. (2010) [77] conducted comparative LCA programs and discovered that energy savings in recycling projects are only attainable if recycling factories are in near location to building sites. They also established the MCDM for CC and RAC. In order to evaluate and compare the environmental effects of producing RCA from Recyclable materials and wasted glass with concrete paving green building , Hossain et al. (2016) [78] performed LCA tests in Hong Kong. They discovered that, as compared to NA, RCA made from waste disposal reduces greenhouse gas (GHG) emissions by 65% while saving

58% non-renewable energy use. In Slovenia, Turk et al. (2015) [79] used the LCA approach to analyse the RAC and NA. Their findings show that RAC has an environmental effect that is around 88% less harmful to the environment than CC, while it is only 96% less harmful in terms of CO_2 emissions, which contribute to global warming. The results also indicate that the usage of RAC is highly sensitive to delivery distance, with lengthy delivery routes leading to the outweighing of environmental advantages. A review study by Laurent et al. (2014) [80] found that the majority of LCAs on solid waste management systems were focused on Europe. In developing countries like the Middle East or China, there are surprisingly few LCA recycling applications. Less than 5% of substantial LCA studies in the domain of solid waste recycling have been conducted in China, which limits waste management activities. However, it is thought that RCA is very different from that in Europe in developing nations, particularly in terms of how the material is produced and transported.

Efficient management of solid waste is crucial for dealing with many environmental problems we face. It helps us tackle issues like climate change by reducing the release of harmful greenhouse gases from landfills. Plus, it prevents substances like halocarbons from discarded items, such as cooling systems or foams, from damaging the ozone layer. Poor waste management can also harm people's health. When waste isn't handled properly, it can expose us to dangerous chemicals and particles. And it's not just humans who suffer—wildlife and ecosystems can also be affected by pollutants like heavy metals released from waste. With the amount of waste we produce increasing every day, it's urgent that we adopt effective waste management strategies. These strategies are vital for addressing environmental challenges and moving towards a more sustainable society where we use resources wisely, limit pollution, and protect both human health and the environment. The employed LCA analysis evaluates the environmental impact of the utilization of end-of-life concrete as an alternative to coarse aggregate in the multi-life cycle dimension. The performed study follows guidelines provided in [81]. Opposed to linear economy models, which consume virgin resources only for the concrete design, the proposed alternative complies with circular economy principles by minimization of waste generation through the crushing of concrete and consequent replacement of coarse aggregate. In this regard, two service life spans are considered while the virgin resources are used only for the production of the standard concrete mixtures. Besides avoiding landfilling of concrete waste, the cement in the original mixtures is partially replaced by SF and FA to reduce the environmental footprint further.

2.9 Multi Criteria Decision Making (MCDM)

In the approximately fourteen years since its establishment, MCDM has captured the interest of academics as an exciting field. Over this period, researchers have delved into around 70 MCDM techniques. MCDM can be broadly classified into two primary categories: multi-attribute decision making and multi-objective decision making. In multi-attribute decision making, the objective is to select the optimal choice from a predefined set of alternatives, each characterized by various attributes. This approach is particularly valuable when dealing with problems that have a limited number of potential solutions [82]. Conversely, in multi-objective decision making, the focus is on generating alternatives that optimize the multiple objectives established by the decision maker. The ultimate choice should align with the decision maker's constraints and priorities. Often, this context presents an array of alternatives that can be extensive or even limitless. All the techniques that have been developed for MCDM have different basic presumptions, information needs, analytical models, and decision-making processes. This suggests that it is crucial to use the best relevant approach to address the issue at hand, as the employment of an inappropriate technique will always result in poor judgments. As a result, bad selections will cost you a lot of money. However, the choice of a suitable technique is a difficult one to make because of the wide range of MCDM techniques. Multiple non-commensurable and competing criteria, variable units of measurement across the criteria, and the availability of alternatives that differ greatly are only a few of the distinctive features of MCDM analysis. Therefore, five random MCDM were used in this study to make sure reaching the best alternative regardless the technique process. Additionally, the goal of this study is to evaluate and empirically validate numerous MCDM techniques that may be used to extend MCDM into circumstances including collective decision-making and the handling of uncertainty.

2.9.1 Technique for Order Preference by Similarity to Ideal Solution (TOPSIS)

TOPSIS technique proves practical and efficient for choosing and categorizing alternatives based on distance measurements. In essence, TOPSIS positions the selected alternative as far from the worst solution and as close to the ideal solution as feasible. The process involves constructing a decision matrix, normalizing it to create a non-dimensional normalized matrix, and determining ideal solutions (best and worst) for ranking parameters. The relative closeness coefficient (RCC) is then computed for each choice based on positive (D+) and negative (D-) separation matrices. The choice with the highest RCC is deemed the best. A study by M. Ahmed et al. 2020 [83] used TOPSIS to linguistically evaluate the potentiality order of concrete mixture design methods. Results highlighted the significance of the water-to-cement (w/c) ratio and density, with optimal w/c ratio and high density leading to sustainable concrete quality that balances technical, environmental, and economic requirements for durable concrete. K. Rashid et al., (2018) [84], employed the TOPSIS technique to optimize waste concrete mixtures, focusing on mechanical and environmental performance. The study used five criteria, including workability, density, compressive strength, CO_2 emission, and minimal use of non-renewable raw materials. Evaluating mixtures with RCA as a partial replacement for NA, the study found that the 20% RCA mixture consistently met design criteria and outperformed other options at both 28 and 63 days. The study highlighted the efficacy of MCDM techniques, particularly TOPSIS, in prioritizing various options consistently. In this study [85], an objective evaluation of concrete attributes was achieved through comprehensive testing, employing the TOPSIS technique. The results indicated that the best concrete series, determined objectively by TOPSIS, comprised 10% SF and varied ratios of RCA. Notably, this optimal concrete series demonstrated performance comparable to, or even better than CC.

2.9.2 VIsekriterijumska optimizacija i KOmpromisno Resenje technique (VIKOR; Multi-criteria optimization and Compromise Solution

The VIKOR technique is a powerful tool to compensate for multi-criteria decision making and is used to solve problems arising from inconsistent and inappropriate criteria. This strategy is used when a decision maker is not able to formulate his preferences at the beginning of the system design. As a result, a solution is needed for the decision maker that is closer to the optimal answer. Opricovic and Tzeng. (2003) [86] proposed a fresh model for defuzzification in a multi-criteria decision model with mixed fuzzy criteria and a set of crisp criteria based on the VIKOR technique and TOPSIS. he used the VIKOR technique with fuzzy numbers to evaluate plans for reducing costs in hazard-prone regions. Their approach involves generating alternatives, defining criteria, weighting criteria, and using VIKOR for ranking. These alternatives include hazard mitigation plans like urban redevelopment and land use changes, evaluated using criteria related to safety, sustainability, environment, economics, culture, and politics. The results provided a comprehensive approach for decision-making in areas prone to natural hazards. Opricovic and Tzeng. (2003) [87] designed a multicriteria model for assessing land-use plans in disaster-prone regions to minimize future social and financial costs. The process involves generating alternatives, defining criteria, weighting criteria, and using a compromise ranking technique. These alternatives consist of various sustainable hazard mitigation scenarios, primarily based on detailed land-use plans. This model’s result offers a comprehensive approach for evaluating conflicting effects and impacts within geographical units, aiding decision-making in disaster-prone regions. Liu and Wang (2011) [88] improved the VIKOR technique for multiple attribute group decision-making with generalized interval-valued trapezoidal fuzzy numbers, encompassing both attribute values and weights. This adaptation is crucial for decision-making scenarios where information is expressed in fuzzy numbers. The study also applied the VIKOR technique to rank candidate materials and conducted weight sensitivity analysis, providing valuable insights for material selection. However, a limitation is noted as the study didn't consider the processability of the additional criteria studied.

Regarding the practicality of recycling, this research [89] delves into the practicality and environmental impact of recycling, composting, and conversion for future adoption in waste management. It evaluates local waste management techniques, providing insights for environmentally friendly waste management systems. Various waste management options are analysed and prioritized for an integrated solid waste management approach. Sensitivity analysis, employing the VIKOR and TOPSIS techniques, is used to assess solid waste management possibilities. The study suggests utilizing the VIKOR technique to compare the production of "green" concretes from recycled gypsum cement and RCA with conventional concrete made from NA and regular portland cement. The VIKOR technique aids in determining the best or acceptable alternatives, considering both environmental and financial factors, based on economic and environmental evaluation criteria. The findings of this study indicated that the use of recycled gypsum cement and RCA was the best option for both structural and non-structural concrete, whether environmental and economic factors were given equal weight, or one of the two criteria was given higher weight. The worst option in both

Finally, a technique for selecting the optimal repair material for concrete buildings is presented in this study [90], complemented by the VIKOR technique. The result of this approach assists civil engineers in modelling and selecting the most suitable repair materials according to predefined criteria. To ensure the reliability of the results, a case study is conducted to validate the proposed technique. Since the weighting of criteria significantly influences the ranking of repair materials.

2.9.3 Evaluation based on Distance from Average Solution technique (EDAS)

Inventory classification is a valuable technique for managing large quantities of inventory items or items in various fields efficiently. Traditionally, this involves categorizing items based on a single criterion. However, a more practical approach is to treat inventory classification as a multi-criteria problem. In this study [91], a novel technique, EDAS, is introduced for tackling multi-criteria inventory classification challenges. The alternatives are assessed by considering both positive and negative distances from the average solution. They developed this technique for inventory categorization of items. It proved that the EDAS strategy is effective and takes less processing than earlier other classification techniques. Additionally, a comparison of the EDAS technique to a few commonly employed techniques served to illustrate how effective the MCDM technique was. The distances between each alternative and the average answer according to each criterion are utilized in this technique to assess the alternatives.

In real-world situations, we frequently encounter the need to evaluate different alternatives while considering multiple inconsistent criteria. This area of decision-making is known as MCDM. Several methods and techniques are available for solving MCDM problems, with the EDAS technique being particularly efficient. Given that uncertainty is often inherent in MCDM problems, utilizing fuzzy MCDM methods can be extremely advantageous for addressing complex decision-making challenges. This study [92] advances the EDAS technique by adapting it for handling problems in a fuzzy environment. To demonstrate its application, the study presents a case involving supplier selection. Furthermore, a sensitivity analysis is carried out, using simulated criteria weights to evaluate the method's stability and reliability. The study's findings emphasize that the extended fuzzy EDAS method is effective and provides robust stability when addressing complex problems. The extended fuzzy EDAS technique is composed of the following stages:

1- Create the average decision matrix (X)

2- Construct the matrix of the criteria weights (W)

3- Construct the matrix of average solutions (AVJ)

4- Assume that B is the collection of beneficial criteria and N is the group of non-beneficial criteria. The matrices of positive distance from average (PDA) and negative distance from average (NDA) are calculated at this phase based on the kind of criterion (beneficial or non-beneficial).

5- For each alternative, compute the weighted sum of positive and negative distances.

6- For each alternative, the normalize values (SPi) and (SNi) are determined.

7- Calculate the appraisal score (ASi) for all alternatives.

8- Rank the alternatives in decreasing values of assessment score value (ASi).

The EDAS technique finds utility in various fields, including construction, as demonstrated in this study [93]. Safety risk assessments for metro construction projects are crucial to prevent severe accidents that could lead to significant financial losses and casualties. This study introduces a comprehensive risk assessment framework that combines credal networks with an improved evaluation process based on the EDAS technique. This framework's result offers significant benefits. Firstly, it offers a clear representation of the interrelationships among different risk factors. Secondly, it addresses the inherent epistemic uncertainty in expert judgments through imprecise probabilities, which are then effectively and accurately propagated using advanced inference algorithms.

2.9.4 Weighted Sum Model (WSM)

This technique holds a venerable status as the oldest and most prevalent model in decision-making methodologies. It finds extensive use in computations based on real criteria values, particularly in scenarios characterized by a single dimension. Underlying the WSM is the additive utility assumption, which suggests that the overall utility or value of a decision alternative can be expressed as the sum of its individual criterion values weighted by their respective importance. In situations where all units are identical and the decision-making process is one-dimensional, the WSM proves to be easily implementable and interpretable. However, challenges arise when attempting to apply the WSM to address multidimensional MCDM problems. In such complex scenarios, where decisions involve consideration of multiple criteria with varying importance levels and interdependencies, the simplistic nature of the WSM may lead to oversimplification or misrepresentation of the decision problem, thereby limiting its effectiveness as a decision support tool.

The additive utility assumption is then violated by mixing various dimensions, and as a result, different units, leading to the equivalent of “adding apples and oranges”. Obtaining a weighted total of the performance ratings of each choice across all qualities is the fundamental tenet of the WSM technique.

2.9.5 Weighted Product Model (WPM)

It is quite similar to WSM, but it calculates the weighted normalized matrix in a different way [94]. Instead of simply multiplying values, it involves raising the base to the power of the weights assigned to each criterion. This approach allows it to be used for both single and multi-dimensional decision problems. This method, known as "dimensionless analysis," removes the need for units of measure in the analysis. As a result, the WPM can be applied to both single- and multi-dimensional MCDM scenarios. In a related study [96], a combination of these two techniques was employed to choose between different types of alternatives. For instance, the combination of different types or lengths of fibres is termed "hybrid fiber," while mixing various fiber lengths in concrete is referred to as "graded fiber."

2.9.6 Comparing of five techniques

By comparing the five techniques, differences can be found between them. Diversity makes it easier to choose the best solution from a large pool of possibilities for a particular problem, but since these techniques are so widely varied, making the right decision is more difficult. Each technique has its own advantages and disadvantages. For example, TOPSIS suggests that the chosen option is as far away from the worst solution as is realistically reasonable and as close to the perfect answer as is practicably attainable. However, when a decision maker is unable to clearly express his preferences at the beginning of the system design, the VIKOR technique is employed. Thus, the decision maker needs a solution that is more closely related to the ideal response. Moreover, when it comes to the efficiency and fast process, the EDAS techniques is used. They created this technique to classifying goods in an inventory and other products in different field. This technique’s effectiveness and quicker processing time compared to prior other mentioned techniques were demonstrated. Additionally, when dealing with identical units, the WSM is suitable for single-dimensional settings. However, it faces challenges when handling MCDM problems. This is why the WPM is employed when dealing with multidimensional scenarios. WPM can be applied to solve both single- and multi-dimensional decision-making problems. What distinguishes WPM is its “dimensionless analysis” nature, as it doesn’t incorporate any units of measurement.

In this thesis, an in-depth analysis has been conducted on five different techniques, evaluating a total of fourteen concrete mixtures based on various criteria. The research outlines a systematic approach for selecting the optimal concrete mix for each technique, illustrating a step-by-step process and meticulously comparing the results. Figure 4 visually depicts the common steps shared by all techniques, providing a clear overview of the methodology employed throughout the study.

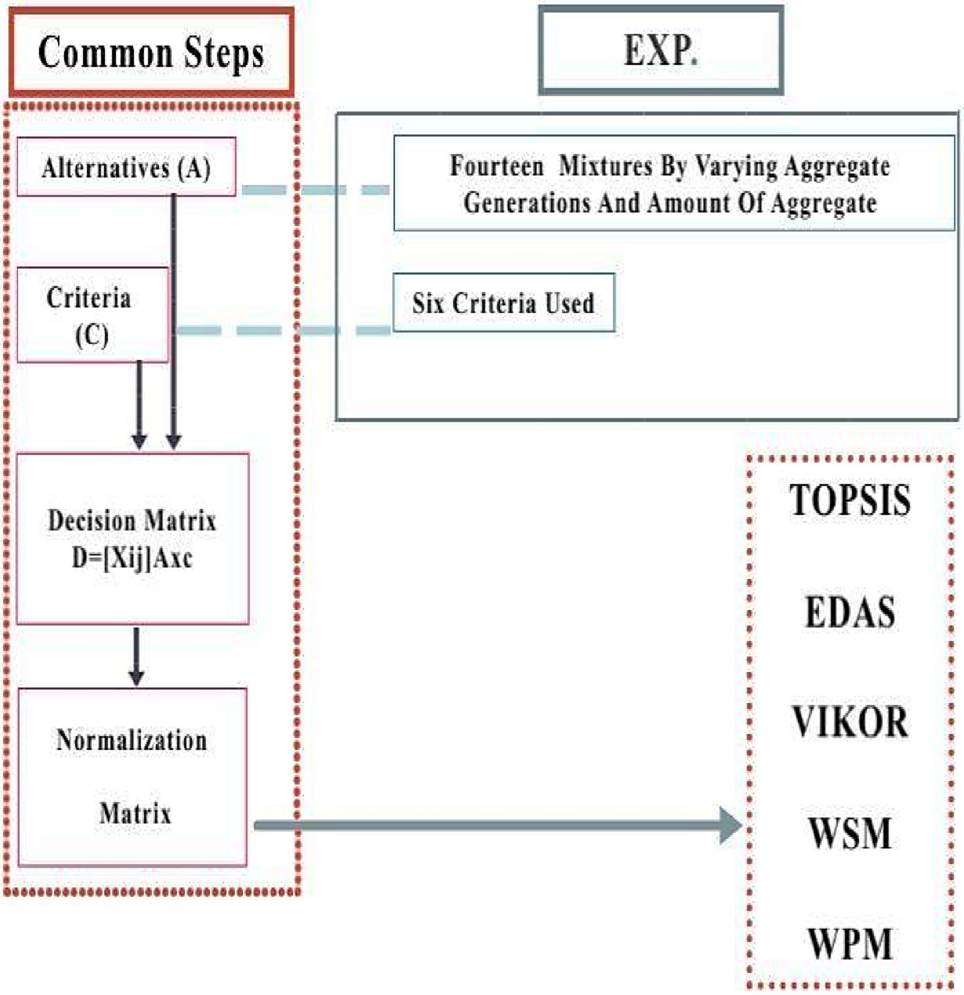


Figure 4. MCDM’s common steps of the five used techniques

CHAPTER 3: Methodology of thesis

All the experiments were done in the laboratory of building materials and building physics at Széchenyi István University. This part explains the process employed to accomplish this Ph.D. work's goal. The materials utilized, the processes of the experimental and analytical work, and the techniques carried out to complete each stage are detailed. This chapter describes the research process and offers a flowchart for the whole study program.

3.1 Program introduction

The research work divided into four stages to combine the diversity of the major performance keys and create a robust framework that can be employed as performance, sustainable, and economical based-design applications on the second generation of recycling concrete, MRAC. The four stages prioritize the technical, environmental, and economic perspectives. The dissertation stages are summarized in Figure 5.

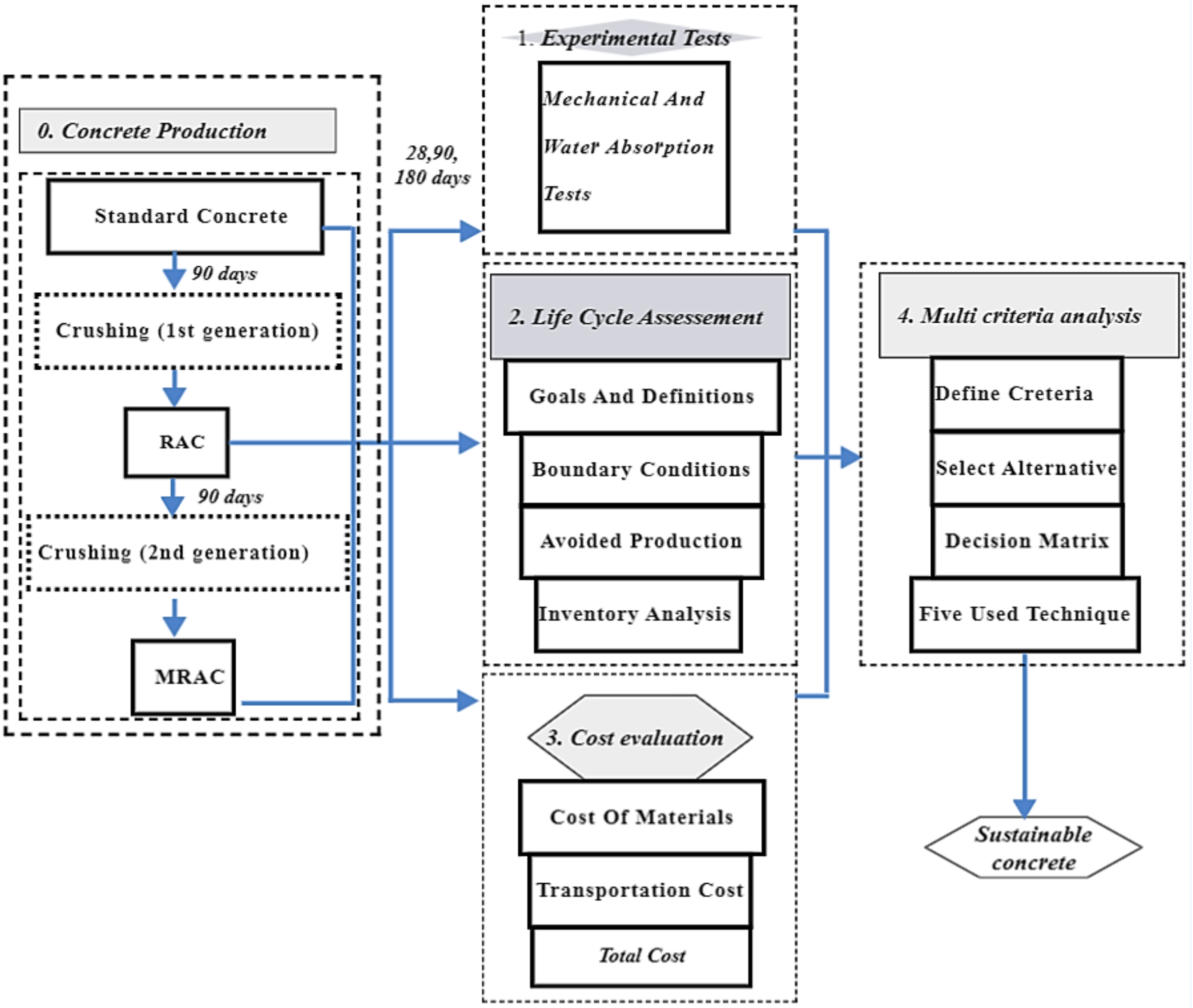


Figure 5. Dissertation stages

3.2 First stage: Concrete production and experimental testing

Experimentally, two generations of concrete at both fresh and hardened states prepared and tested. The standard concrete which included four mixtures:

- CC, which is a concrete produced with only NA.
- 20F, which is a concrete produced by
  replacing 20% of cement with FA.
- 12S, which is a concrete produced by
  replacing 12% of cement with SF.
- 20F-12S, which is a concrete produced by
  replacing 20% and 12% of cement with FA and SF.

The first generation was produced by using the rubble of standard concrete after testing as RCA with different proportions to produce RAC. Whereas:

- 20F-R30, which is a concrete produced by
  replacing 20% of cement with FA and 30% of NA with RCA.
- 20F-R70, which is a concrete produced by
  replacing 20% of cement with FA and 70% of NA with RCA.
- 12S-R30, which is a concrete produced by
  replacing 12% of cement with SF and 30% of NA with RCA.
- 12S-R70, which is a concrete produced by
  replacing 12% of cement with SF and 70% of NA with RCA.
- 20F-12S-R30, which is a concrete produced by
  replacing 20% and 12% of cement with FA and SF,
  additionally, replacing 30% of NA with RCA.
- 20F-12S-R70, which is a concrete produced by
  replacing 20% and 12% of cement with FA and SF,
  additionally, replacing 70% of NA with RCA.

While the second generation was produced by using the rubble of RAC that was produced in the first generation after testing as the MRCA with different proportions to produce MRAC.

- 20F-12S-RR30/30, which is a concrete produced by
  replacing 20% and 12% of cement with FA and SF,
  additionally, replacing 30% of NA with MRCA made from crushed 20F-12S-R30.

- 20F-12S-RR30/70, which is a concrete produced by
  replacing 20% and 12% of cement with FA and SF,
  additionally, replacing 70% of NA with MRCA made from crushed 20F-12S-R30.
- 20F-12S-RR70/30, which is a concrete produced by
  replacing 20% and 12% of cement with FA and SF,
  additionally, replacing 30% of NA with MRCA made from crushed 20F-12S-R70.
- 20F-12S-RR70/70, which is a concrete produced by
  replacing 20% and 12% of cement with FA and SF,
  additionally, replacing 70% of NA with MRCA made from crushed 20F-12S-R70.

In total, fourteen concrete mixtures were produced in three phases. The loop cycle of concrete production is shown in Figure 6. While the physical properties are shown in Table 3.

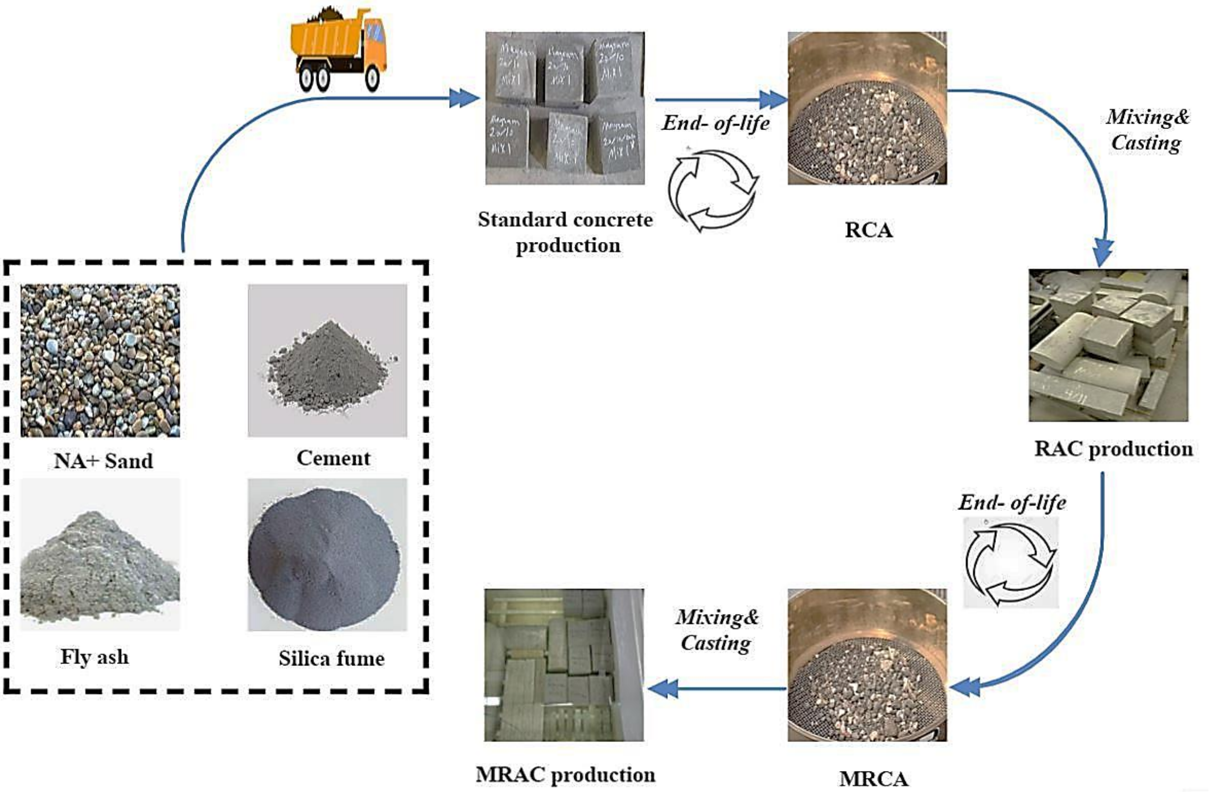


Figure 6. Loop cycle of concrete production

3.2.1 Aggregate's water absorption

The average of strength of both NA and RCA/MRCA was between 29-32 MPa. The test was conducted utilizing a tamping rod, plunger base plate, and diameter open-ended steel cylinder. Using the machine for compressive strength as well. Additionally, considering the significant variations between NA and crushed aggregates, methods used to evaluate water absorption in NA were still relevant for RCA or MRCA. Water absorption is an essential physical attribute of aggregates. Therefore, in the present research, the water absorption of crushed aggregate was determined using a calculation based on the saturated surface dry of the aggregate's particles. However, the only variables were the aggregate type and the percentage of NA replacement. The difference between the aggregate's initial water absorption capacity, which is shown in Table 3. and the aggregate's water content at the time of mixing has been used to account for the water absorbed by RCA and MRCA (air-dried). When an aggregate's particles' permeable pores are full of water without having free water on their surfaces, the state is known as saturated surface dry. The following actions, which are advised by most standards, required to be taken to determine the water absorption capacity based on the idea of saturated surface dry. The ability to absorb water was calculated using Eq. (1).

1) By immersing in water for no less than 24 hours, the aggregate was made saturated.
2) With the use of a cloth, the wet layer covering the surface was removed, and the dry, saturated bulk of the surface was weighed. It was possible to achieve the saturated surface dry condition in accordance with the following specifications by towelling the aggregates' surface.
3) The samples were then dried in an oven at 110 ± 5 °C until totally dry, or until constant mass for at least 24 hours.

$$Water\ absorption = \frac{W_{weighted\ surface\ dry} - W_{weighted\ of\ oven\ dry}}{W_{weighted\ of\ oven\ dry}} \cdot 100 \qquad \text{Eq. (1)}$$

Water absorbed by RCA and MRCA has been balanced by keeping the same amount of water as it was in control concrete, in return, the increasing of superplasticizer amount has been done to keep the strength of recycled concrete high, because the water can negatively affect the strength.

Table 3. Aggregates' physical properties

Aggregate types	Water absorption (%)	Specific gravity (g/cm^3)
Natural aggregate, NA	1.01	2.610
Recycled aggregate, RCA	5.50	2.530
Multi-recycled aggregate, MRCA	5.80	2.500
Fine aggregate	2.00	2.620

Cement (Ordinary portland Cement, CEM I 52.5 N), FA (Microsite$_{20}$, which is a superb latent hydraulic cement admixture type II for the manufacture of high-quality concretes and mortars), SF (Sika Hungary), fine aggregate (0/4 mm), NA (4/16 mm), RCA (4/16 mm), MRCA (4/16 mm), however, all aggregate types kept in the water tank for 24 hours. The proportion of the fractions was 36.1% fine aggregate (0/4 mm) and 24.7% coarse aggregate (4/8 mm) and

39.2% coarse aggregate (8/16 mm). Superplasticizer (Sika ViscoCrete-5 New), and drinking water were the main ingredients that used in the production of designed concrete mixtures. FA and SF replaced the cement partially with the proportion of 20% and 12%, respectively. Studies by Jalilifar et al. (2016) [6] and Dimitriou et al. (2018) [7] indicate that using FA and SF with greater ratios than 20% and 15%, respectively, lowers compressive strength. However, according to Zhu et al. (2011) [97], RAC was created by replacing NA with 30%, 70%, and 90% RCA, respectively, before the rubble was crushed to create second-generation concrete. Nonetheless, the RCA's quality after two crushing cycles met the structural requirements, which inspired researchers to do more investigations using the same replacement aggregate ratio. The NA and fine aggregate were quartz Danube River aggregate, while RCA and MRCA were crushed and produced in the lab from the tested specimens. Physical and chemical properties of cement, FA, SF.

Table 4. Physical and chemical properties of cement, FA, SF

Properties	**Material**		
	Cement	**FA**	**SF**
Density (g/cm^3)	3.13	2.5	2.2
Blaine fineness (m^2/kg)	420	730	-
Loss on ignition (%)	3.6	3.4	3.11
SiO_2	20.5	52	93.43
Al_2O_3	4.4	25	0.17
Fe_2O_3	2.3	7	0.69
CaO	63.3	5	0.03
MgO	2.1	-	-
NaO_2Eq	0.66	-	-
Clinker	97	-	-

All grading curves have shown in Figure 7. The physical and chemical properties of cement, FA and SF are shown in Table 4.

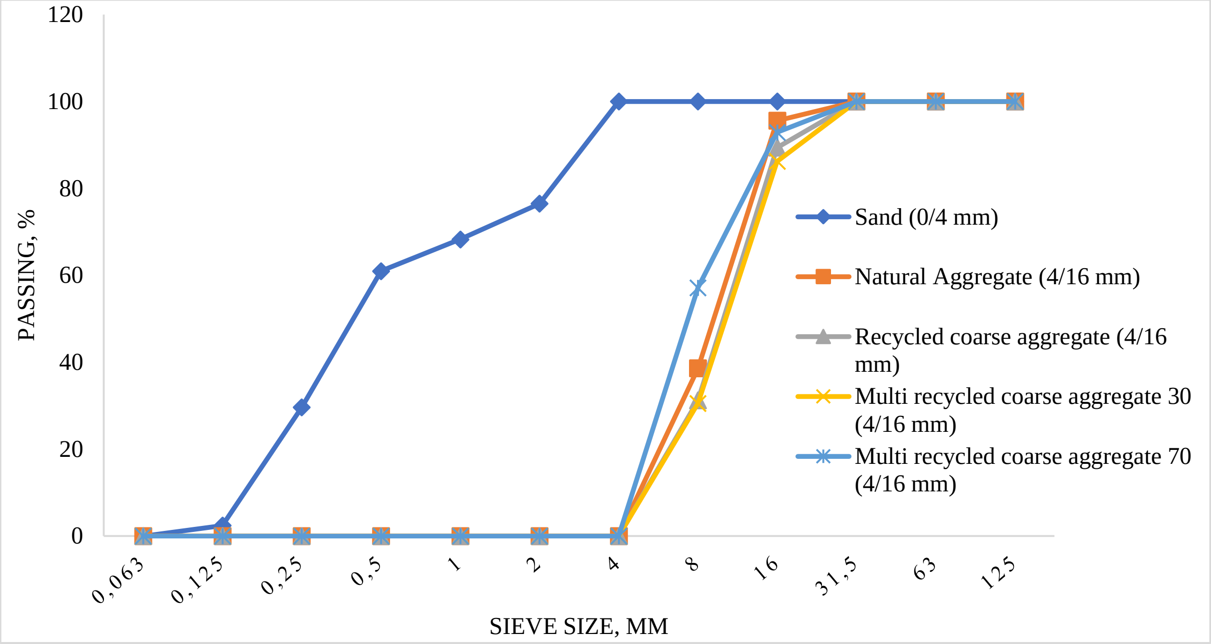


Figure 7. Grading curves of all used aggregate types

Table 5. shows the concrete production series and material proportions of designed concrete mixtures.

Table 5. Concrete mixtures and material proportions

Mixture name	**Classification**	**Cement, kg/m^3**	**FA, kg/m^3**	**SF, kg/m^3**	**Fine aggregate, kg/m^3**	**NA, kg/m^3**	**RCA, kg/m^3**	**MRCA, kg/m^3**	**Superplasticizer, kg/m^3**	**Water, kg/m^3**
CC	Series I, Standard concrete	360	0	0	686	1209	0	-	4.32	144
20F		288	72	0	686	1209	0	-	3.60	144
12S		317	0	43	686	1209	0	-	4.32	144
20F-12S		245	72	43	686	1209	0	-	3.96	144
20F-R30	Series II, First generation	288	72	0	686	848	363	-	4.68	144
20F-R70		288	72	0	686	360	848	-	4.86	144
12S-R30		317	0	43	686	846	364	-	5.40	144
12S-R70		317	0	43	686	364	846	-	5.62	144
20F-12S-R30		245	72	43	686	849	360	-	5.40	144
20F-12S-R70		245	72	43	686	364	849	-	5.76	144
20F-12S-RR30/30	Series III, Second generation	245	72	43	686	846	-	363	4.68	144
20F-12S-RR30/70		245	72	43	686	363	-	846	5.04	144
20F-12S-RR70/30		245	72	43	686	846	-	363	5.04	144
20F-12S-RR70/70		245	72	43	686	361	-	846	5.76	144

3.2.2 Preparation of specimens and test method

During the experiments, the dry materials added to the pure water in the exact amount after one minute, when the mixture began to mix, the superplasticizer was added to obtain a perfect concrete mixture, reduce water amount and increase the strength of concrete. Mix the concrete for approximately 3–4 min until a uniform, workable consistency is achieved. Properly mixed concrete should look like thick oatmeal and hold its shape when squeezed in a gloved hand. The next step was a flow table test to check the fresh concrete and determine its workability of the concrete. Then the cube, cylinder, and prism moulds were prepared for casting the concrete. After that, the specimens were stored in the room for 24 hours, then cured in water for 7 days, and then left in the room until the day of testing. The manufacturing steps of the specimens are shown in Figure 8.

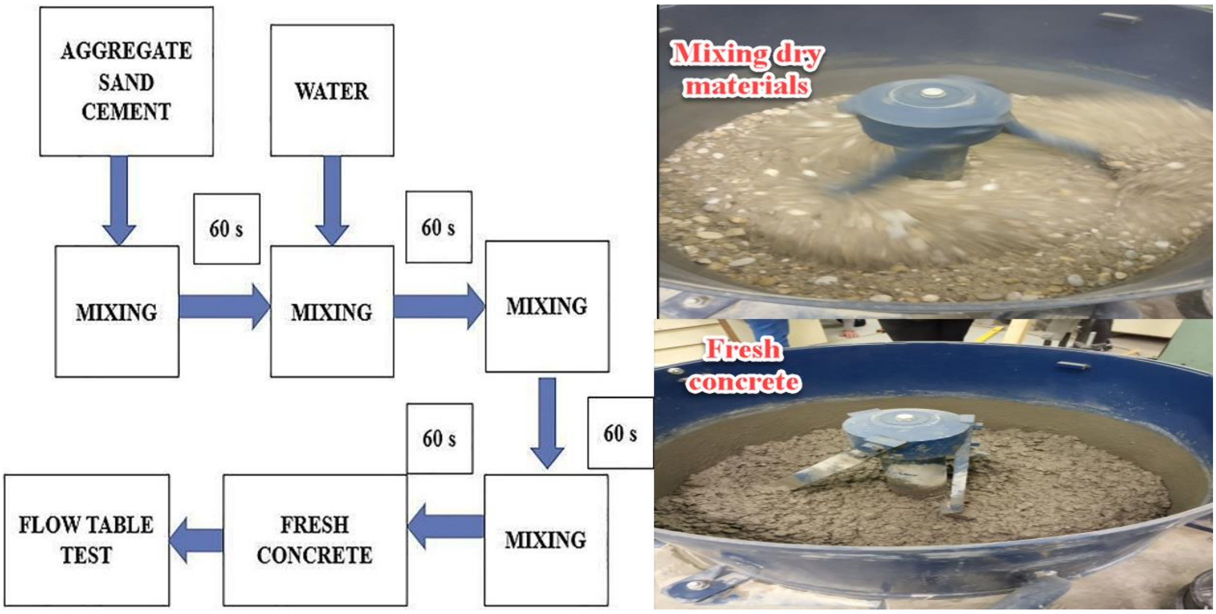


Figure 8. Process of experimental mix

3.2.3 Flow table test

The standard used in this test was MSZ EN 12350-5 (2019) [98] to ensure that all concrete mixtures were produced to be workable between 420 and 480 mm and to optimize the superplasticizer amount for each mixture. The quickest way to judge the quality of a product is to compare it to its competitors. The flow table test can also be used to determine the transportable moisture limit of solid bulk cargo. It is generally used to evaluate concrete that is too fluid (workable) to be assessed using the slump test, as the concrete will not keep its shape once the cone is removed. The used equipment is:

- Flow table were used with a grip and a hinge (70×70 cm).

- Abram’s cone (metal cone), open at the top and at the bottom (30 cm high, 17 cm top diameter, 25 cm base diameter).
- Water bucket and broom to wet the flow table.
- Tamping rod (60 cm long).

Whereas the procedure of the flow table test is:

- Wetting the flow table equipped with clip and hinge (70×70 cm).
- Placing the Abrams cone in the centre of the flow table.
- Filling the Abrams cone with fresh concrete in two equal layers. Each layer is tamped 10 times with a tamping rod.
- After 30 seconds lift the cone allowing the concrete to flow.
- Lift the flow up 40 mm and then drop it down 15 times, causing the concrete to flow.
- Measure the diameter of flow of the concrete.

Figure 9. shows the flow table test which used in the experimental stage for all mixtures.

Figure 9. Flow table test of fresh concrete

3.2.4 Compressive strength test

Compressive strength is one of the most essential technical properties of concrete for designers. The compressive strength of a certain concrete mixture is graded, which is typical industry practice. To get this value, cubes examined concrete specimens in a compression testing machine (channel model, ELE International-ADR2000, with speed of 0.6 MPa/s). Based on the various design regulations in each nation, test requirements vary. Concrete’s compressive strength is expressed as the typical compressive strength of 150 mm size cubes evaluated after

28 days. Compressive strength tests are also carried out in the field of construction. Compressive strength is tested on materials, components, and structures. The ultimate compressive strength of a material is defined as the value of uniaxial compressive stress attained when the material fully fails. Figure 10 shows the tester machine of compressive strength.

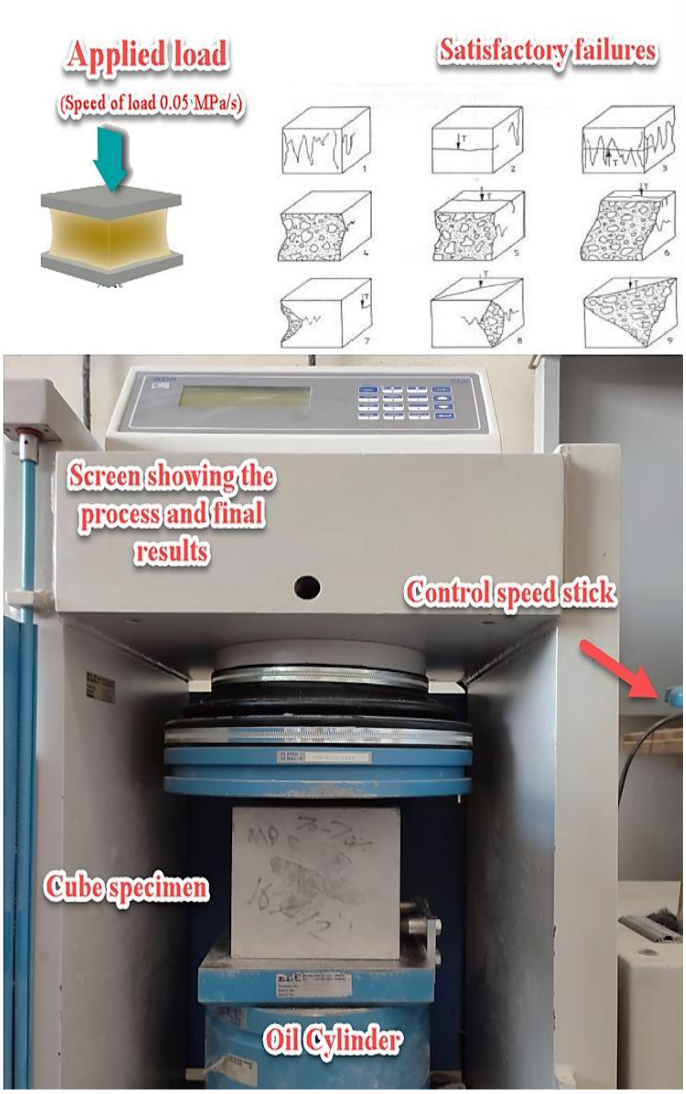


Figure 10. Compressive strength test

The number of cube-shaped specimens utilized for compressive strength testing was eight for each mixture, with a dimension of 150×150×150 mm (cylinders of various sizes can also be used to measure compressive strength), that means four specimens from each mixture were examined at 28 days of age, and another four cube-shaped specimens were tested at 90 days and 180 days of age, in accordance with the standard MSZ EN 12390-3:2019 [99].

3.2.5 Flexural strength test

Flexural strength, also referred to as rupture modulus, bend strength, or transverse rupture strength, is a material characteristic defined as the stress in a material just before it yields in a flexure test. The most typical test is the transverse bending test (Matest – YIMC 109NC, with speed of load 0.05 MPa/s), which entails using a three-point flexural test technique to bend a specimen with a circular or rectangular cross-section until it fractures or yields. Flexural strength is a measurement of the material's maximum internal stress at the point of yield. It is quantified by measuring levels of stress. Figure 11 presents the flexural strength machine.

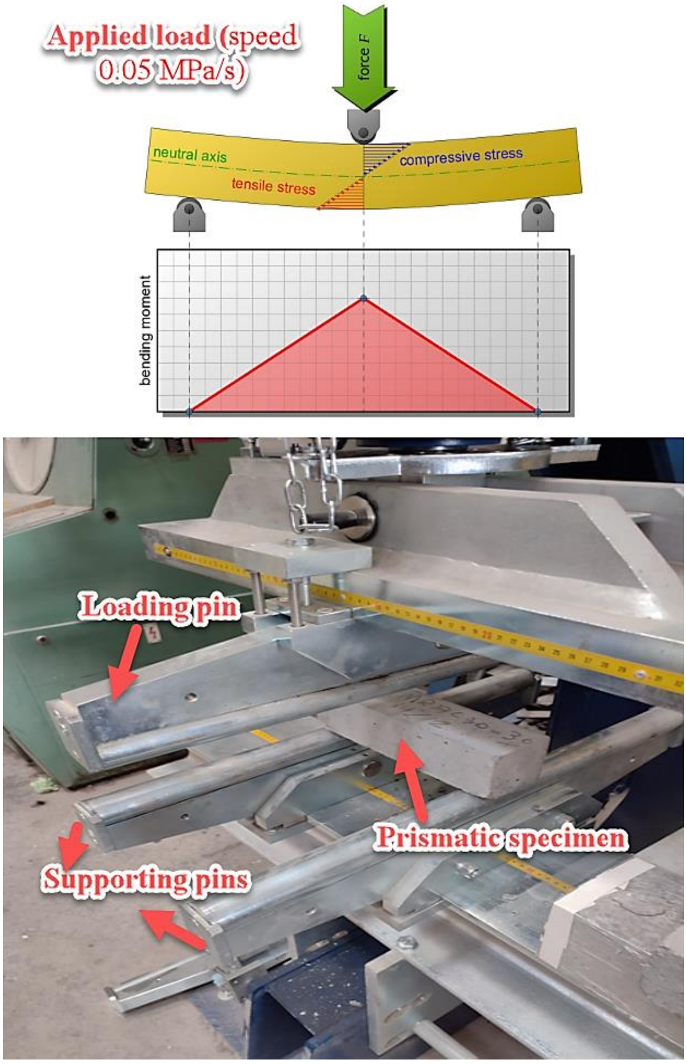


Figure 11. Flexural strength test

The flexural strength test conducted using four prismatic specimens per combination with a size of 70×250×250 mm at 28 days and the same number at 90 and 180 days in line with the standard MSZ EN 12390-5:2019 [100].

3.2.6 Splitting strength test

The ability to resist tensile cracking, which can result from structural loads (the test has been done by universal closed-loop hydraulic testing machine, WEB-ZD 40, with speed 0.05 MPa/s), makes tensile strength one of concrete's key characteristics. According to estimates, concrete's tensile strength is equivalent to 10% of its compressive strength.

The samples were cylinders with a diameter of 15 cm and a height of 30 cm. The employed metal moulds have a mean interior diameter of 15 cm ± 0.2 mm and a height of 30 cm ± 0.1 cm. However, a thin coating of moulds oil applied to prevent the concrete from adhering to the moulds after use. The concrete was poured into the moulds in 5 cm thick layers, each layer was compressed. After compacting the top layer, I used a trowel to level the concrete surface with the moulds' top. I covered the concrete with a glass or metal plate to stop water evaporation. For curing, the specimens were kept at a location that was 27 ± 2 °C for 24 hours. Following this time, specimens were taken from the moulds and allowed to dry for the required time in clean, fresh water. Figure 12 shows the used splitting tensile machine.

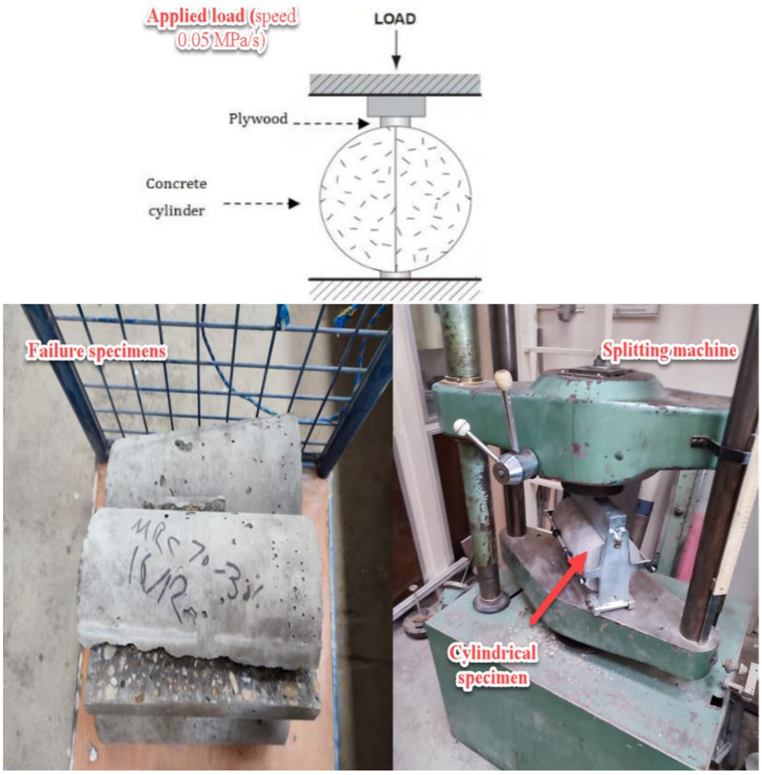


Figure 12. Splitting strength test

In this work, four plus four cylindrical test specimens with a size of 15×30 cm was generated for each mixture at the ages of 28, 90, and 180 days in accordance with the standard MSZ EN 12390-6:2010 [101].

3.2.7 Water absorption test

Practically, due to the thermal process caused by water absorption, which is generated by the surface tension of capillary pores, the transport abilities of water in unsaturated concrete are substantially proportional to the water content of the concrete. However, size, replacement quantity, physical characteristics of RCA/MRCA, and the qualities of the mortar, all influence the water absorption of RAC/MRAC, which is greater than that of CC [102]. According to the research [103], the workability of RAC is affected by the usage of RCA. Whereas, the consistency of RAC has raised, and the water/cement effective ratio is lowered as a result of the connected mortar’s capacity to absorb water. Marie and Quiasrawi [63] have studied the effect of MRCA on water absorption of concrete and they emphasized that the concrete absorption of the RAC and MRAC is larger than that of CC by 50% and 20%, respectively. In similarity, researchers found that aggregate absorption increases, and density reduces with each recycling cycle during their investigation on MRCA and their impact on the durability of concrete [104].

The tap water utilized as a consumption water for mixing process that fulfils with the requirements and European standard. The water absorption test determined by immersing three 150×150×150 mm cubes in water until fully saturated, i.e., until they attained constant mass. The samples were then dried in an oven at 50-60 °C until totally dry, or until constant mass. Relative masses were noted in order to calculate the water absorption after 90 days. The test had certain limitations in that it could only quantify the volume of viewable pores and so could not reflect the concrete’s absolute porosity.

The specimens were cast in different-sized moulds made of steel and plastic to create the standard for each test. Table 6. listed the quantities and shapes of the test specimens for each mixture. All specimens were kept in lime-saturated water for seven days, according to the standard MSZ EN 772-11:2011 [105], before being transported to laboratory conditions (20 ± 2 °C) until testing time. The tests were conducted, respectively, at 28, 90, and 180 days. 210 cubes, 168 prisms, and 168 cylinders altogether were produced. A slump flow table test was used to assess the consistency of the fresh mixtures.

Table 6. Shape and number of used specimens for all mixtures

Type of Test	Type of specimen	Days		
		28	90	180
Compressive strength	Cube (15×15×15 cm)	4	4	4
Flexural strength	Prism (7×7×25 cm)	4	4	4
Splitting strength	Cylinder (15×30 cm)	4	4	4
Water absorption	Cube (15×15×15 cm)	-	3	-

3.3 Second stage: Life cycle assessment

3.3.1 Boundary conditions

The boundary conditions used in this study include the processes associated with the production of concrete (standard and alternative) for each particular mixture together will all major flows of raw materials, emissions, and transportation. Performed analysis excludes processing of the concrete mixtures (casting or mixing) as the production steps are identical for each material and generation as well as the use stage. For the first and second generations of recycled concrete, the transportation of 103 km by diesel lorry (EURO 4). The transportation costs are included for better reliability of the presented results, and to avoid overrepresentation of environmental benefits. As reported by Yazdanbakhsh et al. (2018) [106], the transportation distance matters for the replacement of low-grade materials substantially. A clearer description of the boundary conditions is depicted in Figure 13.

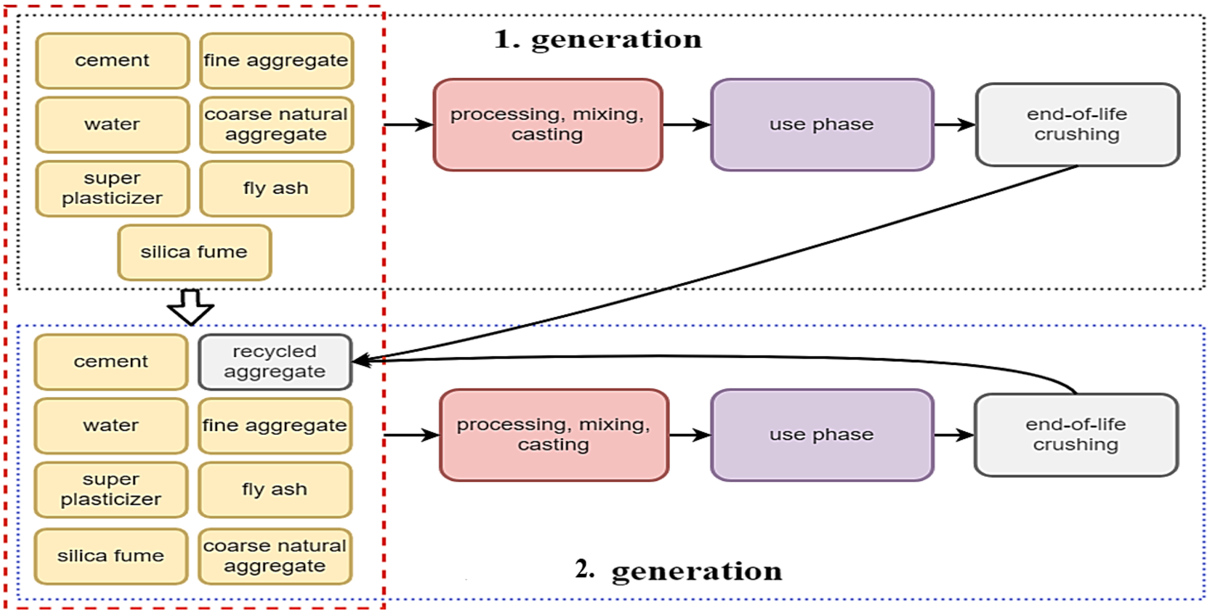


Figure 13. Boundary conditions for the two generations of concrete

3.3.2 Avoided production

The environmental benefits calculated based on avoided production of NA in the 1st and 2nd generations of designed concrete. Besides, the replacement of NA by crushed end-of-life concrete, a partial replacement of portland cement by SF and FA is also considered in all generations of designed concrete. The avoided landfilling of used concrete is not intended as a benefit according to rules associated with European standards for LCA analysis (ISO 14040, 2006) [81].

3.3.3 Inventory analysis and impact assessment

Here, the obtained data modified according to the functional unit and included in the Simapro LCA software 9.0. The quantities of particular components were given by mixture proportions provided in Table 2. For this study, the Impact 2002 + Methodology (version 3.5) by Simapro 9.0 was selected as it allows the presentation of not only midpoint impact categories, but also endpoint indicators and further conversion into a single score that can be used for multi-criterial decision-making analysis.

This method includes a complex list of 15 impact categories provided a robust platform for the identification of environmental burden on both midpoint and endpoint levels. The impact categories included in the assessment are listed as follows:

- Aquatic acidification (AAC),
- Aquatic ecotoxicity (AE),
- Aquatic eutrophication (AEU),
- Carcinogens (CA),
- Global warming potential (GWP),
- Ionizing radiation (IR),
- Land occupation (LO),
- Mineral extraction (ME),
- Non-carcinogens (NCA),
- Non-renewable energy (NRE),
- Ozone layer depletion (OLD),
- Photochemical oxidation (PO),
- Respiratory inorganics (RI),
- Terrestrial acidification/nitrification (TAN), and
- Terrestrial ecotoxicity (TE).

The impact assessment stage uses a qualitative technique to categorize the inventory data into several impact groups. The situation has been settled for several midpoint impact categories, such as GWP, since their contributing flows may be identified. Therefore, a certainty index is employed to represent the reliability of the assortment procedure. A normalizing step is then performed after that to reach the endpoint categories, which calculated as the sum of normalizing chosen midpoint categories (climate change, ecosystem quality, resources, and human health) using the Eq. (2) to (5) [107].

$$Climat\ change = GW \qquad \text{Eq. (2)}$$

$$Ecosystem\ quality = \sum(AE + TE + AA + AA + AEU + TAN + PO + OLD + LO) \qquad \text{Eq. (3)}$$

$$Resources = \sum(ME + NRE) \qquad \text{Eq. (4)}$$

$$Human\ health = \sum(CA + RE + IR + OLD + PO + NCA) \qquad \text{Eq. (5)}$$

However, the total environmental load expressed as a single score (the definition is different for the various impact assessment methods that use single scoring). In this score, characterization, damage assessment, normalization and weighting are combined using Sima Pro 9.0.

3.4 Third stage: Cost evaluation

Several standards and regulations have been created in recent years for the application and coordination of the cost analysis technique [108]. Yet, there is still no clear way to calculate costs [109]. However, it offers a financial perspective of a product's life cycle, whereas the LCA gives environmental data on pollutant and climate-changing emissions. Several initiatives have been made to integrate the cost-of-living analysis and LCA because cost analysis is not standardized as LCA. The perspective, embodied by one or more actors involved in the life cycle of the product, must be fixed in order to perform the cost analysis and serve as the basis for the calculations. The National Ready Mixed Concrete Association (NRMCA) states that the standard price of a cubic yard of concrete is \$108 [110]. However, MRCA utilized in this work, which is promoted because its direct costs and transportation are lower than those of NA and its manufacturing prices are lower than those of standard concrete. As a result, the comparison of the direct costs of three aggregate types is studied in this paper. The RCA and MRCA were manually crushed in the university's laboratory, therefore there was no need to transfer none of them. In this scenario, the producer perspective which corresponds with the laboratory where RCA and MRCA are produced was chosen to provide an assessment of potential production costs as well as associated costs with pollution and climate-changing emissions. The total cost of each concrete mixture (without transportation costs) was determined by adding the costs of each component needed to produce one cubic meter of concrete according to the suppliers [111, 112, 113, 114, 115]. As shown in Table 7. Whereas all materials were purchased and carried to the laboratory together with a total price of 20 km / 2800 Ft.

Table 7. Cost of concrete materials

Ingredient	Cost (Ft/kg)
Superplasticizer (Visco-Crete 5)	1865.50
Cement (CEM 52.5 N)	70.00
SF (Sika)	66.50
FA (Microsite 20)	21.00
NA	3.50
Fine aggregate	3.50
RCA	1.40

3.5 Fourth stage: multi-criteria decision making

A common step in all the MCDM techniques is the creation of a decision matrix, which is then normalized to generate the normalization matrix. In this research two scenarios have been applied to evaluate the fourteen mixture’s alternatives, according to the mentioned criteria:

1) The initial scenario employed to determine the weight allocation for each criterion was the “equal performance” scenario. In this scenario, each criterion was assigned an identical weight, and the weight assessment was based on the premise that all criteria were equally important or relevant. Consequently, the total sum of weights across all criteria amounted to 100%. This approach ensured that no single criterion was given more importance than the others, allowing for a balanced evaluation of the decision-making process. Without a doubt, the lowest-priced, ecologically friendly, and sufficiently strong concrete will be the most sustainable.
2) The second scenario used in this thesis is the entropy method. It is a weighting technique often used to analyse value distribution in decision-making [82]. Constructing a decision matrix simplifies the process of comparing the weight (W_j) to any criterion (C_j). The choice matrix will then be normalized by using Eq. (6). followed by computing the entropy method using Eq. (7), where “k” was derived from Eq. (8), and W_j was derived from Eq. (9).

$$Z_{ij} = \frac{X_{ij}}{\sum_{i=1}^{A} Xij}, (1 \leq i \leq A, 1 \leq J \leq C) \qquad \text{Eq. (6)}$$

$$e_j = -k \sum_{i=1}^{A} (Z_{ij}\ ln\ ln\ Z_{ij}\ ), (1 \leq J \leq C) \qquad \text{Eq. (7)}$$

$$k = \frac{1}{ln\ A} \quad \text{Eq. (8)}$$

$$W_j = \frac{|1-e_j\,|}{\sum|1-ej|}\ , 1 \le J \le C \quad \text{Eq. (9)}$$

In this stage, all the concrete mixtures evaluated based on six parameters: human health, ecosystem quality, climate, resources, costs, and compressive strength of all mixtures. The best total performance among the fourteen concrete mixtures was evaluated using five MCDM techniques (TOPSIS, VIKOR, EDAS, WSM, and WPM).

The TOPSIS technique is a useful and effective technique for selecting and classifying options based on distance measurements. In essence, TOPSIS suggests that the chosen alternative is as far away from the worst answer as is conceivable and that it is as near to the perfect solution as is practically achievable. The first stage in doing TOPSIS is to create a decision matrix. The choice matrix is then normalized to provide a normalized matrix with non-dimensional characteristics that incorporates the parameters and the alternatives. Eventually, RCC determines the best and worst alternatives, as the highest RCC value is the best alternative (Fig. 14).

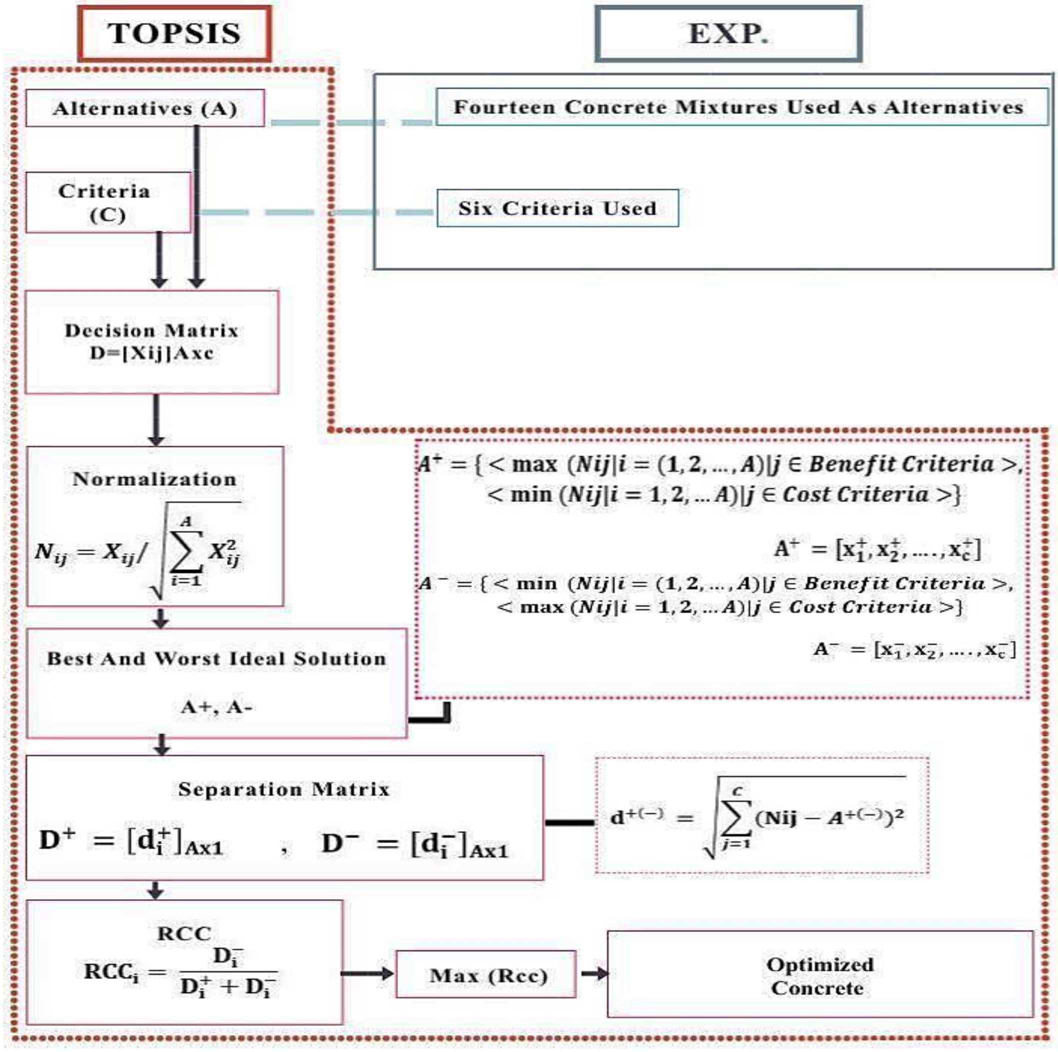


Figure 14. TOPSIS technique

The VICOR technique is an effective method for compensating for MCDM and is used to address issues brought on by erroneous and unsuitable criteria. This approach is employed if a decision maker is unable to articulate his preferences at the outset of the system design. As a result, the decision maker needs a solution that is more closely related to the ideal response. The decision matrix is created and normalized in the initial phases of this approach (Fig. 15). The best and worst values for each criterion are then determined. S_j, R_j, and Q_j are calculated in the end. The best option has the lowest value of such a variable.

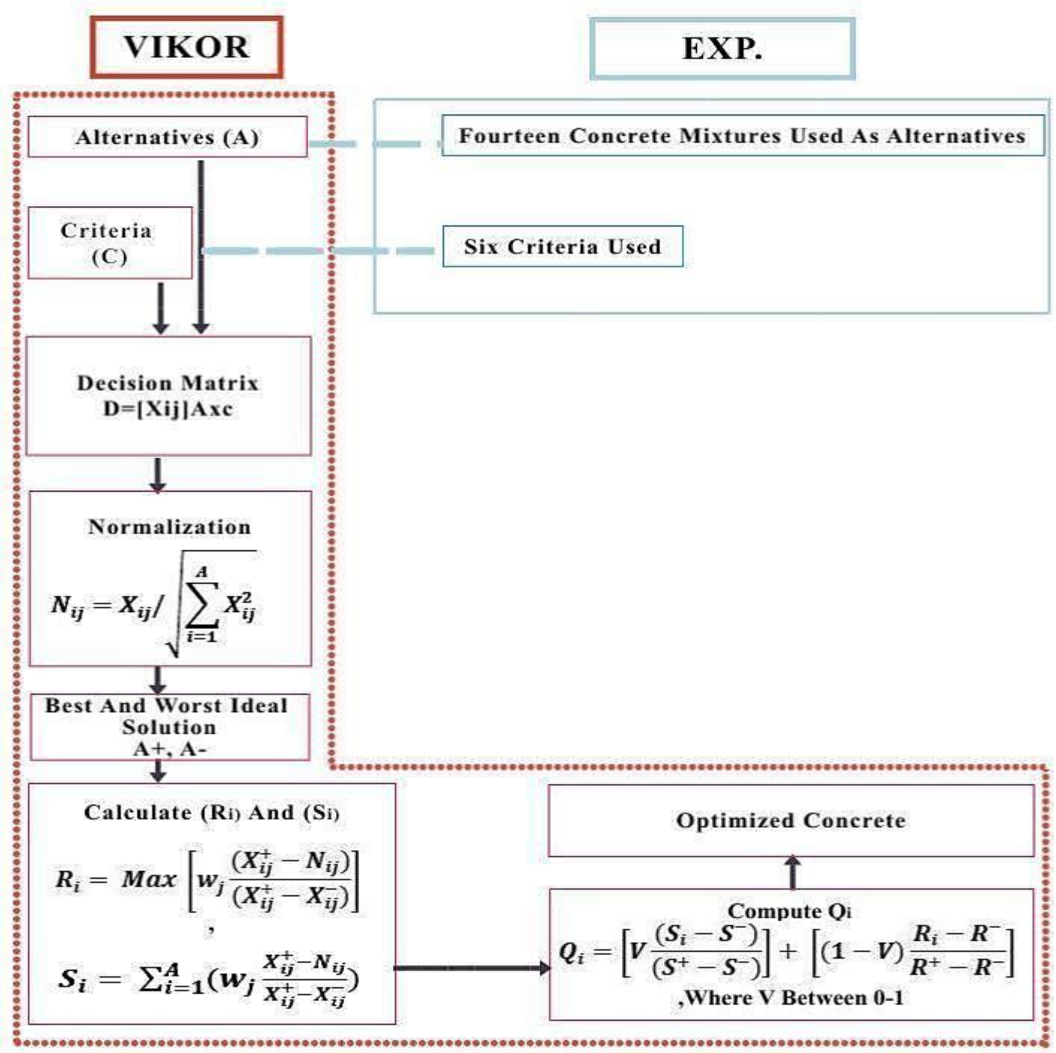


Figure 15. VIKOR technique

The EDAS approach was applied to the construction industry to calculate the proper percentage of cement replacement with a combined application of FA and other supplementary material in M40 grade concrete. In addition, the usefulness of the EDAS as an MCDM tool was proved by comparing it to commonly used methodologies. The distances between each alternative and the average answer according to each criterion are used to assess the alternatives. Figure 16 depicts all EDAS procedures to arrive at the optimal option.

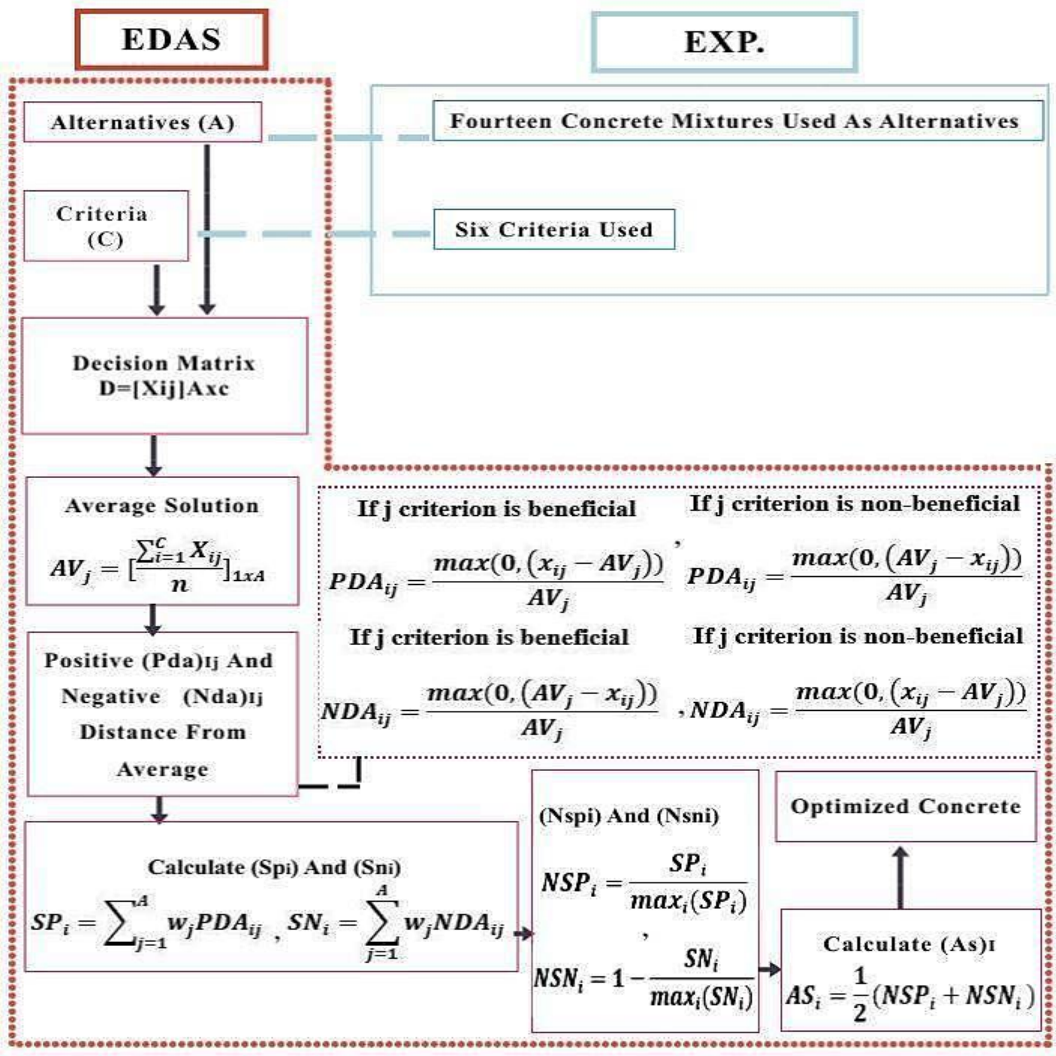


Figure 16. EDAS technique

WSM tends to be employed for computations based on real-world criterion values, particularly in one-dimensional scenarios. When A alternatives and C criteria are present, the decision matrix is created first, and then the weighted normalized matrix is determined using the normalization decision matrix. Lastly, the total of weighted normalized matrix values aids in the selection of the best concrete by ranking and selecting the highest value (Fig. 17).

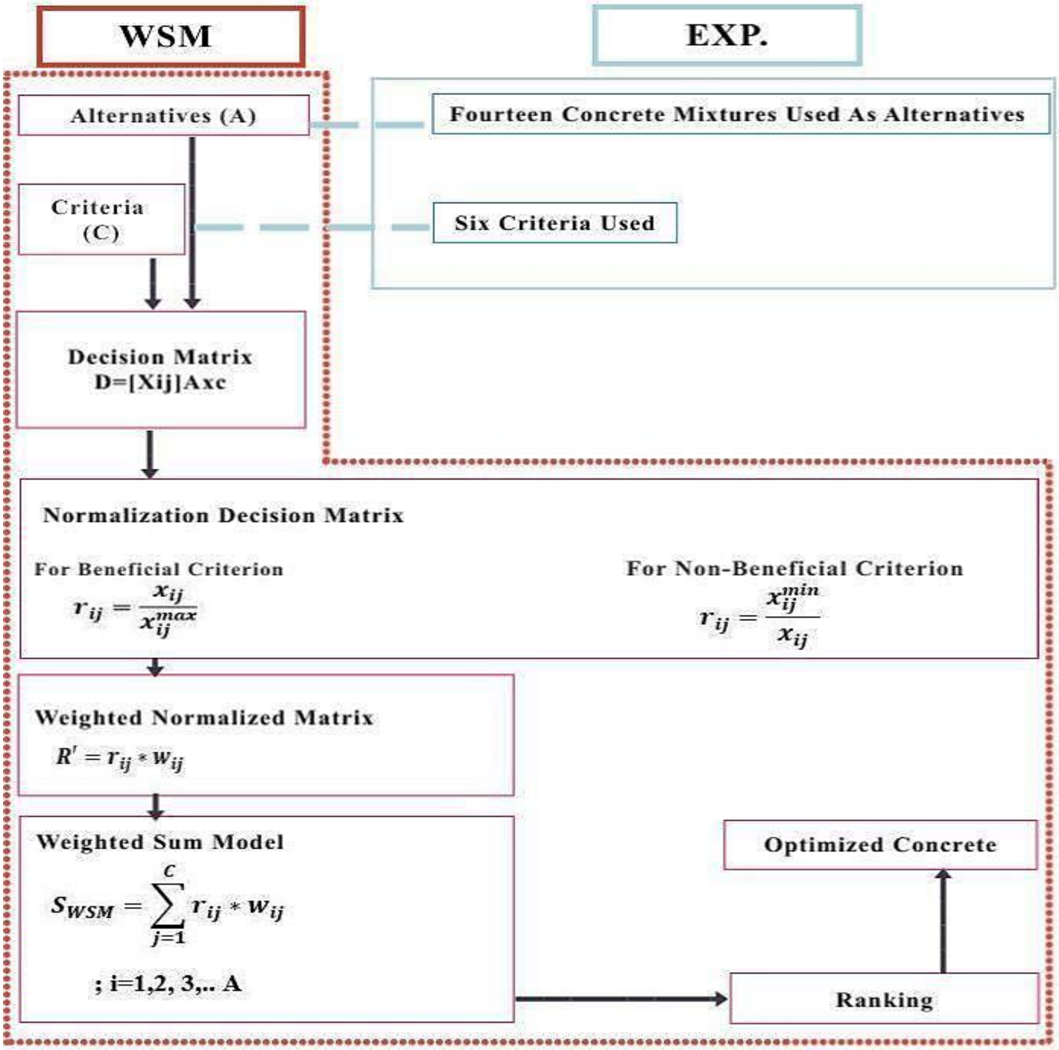


Figure 17. WSM technique

Finally, WPM is identical to the WSM, but the weighted normalized matrix is calculated differently. It is possible to do this by powering the base (normalized decision matrix) with weight rather than numerous values. Each option is compared to all other alternatives by multiplying a sequence of quantities (one for each criterion) and raising each amount to the power equivalent to the respective criterion's relative weight. The fact that this approach may be used to solve single- or multi-dimensional choice problems gives it an additional benefit over the WSM technique. Figure 18 shows all the process of WPM technique from creating the decision matrix to choosing the optimal concrete.

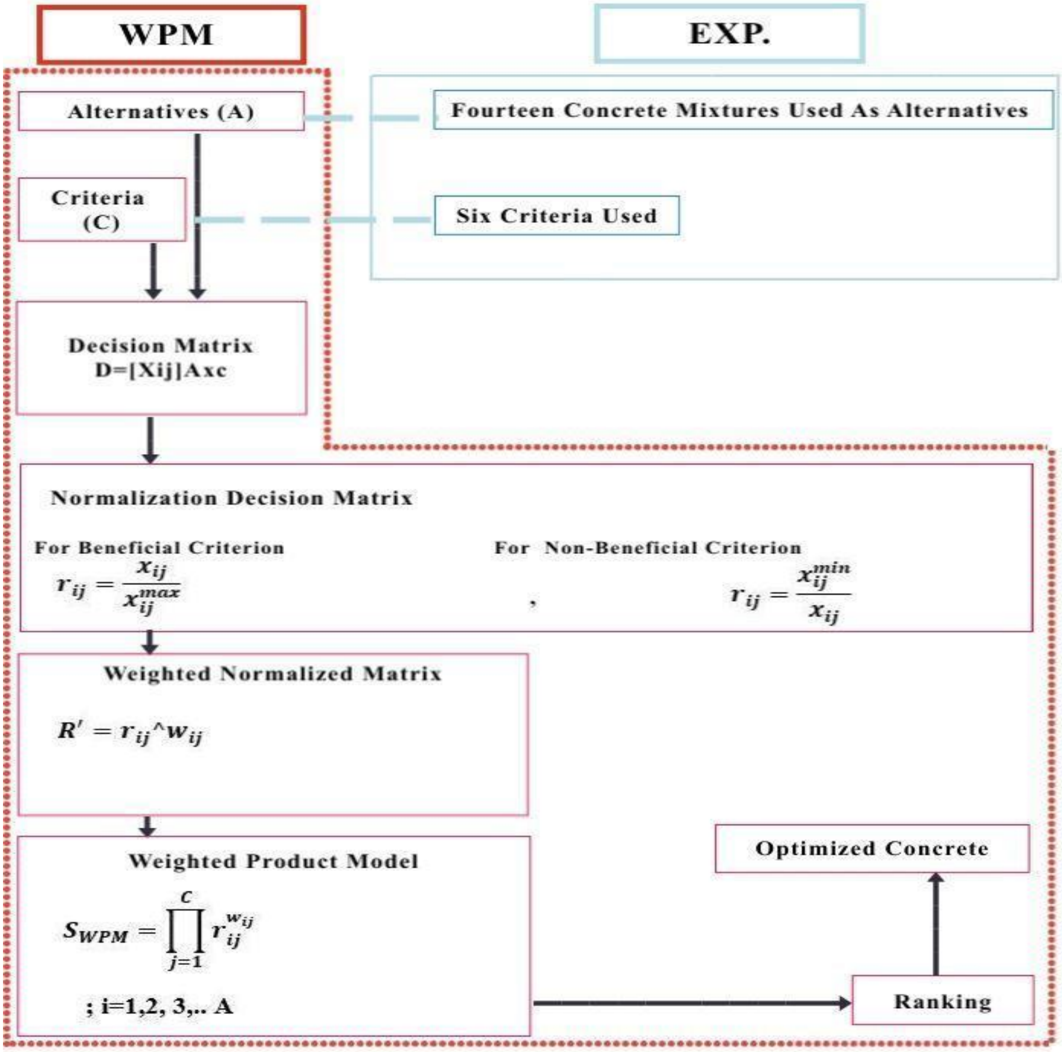


Figure 18. WPM technique

CHAPTER 4: Results and Discussion

The findings of the experimental and analytical program are presented in this chapter to produce HPC using RCA/MRCA and two other materials as SCMs. The mechanical results are divided into three parts, each of which contains a presentation, analysis, and discussion of a portion of the investigated qualities. Fresh properties, mechanical properties, and water absorption are the three groups. Furthermore, the analytical findings are divided into three categories. LCA, cost analysis, and MCDM were all performed.

4.1 Concrete production

4.1.1 Fresh properties of concrete

Based on obtaining a goal strength of greater than concrete class (C55/67), the materials' mixing ratios are used, as it is defined by the American Concrete Institute [44]. Utilizing waste/recycled materials is evaluated in concrete manufacturing in terms of employing FA, SF, RCA, and/or MRCA, however, using 70% RCA/MRCA decreasing the workability of concrete. The negative effect on the workability of incorporating RCA/MRCA could be minimised by compensate the water absorption and using the superplasticizer. The superplasticizer doses were optimized based on the concept of achieving the same workability class for all mixtures. The specified workability class was based on the flow table test to be in the range of 420–480 mm to achieve F3 flowability grade of the fresh mixture. The physical observation was used together with the slump flow table test to assure workable mixtures.

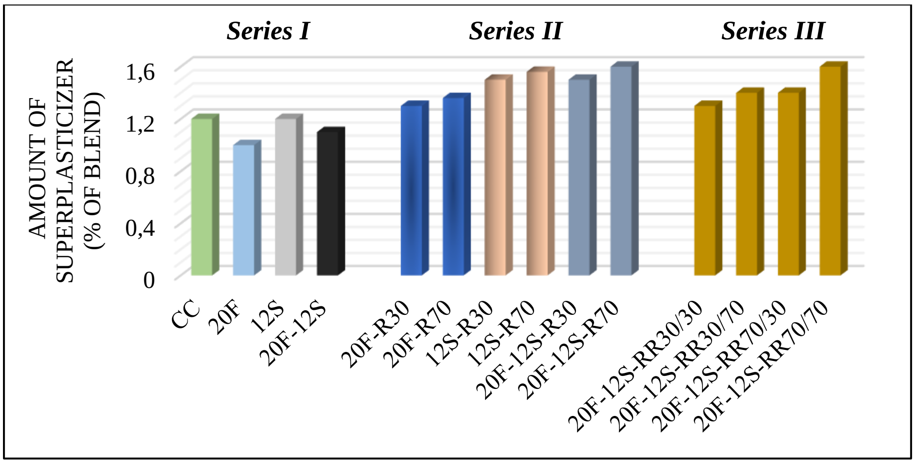


Figure 19. Superplasticizer amount for each concrete mixture

At this point, the superplasticizer amount was different depending on the concrete mixture type. Using FA required lower amount of superplasticizer. The geometry of FA's particles is spherical, allowing them to effortlessly roll over one another and dissolve cement particle agglomerations. The spherical forms decrease resistance at the aggregate-paste interface, resulting in a “ball-bearing impact” at the site of contact. As a result, the workability of concrete mixtures containing FA is increased, and less superplasticizer is required to achieve the desired workability. Moreover, the usage of SF increased the demand for superplasticizers. The increased surface area of the SF’s particles was responsible for this larger quantity, which reduces the amount accessible in solution on the surface of cement particles, consequently, decreases the workability of SF-containing mixtures. My findings align with previous studies, such as [116] where each SCMs was used separately. However, my fresh properties experiment demonstrates that combining specific proportions of SCMs (12% SF and 20% FA) in the same concrete mixture can effectively balance the superplasticizer quantity and enhance various other concrete properties.

As indicated in Figure 19 the usage of RCA or MRCA needed a large dosage of a superplasticizer than standard mixtures. Interestingly, when using MRCA, less superplasticizer was required compared to RAC mixtures. Specifically, the 20F-12S-RR30/30 mixture required 13.3% less superplasticizer than the 20F-12S-R30 mixture. This reduction in superplasticizer usage can be attributed to the lower porosity in the 20F-12S-RR30/30 mixture compared to the 20F-12S-R30 mixture. This observation aligns with the findings of [60], which reported a decrease in the total pore volume in MRAC compared to RAC. Ultimately, MRAC proved that, in practice, demolition waste from any RCA-built structure can be recycled, and its aggregate may be utilized to make MRCA, reducing the porosity of fresh concrete. Additionally, as discussed in series I, a certain ratio of FA and SF in the same concrete mixture can balance the quantity of superplasticizer, when they used in the same mixture. All measurements of the flow table test that were acquired for all series were satisfied.

4.1.2 Compressive strength results

Compressive strength is a vital property frequently studied in concrete research. The prevailing consensus in the literature is that an increase in RCA content tends to result in a reduction in strength. However, it’s worth noting exceptions, such as instances where RCA outperforms NA [118]. Moreover, the substitution of cement with SCMs has demonstrated the potential to enhance strength in specific cases [119]. In my study, the main result of all mixtures’ compressive strength tests at 28, 90, and 180 days is shown in Figure 20. For all tests, the range was 54–76.8 MPa at 28 days, 69–81 MPa at 90 days, and 70–86 MPa at 180 days.

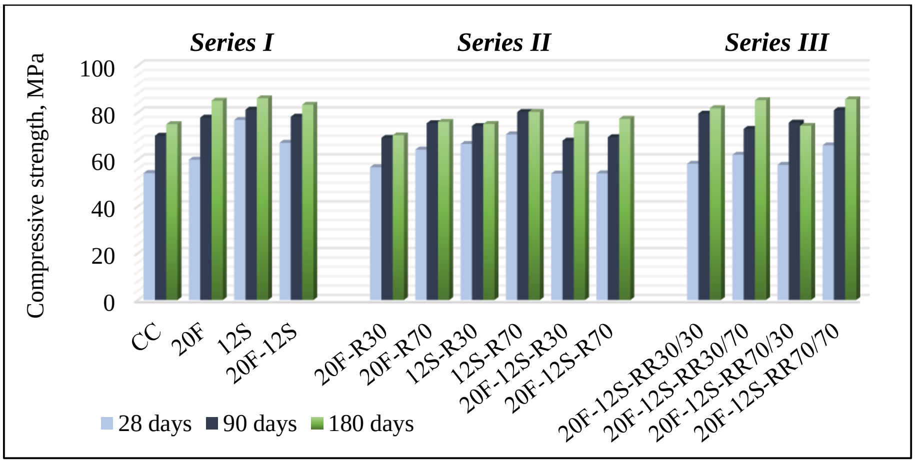


Figure 20. Compressive strength's result of each concrete mixture

Depict the results of compressive strength, flexural strength, and splitting strength at the three ages of test. In series I, when cement was substituted with FA and SF, compressive strength improved by 23.8%, 11.55%, and 11%, respectively, at 28, 90, and 180 days. However, this behaviour can be attributed to the capacity of SF particles to increase compressive strength on one side, which may be connected to its powerful pozzolanic activity. Meanwhile, small FA's particles filled the voids between the cement grains. There isn't much consensus in the research field on how precisely proportioned FA and SF in a single mixture impact the compressive strength of HPC, which can be a new scientific result. My work's findings match the beneficial effect of cement substitution (but only SF) on mechanical strength when doses 10 to 20 % are used in this research [119]. Additionally, this effect partially compensates the slight deterioration of mechanical performance induced by NA replacement. The individual results of the compressive strength and the standard deviation at 28 days of age are showed in Table 8.

Table 8. The individual results and standard deviations of compressive strength at age of 28 days, measured on cubic specimens

Mixtures	**Date of testing**	**Specimens**				**Average**	**Standard deviation**	
		1	**2**	**3**	**4**		**Population**	**Sample**
CC	18/11/2020	53.9	54.0	55.4	53.8	54.275	0.653	0.754
20F	20/11/2020	59.0	57.9	60.8	61.9	59.895	1.540	1.783
12S	22/11/2020	76.0	76.9	78.4	75.8	76.775	1.025	1.184
20F-12S	23/11/2020	69.5	67.5	68.0	63.5	67.125	2.218	2.561
20F-R30	19/08/2021	54.8	58.0	59.5	54.4	56.675	2.146	2.478
20F-R70	19/08/2021	60.0	64.2	66.1	66.8	64.275	2.645	3.054
12S-R30	19/08/2021	65.8	65.0	67.1	68.5	66.603	1.329	1.535
12S-R70	19/08/2021	69.4	72.0	71.2	70.3	70.725	0.973	1.123
20F-12S-R30	21/08/2021	54.0	53.8	53.3	55.0	54.025	0.617	0.713
20F-12S-R70	21/08/2021	53.9	54.0	53.4	55.1	54.105	0.621	0.717
20F-12S-RR30/30	12/01/2022	57.8	59.6	58.0	57.6	58.250	0.792	0.915
20F-12S-RR30/70	12/01/2022	61.0	59.7	63.0	62.6	61.575	1.316	1.519
20F-12S-RR70/30	14/01/2022	56.8	60.0	57.8	56.2	57.700	1.445	1.669
20F-12S-RR70/70	14/01/2022	65.0	67.1	66.3	65.8	66.050	0.763	0.881

In series II, the using of 12% SF and/or 20% FA with 70% RCA increased the compressive strength, compared to RAC containing 30% RCA. For instance, at ages of 90, and 180 days, respectively, compressive strength values of 20F-12S-R70 were greater than those of 20F-12S-R30 by increases of 2.2%, and 2.79%. Even at the age of 28 days, an advantageous effect was not as great as it was at later ages (just 0.18%). This was related to a lower water-cement ratio because of increased absorption and the high specific roughness and surface of RCA compared to NA.

The individual results of the compressive strength and the standard deviation at 90 days of age are showed in the Table 9.

Table 9. The individual results and standard deviations of compressive strength at age of 90 days, measured on cubic specimens

Mixtures	**Date of testing**	**Specimens**				**Average**	**Standard deviation**	
		1	**2**	**3**	**4**		**Population**	**Sample**
CC	21/01/2021	73.0	70.6	67.1	69.8	70.110	2.103	2.429
20F	23/01/2021	79.5	77.1	77.9	76.8	77.825	1.047	1.209
12S	25/01/2021	80.8	81.2	80.5	82.0	81.125	0.562	0.650
20F-12S	26/01/2021	77.6	78.0	80.5	76.8	78.228	1.382	1.596
20F-R30	21/10/2021	66.0	70.1	70.0	71.0	69.278	1.931	2.230
20F-R70	21/10/2021	74.6	76.9	73.9	76.1	75.373	1.181	1.363
12S-R30	21/10/2021	73.8	73.6	75.0	74.5	74.225	0.558	0.644
12S-R70	21/10/2021	78.1	79.5	82.0	81.3	80.228	1.525	1.761
20F-12S-R30	23/10/2021	65.0	69.0	68.8	69.3	68.018	1.753	2.025
20F-12S-R70	23/10/2021	68.9	70.0	71.1	67.9	69.475	1.203	1.389
20F-12S-RR30/30	14/03/2022	80.2	78.6	79.4	79.7	79.463	0.599	0.692
20F-12S-RR30/70	14/03/2022	77.1	77.1	78.1	76.0	77.063	0.743	0.857
20F-12S-RR70/30	16/03/2022	74.3	75.2	77.3	76.1	75.725	1.110	1.281
20F-12S-RR70/70	16/03/2022	80.3	81.5	79.7	82.3	80.943	1.031	1.191

Comparing Series III to Series II, utilizing a high dosage of MRCA improves concrete’s compressive strength. For example, the compressive strength of 20F-12S-RR70/70 was 22%, 16.5%, and 11% greater than 20F-12S-R70 at 28, 90, and 180 days, respectively. The improvement could be due to the rough surface of MRCA, and the high number of fine particles produced by the second generation of double crushing procedures. However, the use of SCMs once again in the second generation as a cement replacement can be the third reason contributing to the MRAC’s increased compressive strength. Zhu et al. 2011 substituted 30%, 70%, and 90% of the NA with the RCA, respectively. While using FA as a partially cement replacement. The results showed that the RCA’s quality of two generations of concrete met the requirements for structural concrete. Finally, the individual results of the compressive strength and the standard deviation at 180 days of age are showed in Table 10.

Table 10. The individual results and standard deviations of compressive strength at age of 180 days, measured on cubic specimens

Mixtures	Date of testing	Specimens				Average	Standard deviation	
		1	2	3	4		Population	Sample
CC	21/04/2021	70.0	76.1	75.7	78.2	75.000	3.038	3.509
20F	23/04/2021	84.2	82.5	87.5	85.9	85.025	1.867	2.156
12S	25/04/2021	86.8	84.0	85.8	87.3	85.975	1.261	1.456
20F-12S	26/04/2021	82.0	84.3	84.7	81.8	83.200	1.309	1.512
20F-R30	21/01/2022	71.1	70.3	68.6	71.2	70.275	1.062	1.226
20F-R70	21/01/2022	76.1	75.3	76.6	76.0	76.005	0.464	0.536
12S-R30	21/01/2022	75.8	76.9	73.4	74.3	75.100	1.347	1.555
12S-R70	21/01/2022	80.8	83.2	82.1	74.8	80.235	3.251	3.754
20F-12S-R30	23/01/2022	72.7	74.9	76.4	76.5	75.117	1.565	1.807
20F-12S-R70	23/01/2022	76.9	78.5	75.9	77.9	77.292	0.980	1.132
20F-12S-RR30/30	14/06/2022	81.6	82.5	79.1	83.9	81.770	1.741	2.011
20F-12S-RR30/70	14/06/2022	85.6	88.9	86.3	80.1	85.225	3.204	3.699
20F-12S-RR70/30	16/06/2022	73.4	75.6	70.4	77.7	74.260	2.719	3.136
20F-12S-RR70/70	16/06/2023	85.3	86.1	83.5	87.5	85.590	1.460	1.690

4.1.3 Flexural strength results

A common consensus among researchers is that RCA tends to have a negative effect on flexural strength. This is primarily attributed to the creation of a poor interfacial bond quality between the old adhering mortar and the new mortar [120]. However, in this work, flexural strength exhibited the same pattern as compressive strength. At 28 days, the concrete with 20% FA had a somewhat lower flexural strength than the concrete with 12% SF or CC. However, this behaviour once more supported the idea that SF particles had the ability to make concrete stronger despite any applied force. This might be attributed to its potent pozzolanic effect. Figure 21 shows all the flexural results of all concrete mixtures. In series II, the mixture of FA and SF with RCA shown a small reduction in comparison with series I. Yet, the values were still satisfied. This was related to a lower water/cement ratio because of increased absorption. However, it cannot be generalized to all mechanical characteristics of concrete. RCA might be used to make HPC concrete if properly proportioned and mixed. Moreover, the increased quality of concrete had a beneficial relationship when it comes to flexural strength, and the generated concrete with specific ratios of SCMs in the current study was HPC, which already led to an increase in flexural strength. This result was consistent with that of [120], however the authors did not test the MRAC using SCMs, as my work did.

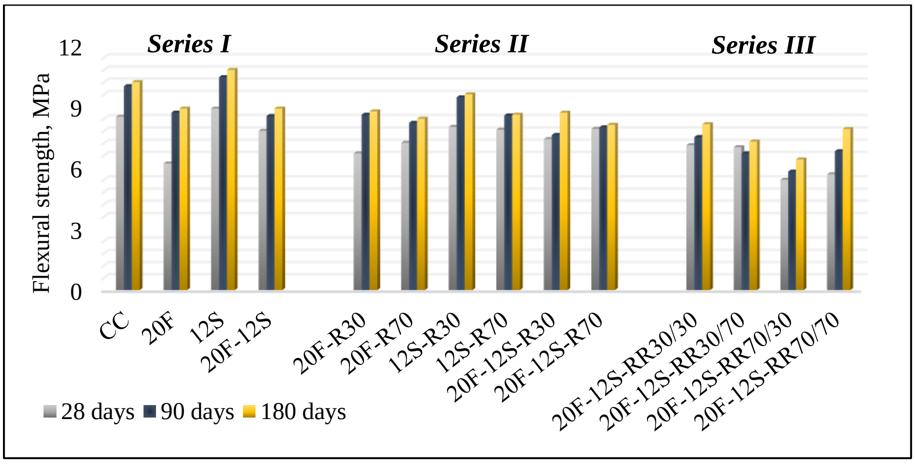


Figure 21. Flexural strength of each concrete mixture

In the case of Series III, particularly the 20F-12S-RR70/70 and 20F-12S-RR30/30 mixtures, positive results were observed over time. Notably, the flexural strength of the 20F-12S-RR30/30 mixture bested that of the 20F-12S-RR30/70 mixture by 1.42%, 10.6%, and 10.45% at 28, 90, and 180 days, respectively. This improvement can be attributed to the hydration of FA and SF, which contributed to the reduction in porosity and microcracks when using an equal amount of MRCA in both MRCA30/30 and MRCA70/70 mixtures (Figure 21). Overall, the pore volume decreased in the second generation of recycled concrete compared to the first generation. However, in the second generation, the porous materials of RCA were replaced by other porous materials of MRCA, thus, the open pores and cracks created in the cut surface could allow the mortar to pass through in the second generation easily. Thomas et al. (2013) [121] found a parallel result using different mixture's types. Even improvements in compressive strength for higher dosages of RCA and lower w/c can be achieved. As concluded, the adverse effect of RCA on mechanical strength depends on w/c as RCA dosage has higher water absorption. Notwithstanding, in my research, only a slight increase in water absorption of used RCA was observed. Moreover, the original concrete mixture reached over 50 MPa, so it didn't reduce the compressive strength of the modified concrete to a greater extent. This idea complies with the observations of Kim (2022) [122], who suggests using RCA from high-strength concrete to provide better performance of concrete.

4.1.4 Splitting strength results

The findings from numerous studies consistently indicate that as the replacement ratio of RCA increases, the splitting tensile strength tends to decrease [9]. However, it's worth noting that some investigations have arrived at the opposite conclusion [119]. In my study, the final mechanical test included testing four cylinders from each concrete mixture produced for splitting strength at the ages of three test ages. Results from each series and those from other series were compared. In series I, 20F-12S mixture, which incorporated 20% FA and 12% SF as replacements for cement, demonstrated competitive splitting strength at all ages (particularly at age 180 days, where the strength improved by 2.27%), in comparison to CC. Which showed that this behaviour could be due to the ability of FA's particles to increase the connection between concrete ingredients under splitting, while the SF's particles strengthened this connection. However, in certain situations, particularly at the age of 28 days, the use of 12% of SF as the only cement replacement resulted in a drop in splitting strength. The early filling of gaps by SF, however, significantly improves splitting strengths, but the advantages begin to diminish at higher levels. Experimentally, the splitting strength was not found to be significantly improved by substitute level in RAC' mixtures regardless of the RCA ratios examined. Even after curing for up to 180 days, the splitting tensile was not higher than at earlier ages (90 days) and even worser. Other research' findings and my work's results agreed [123]. The previous researcher's scanning electron microscope analysis of RAC revealed that, unlike in CC, the failure in RAC begins in the new the interfacial transition zone (ITZ), in high-strength RAC the fractures begin in the old ITZ between the old paste and aggregate. Because of this, the characteristics of high-strength RAC are quite sensitive to RCA quality. However, the slight difference in values may be overlooked. In series III, 20F-12S-RR30/30 exceeded 20F-12S-R30 (original crushed concrete) in regards of splitting strength (by 33.3%, 10.37%, and 7.4%, respectively, at ages 28, 90, and 180 days of the test). This was related to a lower water/cement ratio because of increased absorption, especially in the interfacial transition zone, in return this cause the bonded mortar to develop a stronger and more consistent bond with the freshly mixed cement paste on top of the RCA. Moreover, as opposed to 20F-12S-R70, and for long term test, it was shown that 20F-12S-RR70/70 splitting strength improved progressively by 3.42% only at the age of 180 days, where the MRCA replacement ratio had reached 70%. All results are shown in Figure 22. Additionally, the higher surface roughness of RCA together with increased level of porosity may result in improvement in ITZ [124]. Notwithstanding, the role of detailed parameters of RCA including ITZ performance, role of shape, and porosity should be subjected under separate research due to the complexity of the phenomena.

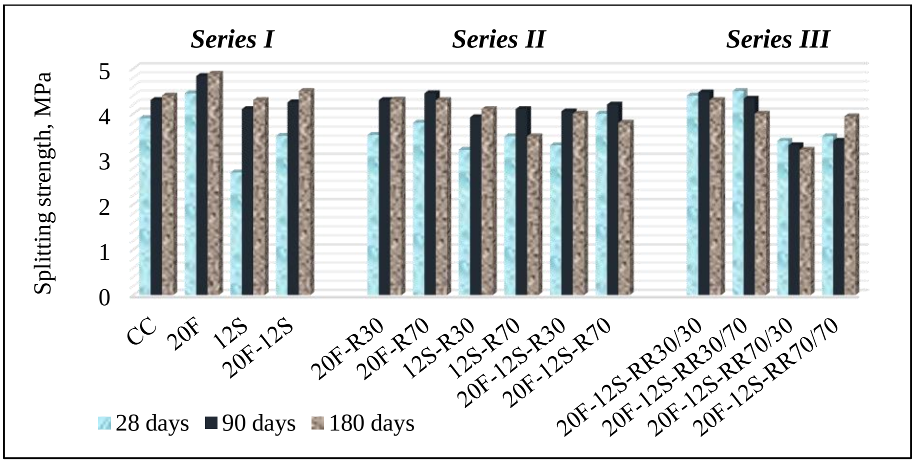


Figure 22. Splitting strength's result of each concrete mixture

4.1.5 Water absorption results

Water absorption was tested for all concrete admixtures by submerging three 150×150×150 mm cubes in water until fully saturated. Following that, the specimens were completely dried in an oven at 50–60 °C. Relative masses were measured after 90 days to estimate water absorption. Because the test could only quantify the volume of visible pores, it could not reflect the porosity of the concrete. When compared to CC and 12S concrete, FA's concrete mixture has the lowest value for water absorption (Figure 23). This behaviour might be related to FA's graded particle distribution, which aided in the filling of the pores inside the concrete. Continuously, in series II, the water absorption values increased in all mixtures. Especially, when SF added to 70% RCA, which proved that the water absorption varied by increasing the ratio of RCA replacement. Furthermore, 20F-R30 had the lowest value of all the series II mixtures, demonstrating that FA's particles are superior to SF particles in filling the pores inside the concrete. The use of two generations of concrete boosted series III's capacity to absorb water, as the experiment also shown. The mixture of 20F-12S-RR30/30, however, showed the lowest water absorption results among all series III's mixtures, while 20F-12S-RR70/70 obtained the highest value (25.7% higher than CC), demonstrating that expanding the recycling cycle and high quantity of replacement ratio increases the concrete's ability to absorb water.

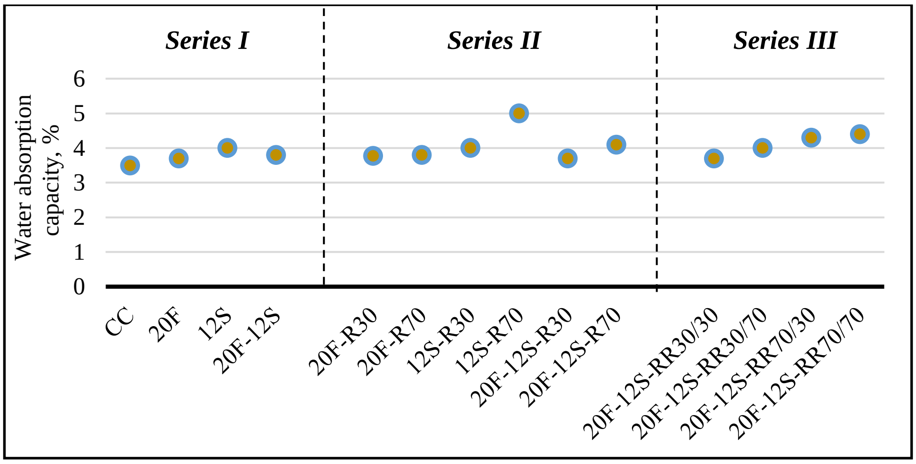


Figure 23. Water absorption values of each concrete mixture at 90 days

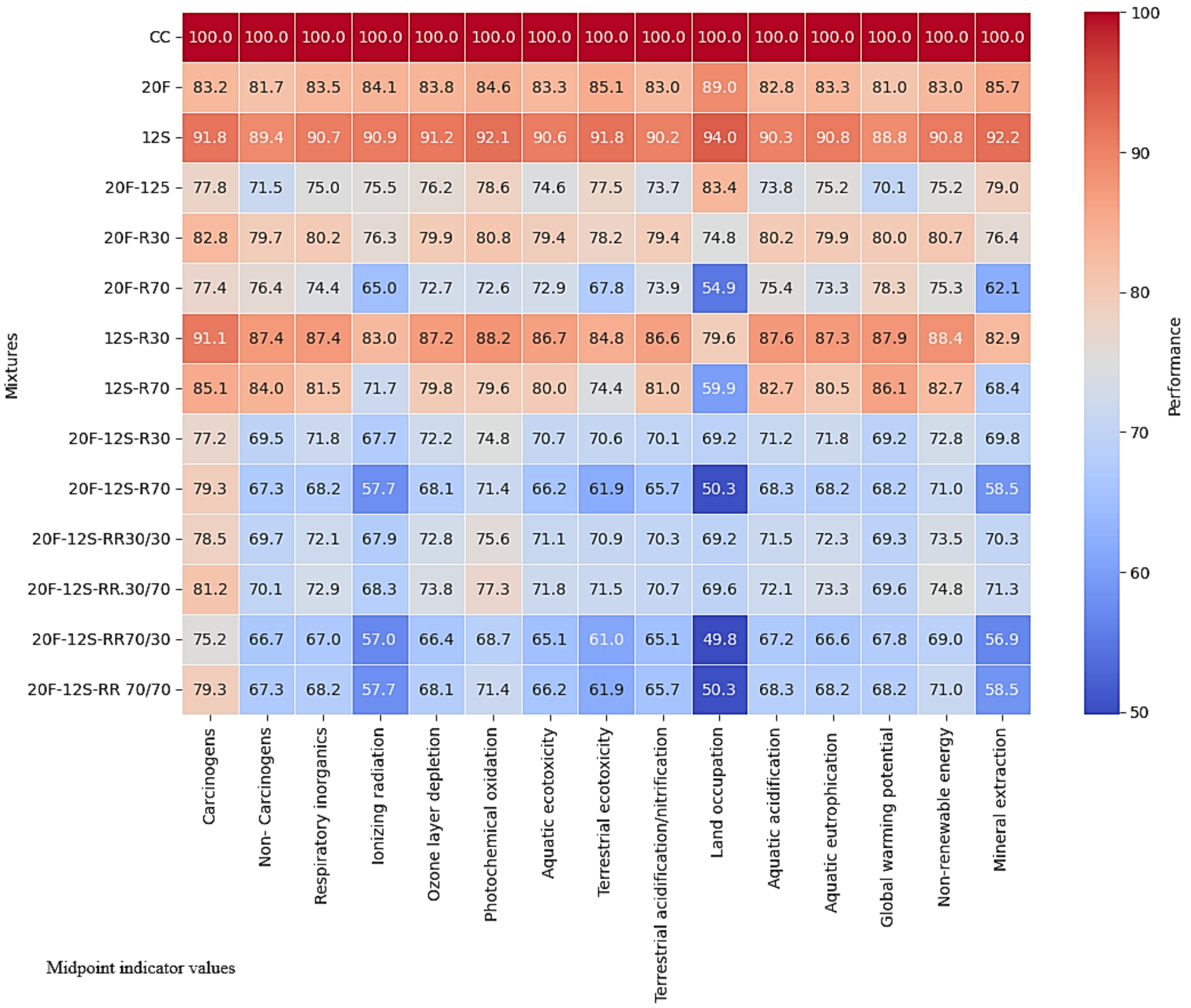
4.1.6 New scientific results of concrete production

1) ***The using of coarse recycled concrete aggregate as a replacement for coarse natural aggregate up to 70% enhances the compressive strength of high strength concrete. [I/A]***
2) ***The combination of the specific ratios of 20% fly ash and 12% silica fume in one mixture obtained a similar compressive strength result as in the control concrete in short term (28 and 90 days). And superior results at long tested time (180 days). [I/B]***
3) ***The using 30% multi recycled concrete aggregate as a replacement of coarse natural aggregate required 13.3% and 6.6% less amount superplasticizer than using 30% recycled concrete aggregate. While using 70% multi recycled concrete aggregate required the same amount of superplasticizer as that in original crushed recycled aggregate concrete. [II/A]***
4) ***At the three ages of experimental tests (28,90, and 180 days), the using multi recycled concrete aggregate up to 70% as a replacement of coarse natural aggregate with two specific ratios of supplementary material enhanced the mechanical properties of multi recycled aggregate concrete in terms of compressive strength. [II/B]***

4.2 Life cycle assessment

4.2.1 Midpoint indicators

Figure 24 displays the environmental score of all designed mixtures with cement and coarse aggregate substitution as determined by an LCA study performed using SimaPro 9.0. Computed of 15 midpoint indicators allude to significant environmental implications of portland cement substitution. Provided comparison at the midpoint level shows significant differences that can be assigned to the replacement level of original constituents. In general, the worst environmental profile belongs to the reference mixture denoted as CC composed from virgin sources only and the highest portland cement dosage. The results demonstrated that alternatives in series I of specified mixtures save around 20% when both SF and FA are used. The 15 midpoints calculated by SimaPro are varied in different benefits. The most noticeable savings were realized in the land occupation category (LO), with over 50% decrease (best to worst mix) in the second generation of concrete (20F-12S-RR70/30, 20F-12S-RR70/70), compared to the CC (100%). Moreover, the global warming potential (GWP) impact category, which corresponds to carbon dioxide emissions, shows a 20% reduction in the first generation and a 25% reduction in the second generation. As mentioned above, the replacement of the cement resulted in the most distinct effects on the overall environmental score, thus 20F-12S mixture reached almost the same level (particularly in global warming) as mixtures in the first and the second generation. From this perspective the replacement of portland cement by SF and FA may be considered as dominating over the replacement of NA. However, this work presented a new LCA for second generation concrete with both replacement ingredients (cement and aggregate), which had not been addressed before in the literature, offering a sustainable alternative mixture for standard concrete. On the other hand, the environmental complexity of LCA analysis inevitably depicts more distinct benefits in other categories such as land occupation, mineral extraction, terrestrial ecotoxicity, and ionizing radiation. It should be noted that the availability of NA became limited, and the utilization of end-of-life concrete or bricks becomes an issue not only with environmental benefits but also with the possibility of the construction works [125]. On top of that, demolition and consequent on-site crushing may reduce transportation and cost significantly as closed-loop recycling provides several side benefits.



Mixtures	Carcinogens	Non- Carcinogens	Respiratory inorganics	Ionizing radiation	Ozone layer depletion	Photochemical oxidation	Aquatic ecotoxicity	Terrestrial ecotoxicity	Terrestrial acidification/nitrification	Land occupation	Aquatic acidification	Aquatic eutrophication	Global warming potential	Non-renewable energy	Mineral extraction
CC	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
20F	83.2	81.7	83.5	84.1	83.8	84.6	83.3	85.1	83.0	89.0	82.8	83.3	81.0	83.0	85.7
12S	91.8	89.4	90.7	90.9	91.2	92.1	90.6	91.8	90.2	94.0	90.3	90.8	88.8	90.8	92.2
20F-125	77.8	71.5	75.0	75.5	76.2	78.6	74.6	77.5	73.7	83.4	73.8	75.2	70.1	75.2	79.0
20F-R30	82.8	79.7	80.2	76.3	79.9	80.8	79.4	78.2	79.4	74.8	80.2	79.9	80.0	80.7	76.4
20F-R70	77.4	76.4	74.4	65.0	72.7	72.6	72.9	67.8	73.9	54.9	75.4	73.3	78.3	75.3	62.1
12S-R30	91.1	87.4	87.4	83.0	87.2	88.2	86.7	84.8	86.6	79.6	87.6	87.3	87.9	88.4	82.9
12S-R70	85.1	84.0	81.5	71.7	79.8	79.6	80.0	74.4	81.0	59.9	82.7	80.5	86.1	82.7	68.4
20F-12S-R30	77.2	69.5	71.8	67.7	72.2	74.8	70.7	70.6	70.1	69.2	71.2	71.8	69.2	72.8	69.8
20F-12S-R70	79.3	67.3	68.2	57.7	68.1	71.4	66.2	61.9	65.7	50.3	68.3	68.2	68.2	71.0	58.5
20F-12S-RR30/30	78.5	69.7	72.1	67.9	72.8	75.6	71.1	70.9	70.3	69.2	71.5	72.3	69.3	73.5	70.3
20F-12S-RR.30/70	81.2	70.1	72.9	68.3	73.8	77.3	71.8	71.5	70.7	69.6	72.1	73.3	69.6	74.8	71.3
20F-12S-RR70/30	75.2	66.7	67.0	57.0	66.4	68.7	65.1	61.0	65.1	49.8	67.2	66.6	67.8	69.0	56.9
20F-12S-RR 70/70	79.3	67.3	68.2	57.7	68.1	71.4	66.2	61.9	65.7	50.3	68.3	68.2	68.2	71.0	58.5

Figure 24. Midpoint impact values of all fourteen mixtures using SimaPro 9.0

4.2.2 Endpoint indicator’s results

The following equations, Eqs. (10) to (13) show the endpoint values for each category of fourteen concrete mixtures, which obtained after normalized the midpoint by using the same software. The Eqs. (10) to (13) are based on Eqs. (2) to (5) in chapter 3.3.3.

Climate change = [34.232, 27.725, 30.417, 24.005, 27.405, 26.815, 30.09, 29.482, 23.683, 23.342, 23.724, 23.205, 23.815, 23.341] Eq. (10)

Resources = [12.385, 10.284, 11.247, 9.317, 9.996, 9.321, 10.947, 10.238, 9.0227, 8.793, 9.0994, 8.55, 9.2609, 8.793] Eq. (11)

Ecosystem quality = [2.223, 1.892, 2.0402, 1.723, 1.7349, 1.5, 1.88, 1.645, 1.565, 1.366, 1.570, 1.346, 1.583, 1.365] Eq. (12)

Human health = [17.513, 14.587, 15.876, 13.101, 14.052, 13.079, 15.33, 14.33, 12.563, 11.985, 12.629, 11.769, 12.772, 11.985] Eq. (13)

Similarly, to midpoint impact, the environmental profiles of both scenarios exhibit the same differences at the endpoint level, when we compare all the results above in each mixture (Figure 25). One can see that the main part of the environmental load is related to climate change, followed by adverse effects on human health, and resource extraction, and only a minor one is relevant to ecosystem quality. Here, the results obtained for mixtures in the standard concrete exhibit a significantly increased environmental burden compared to the second generation. Surprisingly, mixtures of 12S-R30 and 12S-R70 induce a higher load to the natural environment compared to 20F or 20F-12S due to increased cement dosage. In this scenario, the use of SCMs offers clearer advantages in terms of environmental factors. However, 20F-12S-RR70/70 demonstrated somewhat superior results regarding the load on the environment, as compared to first-generation mixtures, and may thus be regarded as an ecologically beneficial mixture for future construction.

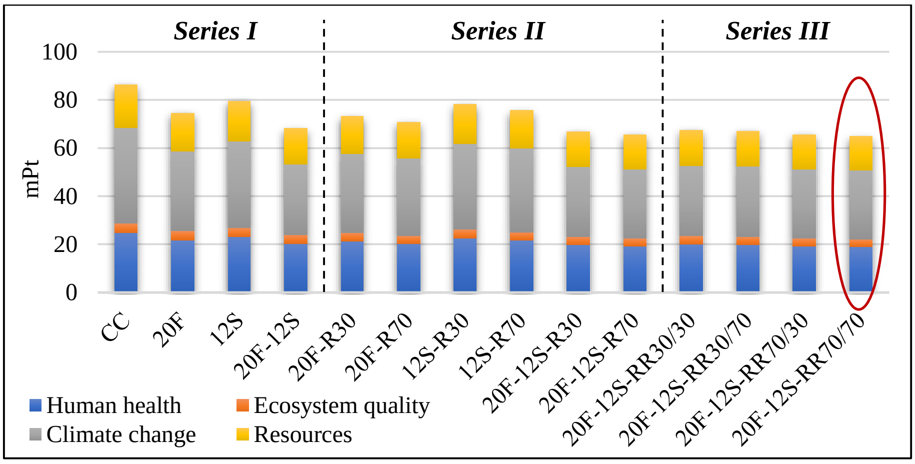


Figure 25. Endpoint score comparison of studied concrete mixtures

4.2.3 Transportation indicator

When it comes to transportation, even if RCA and MRCA were crushed in the lab, the practical analysis was indicated in the dissertation by employing sensitivity analysis. The sensitivity analysis may differ if there was a transportation distance for RCA and MRCA (RCA and MRCA were crushed in the laboratory). Distance may cause it to vary from one nation or city to another. Generally, it should be noted that RCA is provided from fragmented locations and the determination of the transport distance is complicated. To access the sensitivity of obtained results associated with RCA use, the research considered the following transport scenarios:

1) Transportation of 103 km for NA. to evaluate how the transportation of NA to the lab effect the environmental indicators.
2) Transportation of 103 km for NA and 50 km for RCA in replacement ratio 30/70.

3) Transportation of 103 km for NA and 50 km for RCA in replacement ratio 70/30. Considered distances are based on alternative scenario assuming closer distances for RCA transport due to closely located site (103 km) from laboratory. However, the issue of distance is very important as the transportation of large volumes of aggregate requires substantial assets. As shown in Figure 26. The result of transportation distances matters significantly and represent a substantial contribution to overall environmental score.

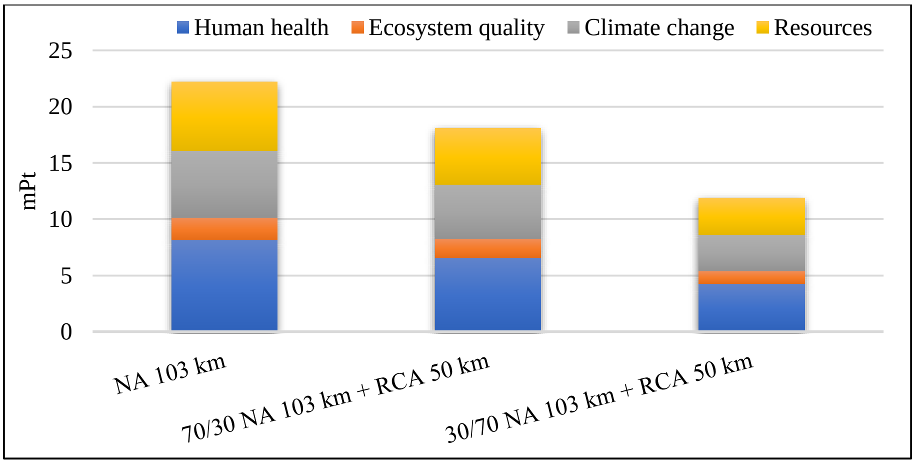


Figure 26. Sensitivity of environmental impact on aggregate transportation

4.2.4 New scientific results of LCA

1) ***The land occupation category decreased 50% in the second generation of concrete. [III/A]***
2) ***The global warming category decreased 20% in the first generation and 25% in the second generation. [III/B]***
3) ***Reusing concrete in the second generation of recycled concrete reduced the overall environmental impact by up to 38.5% for the endpoint categories. [III/C]***

4.3 Cost evaluation results

The calculation of both environmental and economic costs for RCA and MRCA is extremely complicated in laboratory conditions. In fact, several factors should be covered to provide a coherent comparison. On the other hand, the infrastructure for the multiple recycling of end-of-life concrete is not well established (in comparison to NA), therefore cannot be directly compared to the production of NA. In a nutshell, the production of NA is well-established, matured, and optimized process with significant returns to scale. Therefore, this research completed this information to the description of boundary conditions and used 1.4 Ft/kg as an input parameter based on approximately 2-3 times lower costs compared to NA. Moreover, MRCA supply is less expensive than NA because of following points:

1) The lower transportation distances (in my work, it had no expense).
2) The absence of aggregate crushing costs, the RCA and MRCA were crushed manually in the lab. However, for the upscale and contribution to the processing of concrete waste 0.015 MJ/kg can be considered for material crushing based on previous research.
3) The low cost of virgin material.

However, in series I, using FA and/or SF on one mixture, reduce the total cost of the concrete by falling (10,5%) in 20F mixture, compared to CC. Additionally, utilizing SCMs with RCA or MRCA resulted in lower concrete mixing costs. Nevertheless, when comparing the mixes from Series II with Series III, the results demonstrated that the cost-saving benefit was significantly greater when both SCMs and MRCA were used in place of cement and NA (20F-12S-RR70/70), respectively. Consequently, the second generation's mixes have the lowest pricing compared to CC, reducing by 7.32%, 8%, 6%, and 5.38% for 20F-12S-RR30/30, 20F-12S-RR30/70, 20F-12S-RR70/30, and 20F-12S-RR70/70, respectively. Table 11 lists the cost of each key component as well as the overall price of each blend.

Table 11. The single cost of each mixture

Mixture	Cement	FA	SF	Fine aggregate	NA	RCA	MRCA	Superplasticizer	Transport	Total cost
	Ft/kg	Ft/ kg	Ft/ kg	Ft/ kg	Ft/ kg	Ft/ kg	Ft/ kg	Ft/ kg	Ft/ km	Ft/m^3
CC	25200	0	0	2401	4232	0	0	8059	11375 (20 km / 2800 Ft)	51267
20F	20160	1512	0	2401	4232	0	0	6716		46396
12S	22190	0	2873	2401	4232	0	0	8059		51130
20F-12S	17150	1512	2873	2401	4232	0	0	7387		46930
20F-R30	20160	1512	0	2401	2968	508	0	8730		47654
20F-R70	20160	1512	0	2401	1260	1187	0	9066		46961
12S-R30	22190	0	2873	2401	2961	510	0	10074		52384
12S-R70	22190	0	2873	2401	1274	1184	0	10484		51781
20F-12S-R30	17150	1512	2873	2401	2972	504	0	10074		48861
20F-12S-R70	17150	1512	2873	2401	1274	1189	0	10745		48519
20F-12S-RR30/30	17150	1512	2873	2401	2961	0	508	8730		47510
20F-12S-RR30/70	17150	1512	2873	2401	1271	0	1184	9402		47168
20F-12S-RR70/30	17150	1512	2873	2401	2961	0	508	9402		48182
20F-12S-RR70/70	17150	1512	2873	2401	1264	0	1184	10745		48504

-New scientific results of multi recycled concrete aggregate cost

The reuse of concrete as a second generation of recycling concrete reduced the cost by about 6.68%, 3%, compared to the control concrete and series II's mixtures, respectively. Due to lower cost of transportation, crushing cost and used materials. [IV]

4.4 Multi criteria decision making results

The utilization of MCDM techniques in the selection of concrete mixtures represents an innovative approach. It allows for a comprehensive assessment of concrete not solely based on a single aspect but across multiple dimensions before it is applied in real-world applications.

Moreover, MRAC and SCMs is a relatively novel concrete formulation. It can be a practical and advantageous choice when studies like the one presented here are conducted to study its properties, environmental impact, and cost-effectiveness. By examining these multiple facets, MRAC and similar concrete innovations can be thoroughly assessed and optimized for specific applications, promoting sustainability and efficiency in construction practices.

4.4.1 Weighted criteria's findings

The first scenario applied in this study is "equal performance". the total sum of weights across all six criteria amounted to 100%. This approach ensured that no single criterion was given more importance than the others, it is a critical approach to find the most sustainable mixture among different alternatives, regardless of the used criteria. However, another weighted method used in this work "entropy method". It is a popular weighing method for measuring value dispersion in decision-making, using the equations in section (3.5). The results (Table 12.) showed that environmental indicators and cost obtained the biggest value, which refers to the impact of these criteria to evaluate the concrete mixtures as they are done in different generations. However, the most sustainable concrete will undoubtedly be the cheapest, most environmentally friendly, and adequately strong, by using these two separate weighted methods.

Table 12. Each criterion's weight based on both the entropy method and equal performance

	Compressive strength, MPa			**Human health**	**Eco-system quality**	**Climate change**	**Re-sources**	**Cost**
	28 days	**90 days**	**180 days**					
Entropy method	0.1067	0.0339	0.0441	0.1305	0.2126	0.15067	0.1105	0.2106
Equal performance	0.1250	0.1250	0.1250	0.1250	0.1250	0.1250	0.1250	0.1250

Table 13. shows the decision matrix's weight of each criterion used to select the best alternative mixture in each technique. But for all other mixtures, the CC's mixture served as the reference concrete. For the compressive strength criteria, high values indicate great strength. While for the four environmental criteria and cost, low numbers indicate little environmental effect and the best pricing.

Table 13. Decision matrix of fourteen concrete mixtures

Mixtures	**Compressive strength, MPa**			**Human health**	**Eco-system quality**	**Climate change**	**Re-sources**	**Cost**
	28 days	**90 days**	**180 days**					
CC	1	1	1	1	1	1	1	1
20F	1.105	1.109	1.133	0.832	0.851	0.809	0.830	0.904
12S	1.416	1.158	1.194	0.906	0.917	0.888	0.908	0.997
20F-12S	1.238	1.115	1.110	0.748	0.775	0.701	0.752	0.915
20F-R30	1.046	0.987	0.936	0.802	0.780	0.800	0.807	0.929
20F-R70	1.184	1.075	1.013	0.746	0.674	0.783	0.752	0.916
12S-R30	1.228	1.058	1.001	0.875	0.846	0.878	0.883	1.021
12S-R70	1.304	1.144	1.069	0.818	0.74	0.861	0.826	1.01
20F-12S-R30	0.996	0.970	1.002	0.717	0.704	0.691	0.728	0.953
20F-12S-R70	0.998	0.991	1.030	0.684	0.614	0.681	0.709	0.946
20F-12S-RR30/30	1.073	1.134	1.090	0.721	0.706	0.693	0.734	0.926
20F-12S-RR30/70	1.143	1.041	1.136	0.672	0.605	0.677	0.690	0.92
20F-12S-RR70/30	1.064	1.079	0.990	0.729	0.712	0.695	0.747	0.939
20F-12S-RR70/70	1.217	1.155	1.141	0.684	0.614	0.681	0.709	0.946

4.4.2 TOPSIS results

The best alternative based on the TOPSIS technique is the one with the highest Relative Closeness Coefficient (RCC) value, however, to calculate the RCC value for each mixture, the relative closeness coefficient matrixes for both weighting methods were computed and presented in Figure 27. But before reaching the final results the separation matrixes for each weighted method were also calculated and showed in the following equations, Eq.(14) to Eq.(17).

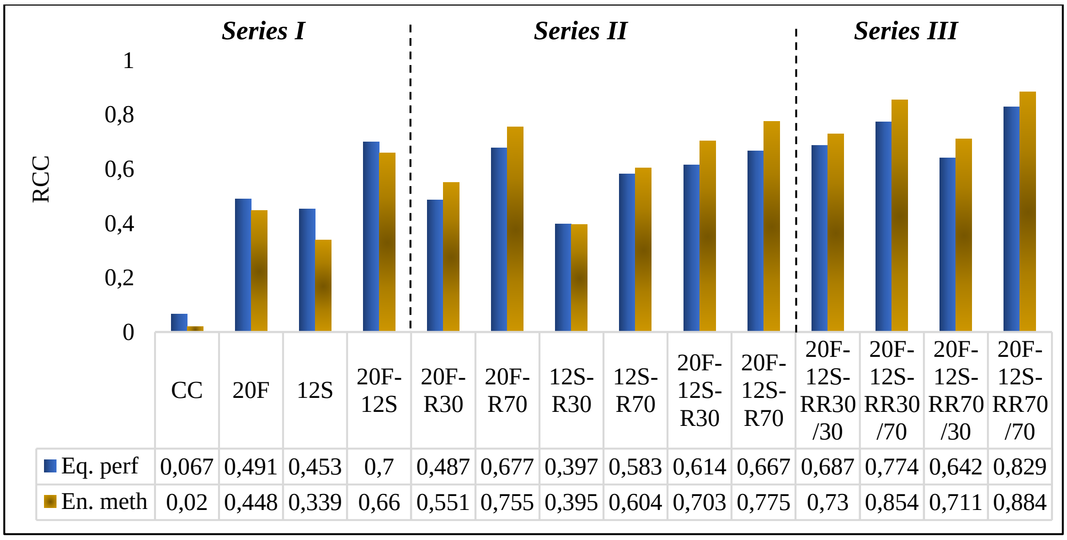
$D^{+}_{\text{(equal performance)}}$ = [0.0327, 0.01779, 0.022, 0.0109, 0.0187, 0.0114, 0.0211, 0.0153, 0.0162, 0.0148, 0.0123, 0.0095, 0.0142, 0.00748] Eq. (14)

$D^{-}_{\text{(equal performance)}}$ = [0.00429, 0.018, 0.0177, 0.0244, 0.0184, 0.0245, 0.0135, 0.0201, 0.025, 0.0286, 0.025, 0.0304, 0.0245, 0.0304] Eq. (15)

$D^{+}_{\text{(entropy method)}}$ = [0.048, 0.027, 0.035, 0.017, 0.022, 0.012, 0.029, 0.019, 0.016, 0.013, 0.014, 0.008, 0.015, 0.006] Eq. (16)

$D^{-}_{\text{(entropy method)}}$ = [0.001, 0.022, 0.018, 0.033, 0.027, 0.037, 0.019, 0.029, 0.038, 0.045, 0.038, 0.047, 0.037, 0.046] Eq. (17)

RCC's results shows that the second-generation mixtures had the first greatest RCC values, with 20F-12S-RC70/70 being deemed the best choice among the alternatives based on the given criteria, while the CC mixture had the lowest value. This demonstrates the beneficial effects of employing MRCA while considering environmental impact, costs, and technical criteria. Additionally, according to the entropy method, the second generation had the top five highest RCC values, confirming the importance of using MRCA in the building and construction sectors.



	CC	20F	12S	20F-12S	20F-R30	20F-R70	12S-R30	12S-R70	20F-12S-R30	20F-12S-R70	20F-12S-RR30/30	20F-12S-RR30/70	20F-12S-RR70/30	20F-12S-RR70/70
■ Eq. perf	0,067	0,491	0,453	0,7	0,487	0,677	0,397	0,583	0,614	0,667	0,687	0,774	0,642	0,829
■ En. meth	0,02	0,448	0,339	0,66	0,551	0,755	0,395	0,604	0,703	0,775	0,73	0,854	0,711	0,884

Figure 27. TOPSIS's technique results

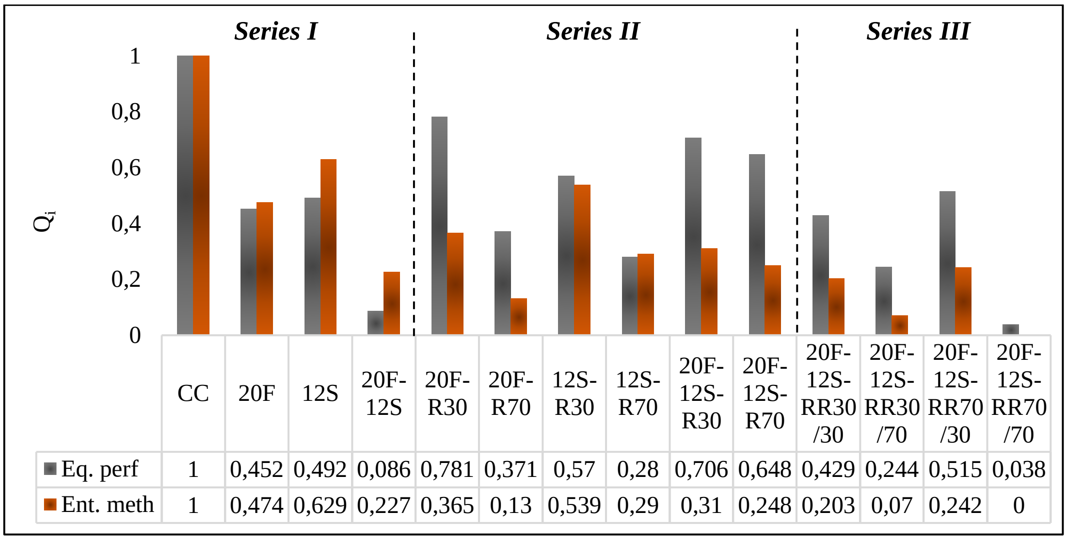
4.4.3 VIKOR results

In the VIKOR technique, the best solution is the one with the lowest Q_i. However, the R_i and S_i indicators for each mixture have been calculated in each weighted method before having the Q_i values. Table 14. Presented the values of R_i and S_i.

Table 14. Ri, Si results

Mixtures	Equal performance		Entropy method	
	R_i	**S_i**	**R_i**	**S_i**
CC	0.1250	0.8805	0.2577	0.9556
20F	0.0926	0.4010	0.1604	0.4921
12S	0.0987	0.3957	0.2035	0.5681
20F-12S	0.0537	0.2605	0.1109	0.2909
20F-R30	0.1250	0.5537	0.1142	0.5072
20F-R70	0.0876	0.3304	0.0716	0.2972
12S-R30	0.0935	0.5685	0.1572	0.6153
12S-R70	0.0712	0.3684	0.1040	0.4256
20F-12S-R30	0.1250	0.4411	0.1296	0.3501
20F-12S-R70	0.1244	0.3592	0.1290	0.2494
20F-12S-RR30/30	0.1020	0.2665	0.1058	0.2738
20F-12S-RR30/70	0.0812	0.2092	0.0842	0.1440
20F-12S-RR70/30	0.1047	0.3679	0.1086	0.3265
20F-12S-RR70/70	0.0592	0.1310	0.0614	0.1226

The final findings of the VIKOR technique Q_i were displayed in Figure 28. In this technique, the lowest value denotes the best ranking among the used alternatives. The top two possibilities out of the fourteen mixtures are 20F-12S-RR70/70 and 20F-12S-RR30/30, with the second-generation mixtures having the top five lowest Q_i values, compared to the CC's result or the first generation of concrete's results, which obtained the biggest values in both weighted methods. These results confirm again the importance of using MRCA (up to 70%) with SCMs, providing a new concrete for the practical construction. This result is consistent with TOPSIS findings.



	CC	20F	12S	20F-12S	20F-R30	20F-R70	12S-R30	12S-R70	20F-12S-R30	20F-12S-R70	20F-12S-RR30/30	20F-12S-RR30/70	20F-12S-RR70/30	20F-12S-RR70/70
■ Eq. perf	1	0,452	0,492	0,086	0,781	0,371	0,57	0,28	0,706	0,648	0,429	0,244	0,515	0,038
■ Ent. meth	1	0,474	0,629	0,227	0,365	0,13	0,539	0,29	0,31	0,248	0,203	0,07	0,242	0

Figure 28. VIKOR technique's results

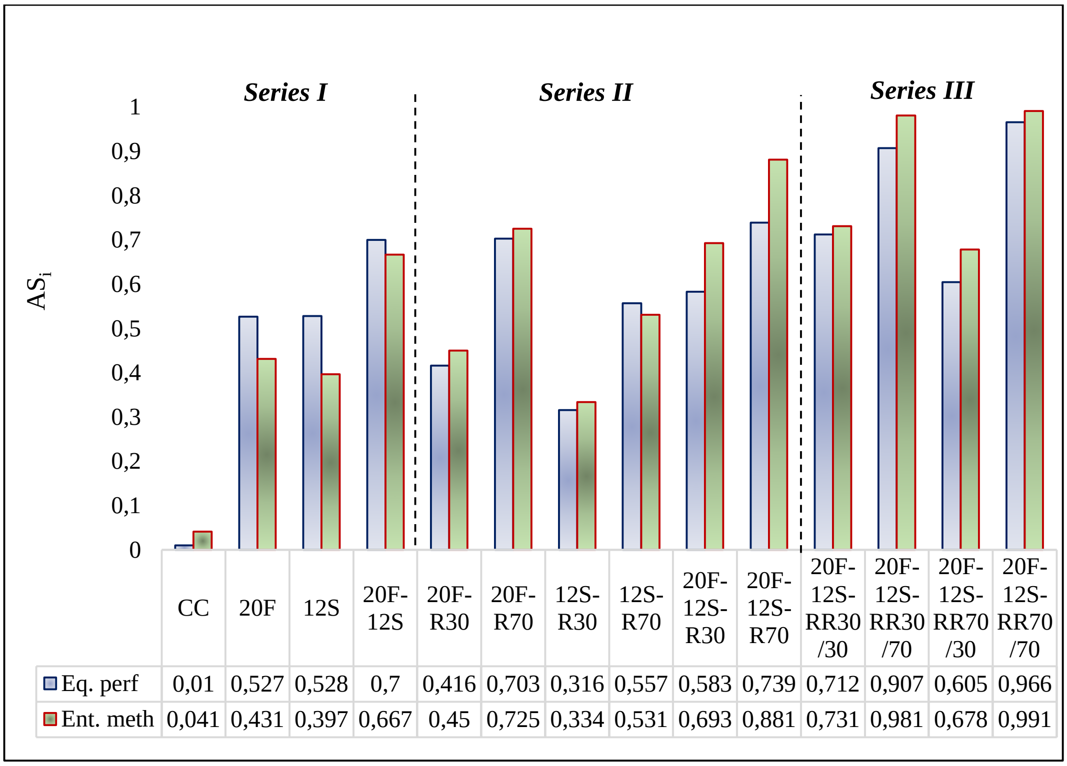
4.4.4 EDAS results

The utilization of MCDM techniques in the selection of concrete mixtures represents an innovative approach. It allows for a comprehensive assessment of concrete not solely based on a single aspect but across multiple dimensions before it is applied in real-world applications. This approach ensures that concrete is evaluated for various aspects, considering factors beyond just one-dimensional criteria. EDAS is an additional MCDM used in this work. Table 15. displays the calculation of NSP_i and NSN_i using two weighting methods, respectively, before having Appraisal Score (AS_i) values.

Table 15. NSP_i and NSN_i results

Mixtures	Equal performance		Entropy method	
	NSP_i	**NSN_i**	**NSP_i**	**NSN_i**
CC	0.021	0	0.082	0
20F	0.284	0.771	0.125	0.737
12S	0.592	0.465	0.344	0.450
20F-12S	0.487	0.913	0.382	0.951
20F-R30	0.115	0.718	0.079	0.821
20F-R70	0.446	0.960	0.471	0.981
12S-R30	0.098	0.535	0.081	0.588
12S-R70	0.309	0.805	0.216	0.845
20F-12S-R30	0.445	0.722	0.505	0.881
20F-12S-R70	0.711	0.768	0.868	0.894
20F-12S-RR30/30	0.535	0.890	0.513	0.949
20F-12S-RR30/70	0.889	0.926	0.982	0.981
20F-12S-RR70/30	0.379	0.831	0.428	0.928
20F-12S-RR70/70	1	0.932	1	0.982

Figure 29. represents the values of AS_i; however, it is important to note that in this technique, the best concrete is characterized by having the largest AS_i. The outcomes obtained from the EDAS technique align with those obtained from TOPSIS and VIKOR techniques. Notably, the second-generation mixtures, such as 20F-12S-RR70/70 and 20F-12S-RR30/70, exhibited the highest AS_i values among all the mixture variations. This reinforces the significance of employing MRAC to produce concrete that is not only cost-effective but also environmentally friendly. These results emphasize the advantages of MRAC over CC or first-generation mixtures.



	CC	20F	12S	20F-12S	20F-R30	20F-R70	12S-R30	12S-R70	20F-12S-R30	20F-12S-R70	20F-12S-RR30/30	20F-12S-RR30/70	20F-12S-RR70/30	20F-12S-RR70/70
🟦 Eq. perf	0,01	0,527	0,528	0,7	0,416	0,703	0,316	0,557	0,583	0,739	0,712	0,907	0,605	0,966
🟩 Ent. meth	0,041	0,431	0,397	0,667	0,45	0,725	0,334	0,531	0,693	0,881	0,731	0,981	0,678	0,991

Figure 29. EDAS technique's results

4.4.5 WSM and WPM results

Once more, the results obtained through both WSM and WPM techniques align with those generated by TOPSIS, VIKOR, and EDAS. The highest S_{WSM} values and S_{WPM} were consistently observed in the second-generation mixtures, specifically 20F-12S-RR70/70 and 20F-12S30/70. This underscores the imperative of utilizing MRAC as a construction material, compared to CC, as it offers a combination of cost-effectiveness and environmental sustainability. Table 16 presents the S_{WSM} and S_{WPM} calculated using both weighted methods.

Table 16. S_{WSM} and S_{WPM} results

Mixtures	Entropy method	Equal performance	Entropy method	Equal performance
	S_{WSM}	S_{WSM}	S_{WPM}	S_{WPM}
CC	0.6892	0.7444	0.6850	0.7376
20F	0.8097	0.8592	0.8059	0.8541
12S	0.7886	0.8443	0.7797	0.8346
20F-12S	0.8841	0.9034	0.8814	0.9017
20F-R30	0.8163	0.8328	0.8146	0.8302
20F-R70	0.8893	0.8975	0.8886	0.8964
12S-R30	0.7813	0.8084	0.7793	0.8063
12S-R70	0.8396	0.8608	0.8381	0.8585
20F-12S-R30	0.8836	0.8713	0.8792	0.8674
20F-12S-R70	0.9316	0.9037	0.9259	0.8985
20F-12S-RR30/30	0.8984	0.9055	0.8955	0.9028
20F-12S-RR30/70	0.9636	0.9440	0.9611	0.9416
20F-12S-RR70/30	0.8844	0.8824	0.8817	0.8798
20F-12S-RR70/70	0.9625	0.9525	0.9613	0.9510

Figure 30 showed the comparation between the two techniques. They came to similar findings. The application of MRCA in actual concrete practice may encourage by the results of all techniques, which showed that the second generation's mixtures were the top five of the best options based on technical performance, economic considerations, and environmental concerns.

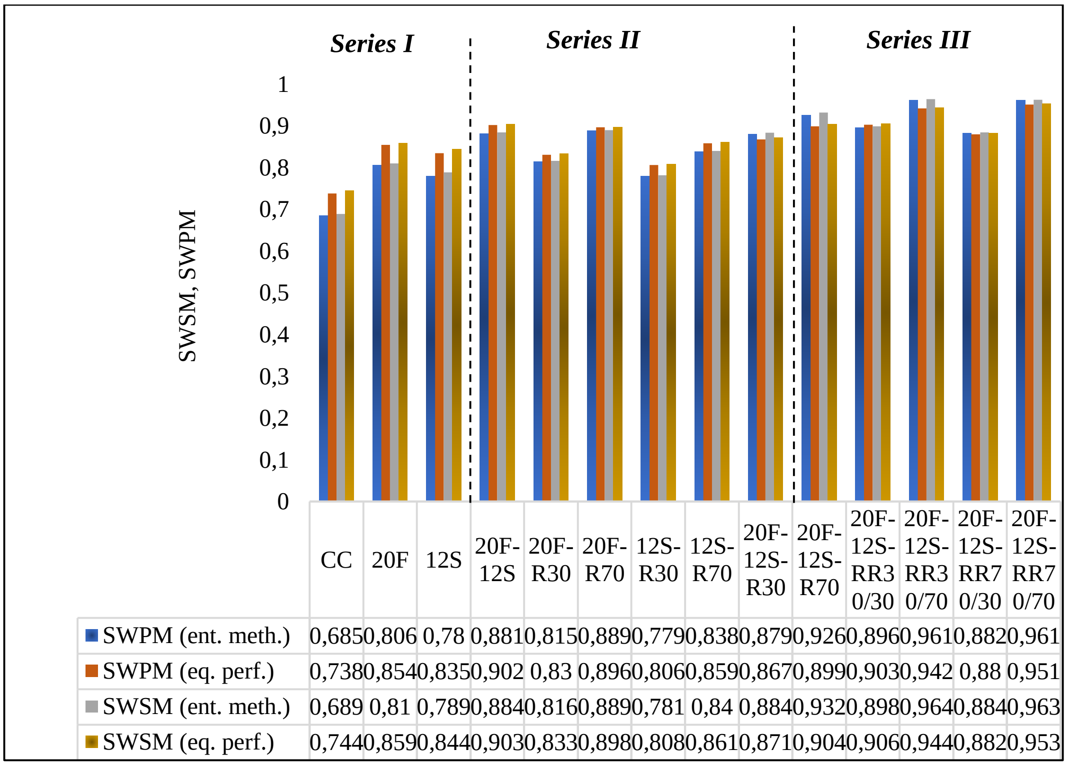
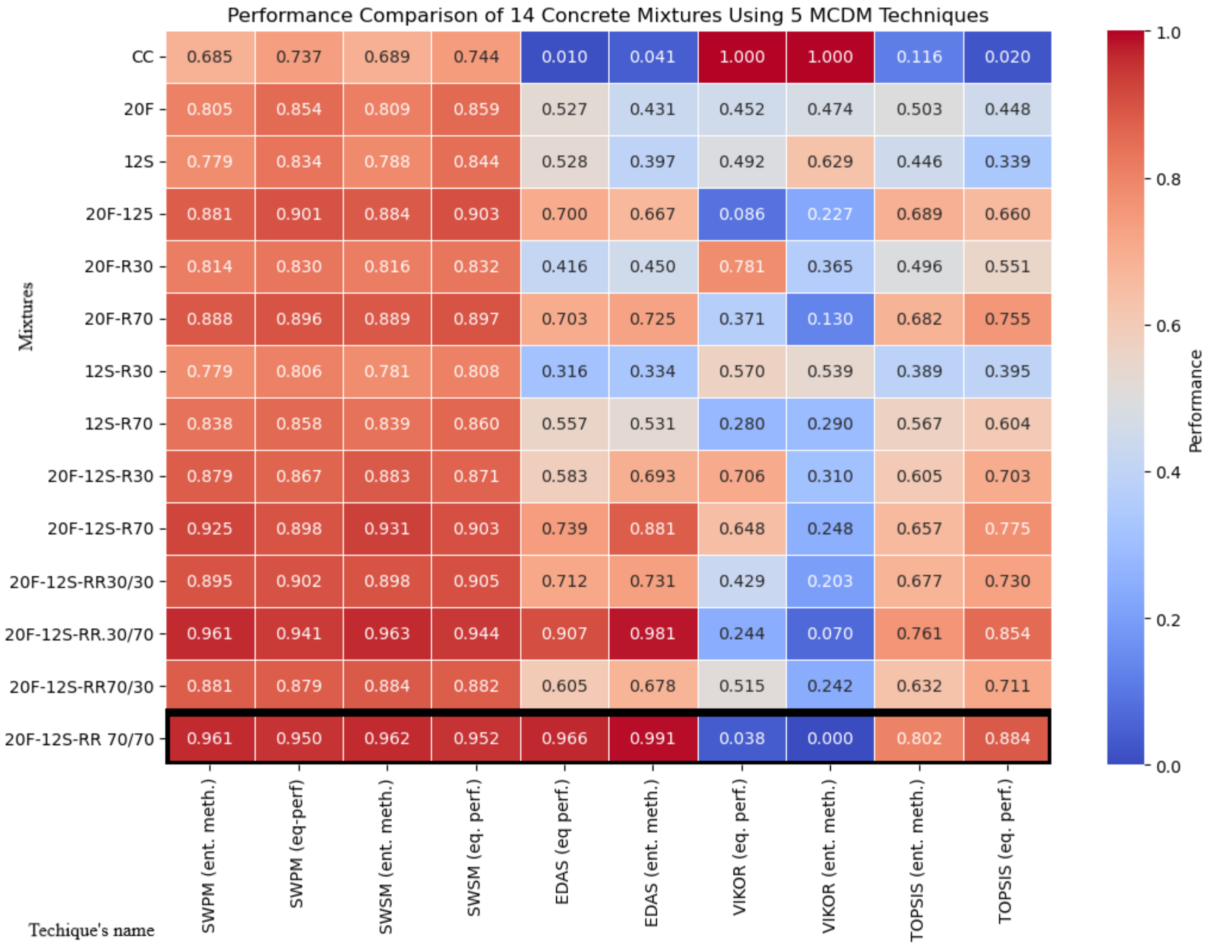


Figure 30. WSM and WPM technique's results

4.4.6 Comparation of five techniques

The results of the five MCDM techniques are compared in Figure 31. Two weighted methods were used in the study to evaluate the fourteen concrete mixtures and produce more accurate findings. It is visible that second generation mixtures are more sustainable than the first concrete mixtures or reference concrete mixtures. Additionally, the 20F-12S-RR70/70 mixture was the best alternative. However, in some techniques, like WSM, it had values that were nearly identical to the best one, due to the process of this technique, which is suitable only for single-dimensional settings. Nevertheless, the overall results of all techniques encourage the using of MRCA up to 70% in concrete. Especially after replacing the cement with additional components like FA and SF. Generally speaking, this novel work can help to increase awareness of the application of recycling concrete as sustainable concrete in the construction field and provide an understanding of the sustainability of MRAC.



Mixtures	SWPM (ent. meth.)	SWPM (eq-perf)	SWSM (ent. meth.)	SWSM (eq. perf.)	EDAS (eq perf.)	EDAS (ent. meth.)	VIKOR (eq. perf.)	VIKOR (ent. meth.)	TOPSIS (ent. meth.)	TOPSIS (eq. perf.)
CC	0.685	0.737	0.689	0.744	0.010	0.041	1.000	1.000	0.116	0.020
20F	0.805	0.854	0.809	0.859	0.527	0.431	0.452	0.474	0.503	0.448
12S	0.779	0.834	0.788	0.844	0.528	0.397	0.492	0.629	0.446	0.339
20F-125	0.881	0.901	0.884	0.903	0.700	0.667	0.086	0.227	0.689	0.660
20F-R30	0.814	0.830	0.816	0.832	0.416	0.450	0.781	0.365	0.496	0.551
20F-R70	0.888	0.896	0.889	0.897	0.703	0.725	0.371	0.130	0.682	0.755
12S-R30	0.779	0.806	0.781	0.808	0.316	0.334	0.570	0.539	0.389	0.395
12S-R70	0.838	0.858	0.839	0.860	0.557	0.531	0.280	0.290	0.567	0.604
20F-12S-R30	0.879	0.867	0.883	0.871	0.583	0.693	0.706	0.310	0.605	0.703
20F-12S-R70	0.925	0.898	0.931	0.903	0.739	0.881	0.648	0.248	0.657	0.775
20F-12S-RR30/30	0.895	0.902	0.898	0.905	0.712	0.731	0.429	0.203	0.677	0.730
20F-12S-RR.30/70	0.961	0.941	0.963	0.944	0.907	0.981	0.244	0.070	0.761	0.854
20F-12S-RR70/30	0.881	0.879	0.884	0.882	0.605	0.678	0.515	0.242	0.632	0.711
20F-12S-RR 70/70	0.961	0.950	0.962	0.952	0.966	0.991	0.038	0.000	0.802	0.884

Figure 31. Comparation results of the tested fourteen concrete mixtures using five multi criteria decision making techniques

4.4.7 New scientific results of MCDM techniques

Among the 14 concrete mixtures examined, the one comprising 70% multi-recycled concrete aggregate, 20% fly ash, and 12% silica fume is identified as the most sustainable concrete mixture. [V]

CHAPTER 5: CONCLUSION

Engaging in environmentally responsible practices that mitigate the environmental impact associated with natural aggregate extraction involves repurposing crushed concrete as an aggregate source. This not only lessens environmental strain but also bears global economic implications, as recycling initiatives become financially competitive, offering sustainable solutions on a long-term scale for each nation. In this dissertation, a detailed life cycle assessment was conducted on two generations of recycled concrete, taking into account the benefits of incorporating optimal proportions of two supplementary cementitious materials, namely fly ash and silica fume. five multiple criteria decision-making techniques were employed, considering criteria such as technical performance, CO_2 emission, volume of materials, human health, ecosystem quality, climate change, resources, and costs, to determine the most favourable alternative that achieves the optimal balance across these criteria. In summary, this research delves into the multi-generational recycling of concrete through a comprehensive analysis covering environmental, economic, and functional performance aspects of engineered composites. The study introduces a robust and inclusive decision-support framework for long-term resource management, integrating insights from diverse fields. The key findings of this investigation can be summarized according to experimental and analytical parts as follows.

1) Experimental conclusions

   The fresh state of fourteen high-performance concrete mixtures was assessed through a flow table test. Subsequently, three primary mechanical tests, including compressive strength, flexural strength, and splitting strength, were conducted at 28, 90, and 180 days. Four samples from each mixture were examined at each age to ensure proper strength evaluation. Additionally, a water absorption test was performed at 90 days of age. The results showed:

- Series I, comparable results from long-term research indicate that the impact of the fly ash and silica fume could raise over time. However, HPC shown that it is among the most effective solutions for material unitization.
- By using fly ash, less superplasticizer was required. Because of their rounded shapes, FA's particles can easily roll over one another and dissolve cement particles. Furthermore, because of the large surface area of these particles, the usage of silica fume increased the demand for superplasticizers. However, adding 12% silica fume and

20% fly ash in one mixture balanced the quantity of superplasticizer, according to recent concrete tests.

- The results indicated that when both fly ash and silica fume were used to substitute cement, the compressive strength rose by 23.8%, 11.55%, and 11% at three test ages. Which is preferable than using fly ash by itself in a single mixture. However, this impact can be explained by the silica fume particles' significant pozzolanic activity, which is possibly connected to their capacity to improve compressive strength on one side. Meanwhile, tiny fly ash particles filled the gaps between cement grains.
- The results showed that FA's concrete mixture has the lowest value for water absorption. This behaviour might be related to FA's graded particle distribution, which aided in the filling of the pores inside the concrete.
- Series II, in the case of an up to 70 % replacement of natural aggregate by recycled concrete aggregate, the compressive strength of the mixture contained 12% silica fume seemed to have the biggest strength by 13.4–26.4 % at the age of 28 and 90 days, compared to control concrete, proving once more the ability of silica fume particles to increase the strength of concrete.
- In series II, the using of 12% silica fume and 20% fly ash with 70% recycled concrete aggregate increased the compressive strength, compared to recycled concrete aggregate containing 30% recycled concrete aggregate. For instance, at ages of 90, and 180 days, respectively, compressive strength values of 20F-12S-R70 were greater than those of 20F-12S-R30 by increases of 2.2%, and 2.79%. Even at the age of 28 days, an advantageous effect was not as great as it was at later ages (just 0.18%). This was related to a lower water-cement ratio because of increased absorption and the high specific roughness and surface of RCA compared to natural aggregate.
- The values of series II's splitting strength slightly decreased. This decrease was only small and negligible. This was related to a lower water-cement ratio because of increased absorption. Recycled concrete aggregate might be used to make HPC concrete if properly proportioned and mixed. Additionally, improved concrete quality has a positive impact on flexural strength. In the current investigation, HPC was produced with a particular ratio of SCMs, which already boosted flexural strength.
- The water absorption values increased in all mixtures. Especially, when SF added to 70% RCA, which proved that the water absorption varied by increasing the ratio of recycled concrete aggregate replacement. Furthermore, 20F-R30 had the lowest value

of all the series II mixtures, demonstrating that FA's particles are superior to SF particles in filling the pores inside the concrete.

- Series III, the optimal replacement amount of cement by SCMs as a function of the compressive strength of multi recycled concrete aggregate was the used ratios. the expectation of getting the best results by utilizing the chosen proportions of fly ash and silica fume is demonstrated in this dissertation, which was done after evaluating several earlier studies and numerous concrete experiments. Particularly the concrete supplemented with fly ash and silica fume and how the high percentage of fly ash reduces the compressive strength and discovered that the perfect ratio of silica fume is between 10 % and 15 % of the cement weight.
- Replacing 70% of natural aggregate by multi recycled concrete aggregate obtained better results than replacing 30% of natural aggregate by multi recycled concrete aggregate, due to the high number of fine particles produced by the second generation of crushing procedures.
- Adoption of multi recycled concrete aggregate could convert the aggregate from a non-renewable resource to a renewable one. Its outcomes were pleasing and on par with recycled concrete aggregate. For example, the compressive strength of 20F-12S-RR70/70 was 22%, 16.5%, and 11% greater than 20F-12S-R70 at 28, 90, and 180 days, respectively. The improvement due to the rough surface of multi recycled concrete aggregate, and the high number of fine particles. Moreover, the use of SCMs once again in the second generation as a cement replacement can be the third reason contributing to the multi recycled concrete aggregate's increased compressive strength.
- The flexural strength of second-generation mixtures increased by time. Especially, when multi recycled concrete aggregate replaced natural aggregate up to 70%.
- At the age of 180, it was discovered the replacement of natural aggregate by 70% of multi recycled concrete aggregate improved compressive strength gradually by 3.42%, compared to original crushed concrete (20F-12S-R70).
- The experiment also shown that series III's ability to absorb water was increased using two generations of concrete. However, the mixture of 20F-12S-RR30/30 showed the lowest water absorption results among all series III mixtures, while 20F-12S-RR70/70 obtained the highest value (25.7% higher than CC), demonstrating that expanding the recycling cycle and high replacement ratio increases the concrete's ability to absorb water.

2) Analytical conclusions

In the first stage, the life cycle assessment of the fourteen concrete mixtures was carried out using two approaches (SimaPro 9. software and weighted equations). In the first approach 15 midpoint were calculated using the software to reach the 4 environmental endpoints (human health, ecosystem quality, resources, climate change). While in the second approach, CO_2 emissions and volume of materials were calculated. The software results showed:

- After calculating 15 midpoints of the fourteen concrete mixtures, the worst environmental profile belongs to the reference mixture, denoted as CC composed of virgin sources only and with the highest portland cement dosage, because of the energy intensity of Portland cement production as well as a substantial environmental load.
- The most obvious savings were obtained in the land occupation category (LO), with over 50% drop (best to worst mix) in the second generation of concrete (20F-12S-RR70/30, 20F-12S-RR70/70) compared to the CC (100%), which proved the importance of using double recycled concrete aggregate with combination of supplementary materials.
- Overall, there was a 20% reduction in the first generation and a 25% reduction in the second generation according to the software findings of the global warming potential (GWP) effect category, which relates to carbon dioxide emissions. The replacement of the cement resulted in the most distinct effects on the overall environmental score, thus the replacement of portland cement by silica fume and fly ash can be accepted as dominant over the replacement of natural aggregate despite significantly higher quantities.
- The environmental complexity of LCA analysis inevitably depicts more distinct benefits in other categories, such as mineral extraction, terrestrial ecotoxicity, and ionizing radiation. At the end, the overall environmental effect was decreased by up to 38.5% when concrete was recycled twice and reused.
- By calculating the endpoint category showed that using the second-generation mixtures saved 27% of the resources, because of using two partial replacement materials (cement and natural aggregate)
- The climate change indicator reduced up to 31.28% by integrating muti recycled aggregate concrete compared to CC concrete.
- The human health and ecosystem quality indicators improved 29% and 34% by using 20% fly ash and 12% silica fume with 70% multi recycled aggregate concrete.

The second approach (manual calculation) was applied to calculate CO_2 and volume of materials and compare the results with software approach. The results showed:

- The cement obtained the highest value of total carbon dioxide by 98.3% in control concrete mixture, due to the use of raw material (cement) in CC compared to other types.
- Concrete using 30% multi-recycled aggregate has its carbon dioxide content decreased by 28.3% through the use of fly ash and silica fume. When the ratio reached 70%, the overall emission was reduced by up to 25.7% due to the increase amount of superplasticizer which caused higher CO_2 emission.
- Comparing between Simapro 9 software's results and weighted equation's results, the values were very similar to each other, improving the accuracy of both used approaches.
- In overall, cement replacement by two specific ratios of supplementary cementitious materials and aggregate replacement by multi recycled concrete aggregate reduced the raw materials in total by 61.3%, compared to control concrete mixture.
- The reuse of concrete as a second generation of recycling concrete decreased the cost by around 6.68%, and 3%, when compared to the control concrete and series II mixtures, respectively.
- The comparison between the manual results and software results showed very close results in case of CO2 emission and global warming potentials, which proved the reliability in both methods.

In the second stage, and after calculating the life cycle assessment and cost of materials, the selection of the best concrete mixture, using 5 MCDM techniques (TOPSIS, VIKOR, EDAS, WSM, and WPM) with two weighted methods (entropy method and equal performance method), were applied. The results showed that:

- According to RCC's (TOPSIS) results, the second-generation mixtures had the highest RCC values, while the CC mixture having the lowest value and 20F-12S-RC70/70 being deemed the best option among the alternatives based on the specified criteria. This illustrates the advantages of using multi recycled aggregate concrete while taking costs, technical requirements, and environmental impact into account. Furthermore, the second generation had the top five highest RCC values based on the entropy technique, indicating the significance of multi recycled aggregate concrete use in the building and construction industries.

- In VIKOR technique, the lowest value denotes the best ranking among the used alternatives. The top two possibilities out of the fourteen mixtures were 20F-12S-RR70/70 and 20F-12S-RR30/30, with the second-generation mixtures having the top five lowest Q_i values, compared to the CC's result or the first generation of concrete's results, which obtained the biggest values in both weighted methods. These results confirm again the importance of using multi recycled concrete aggregate (up to 70%) with SCMs, providing a new concrete for the practical construction.
- Using EDAS technique, 20F-12S-RR70/70 and 20F-12S-RR30/70, showed the highest AS_i indicator among all the mixture variations. This reinforces the significance of employing multi recycled aggregate concrete to produce concrete that is not only cost-effective but also environmentally friendly. These results emphasize the advantages of multi recycled aggregate concrete over CC or first-generation mixtures.
- The highest S_{WSM} values using both equal performance and entropy method was consistently observed in the second-generation mixtures, specifically 20F-12S-RR70/70 and 20F-12S30/70. Which consists of other used techniques results.
- Even the weighted normalized matrix of WPM technique is computed differently from WSM, WPM technique results showed the same results as in WSM technique by using both weighted methods. Specifically, 20F-12S-RR70/70 and 20F-12S30/70. This emphasizes how important it is to use multiple recycled aggregate concrete to create concrete that is both economical and ecologically benign. Finally, this concrete can be used in a variety of construction-related applications, particularly sustainable residential buildings and residential housing.

CHAPTER 6: NEW SCIENTIFIC FINDINGS

High strength concrete was significantly more sensitive to component proportions and mixing processes than other types of concrete. Whereas the aggregate fraction distribution, water to cement ratio, and cement content, as well as the mixing technique, all have a significant impact on its compressive strength and other properties. All mixtures went through flow table testing, and it has demonstrated that the workability window for all varieties of concrete is also met. The following paragraphs summarized the major new scientific findings, which was demonstrated in this research based on an experimental program and analytical work that was carried out:

6.1 Thesis group I

The limitation and boundary conditions for this thesis is on substituting recycled concrete aggregate and two specific ratios of (20% fly ash and/or 12% silica fume) for coarse natural aggregate in high-performance concrete and cement, respectively.

The pressing need to use the coarse recycled concrete aggregates originates from the widespread issue of the enormous volumes of building and demolition debris as a result of wars and natural catastrophes in certain parts of the world, not to mention the scarcity of natural resources in other areas. The coarse recycled concrete aggregate was used as a 70% replacement for coarse natural aggregate to evaluate the product’s effectiveness in terms of its short and long-term properties, particularly because the coarse aggregate is one of the defining factors in achieving the expected benefits from high-strength concrete.

I/A. I experimentally proved that mixture (20F–12S-R70) had higher values of compressive strength than mixture (20F–12S-R30) by an increase of 0.18%, 2.2%, and 2.79% at the ages of 28, 90, and 180 days, respectively.

I/B. I experimentally proved that the increase of recycled concrete aggregate ratio did not reduce the strength but enhanced. The combination of the specific ratios of 20% fly ash and 12% silica fume in one mixture with only 30% recycled concrete aggregate (20FA-12SF-R30) slightly improved the compressive strength of concrete by 0.3% at long time test, compared to control concrete. However, 20FA-12SF-R70 strength had almost the same value as that in control concrete and was better than that in 20FA-12SF-R30 at earlier ages (28 and 90 days) and superior at 180 days (up to 3%).

I/A. At the early ages (28 and 90 days), concrete with up to 70% recycled concrete aggregate exhibited results comparable to control concrete. However, at 180 days, the mixture included 70% recycled concrete aggregate outperformed the control concrete and the 30% recycled concrete aggregate. This behaviour may be explained by the recycled concrete aggregate's high porosity, roughness, and unique surface, which improved the recycled concrete aggregate's interconnection with the new mortar.

In general, when compared to control concrete (Figure 32), all compressive strength values of recycled aggregate concrete mixtures are higher than (C55/67) at age of 28 days, which may be considered as a high strength concrete (ACI Committee, 1997).

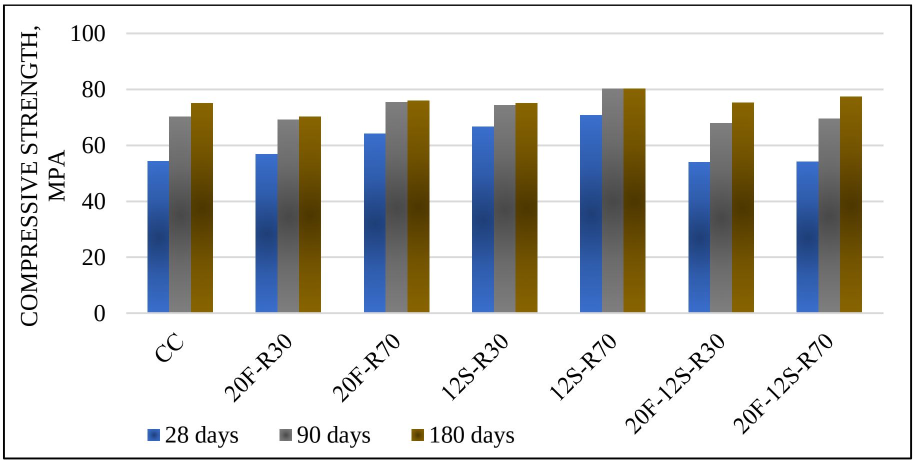


Figure 32. Comparation of compressive strength of control concrete and six recycled concrete mixtures

I/B. The optimal replacement amount of cement by 20% fly ash and 12% silica fume as a function of the compressive strength of recycled concrete aggregate was the used ratios, where the improvement began at older test ages and with replacement of recycled concrete aggregate up to 70%. The capacity of silica fume particles to increase compressive strength on one side, which may be connected to their powerful pozzolanic activity, is responsible for this behaviour. In the meantime, small fly ash particles filled the spaces between the cement grains. There is no consensus in the study area on how precisely proportioned fly ash and silica fume in a single combination affect the compressive strength of high strength concrete employing cement with a strength used class.

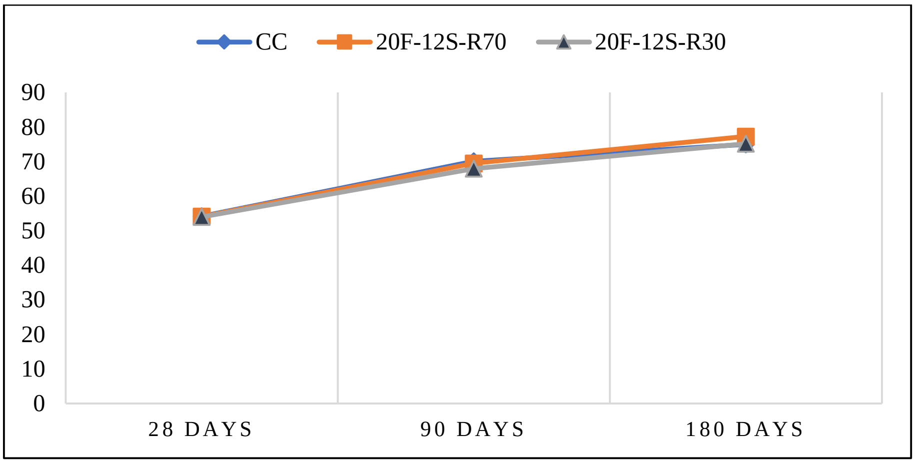


Figure 33. Comparation of compressive strength of control concrete and fly ash, silica fume, recycled aggregate concrete mixtures.

For instance, at ages of 90, and 180 days, respectively, compressive strength values of 20F-12S-R70 were greater than those of 20F-12S-R30 and control concrete by increases of 2.2%, and 2.79%. Even at the age of 28 days, an advantageous effect was not as great as it was at later ages (just 0.18%). This was related to a lower water-cement ratio because of increased absorption and the high specific roughness and surface of RCA compared to natural aggregate.

6.2 Thesis group II

The limitation and boundary conditions for this group of thesis is on substituting multi recycled concrete aggregate and two specific ratios of (20% fly ash and/or 12% silica fume) for natural aggregate in high-performance concrete and cement, respectively.

In the current study, the effect of replacing coarse natural aggregate with multi recycled concrete aggregate, 30% and 70%, respectively, revealed a changing point for obtaining a positive effect, particularly after adding both fly ash and silica fume as a cement replacement in all concrete mixtures.

II/A. I experimentally proved that using 30% multi recycled concrete aggregate as a replacement of coarse natural aggregate required 13.3% and 6.6% less amount superplasticizer than using 30% recycled concrete aggregate. While using 70% multi recycled concrete aggregate required the same amount of superplasticizer as that in original crushed recycled aggregate concrete.

II/B. I experimentally approved that the higher dosage of multi recycled concrete aggregate (70%) enhanced the compressive strength of concrete compared to the recycled concrete aggregate. For instance, the mixture (20F-12S-RR70/70) was 22%, 16.5%, and 11% greater than the mixture (20F-12S-R70) at 28, 90, and 180 days, respectively.

II/A. Due to the multiple crushing process, which produced more small fragments, the total volume of pores in the multi-recycled aggregate concrete reduced as compared to recycled aggregate concrete. Furthermore, a specific ratio of fly ash and silica fume in the same concrete mixture can balance the amount of superplasticizer when they are utilized in the same mixture.

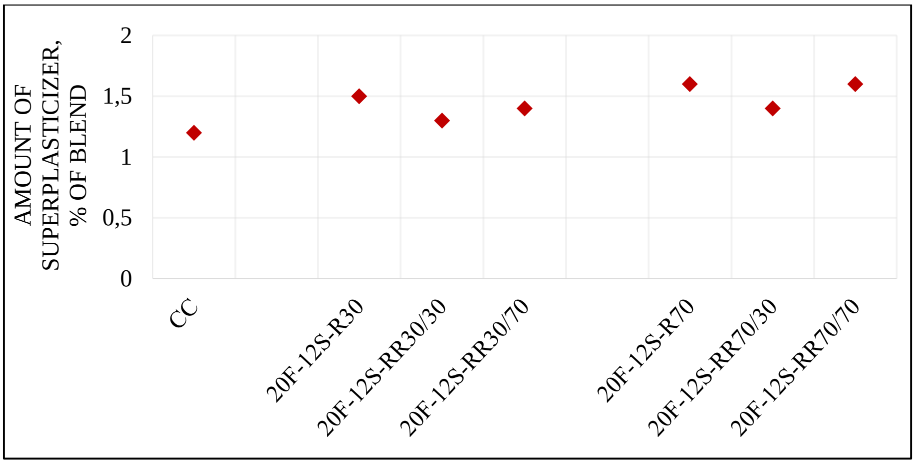


Figure 34. Superplasticizer amount of control concrete,
fly ash, silica fume concrete with 30% recycled aggregate,
and fly ash, silica fume concrete with 30% multi recycled aggregate

II/B. The compressive strength of concrete increased by using 70% of multi recycled concrete aggregate. For instance, at 28, 90, and 180 days, respectively, the compressive strength of mixture with 20% fly ash and 12% silica fume with 70% multi recycled concrete aggregate was 22%, 16.5%, and 11% stronger than 20% fly ash and 12% silica fume with 70% recycled concrete aggregate mixture (Figure 35). The multi recycled concrete aggregate's rough surface and the abundance of small fragments generated by the second generation of double crushing processes may be to blame for the improvement. The improved compressive strength of multi-recycled aggregate concrete in the second generation may also be attributed to the continued use of supplementary cementitious materials as a replacement for cement.

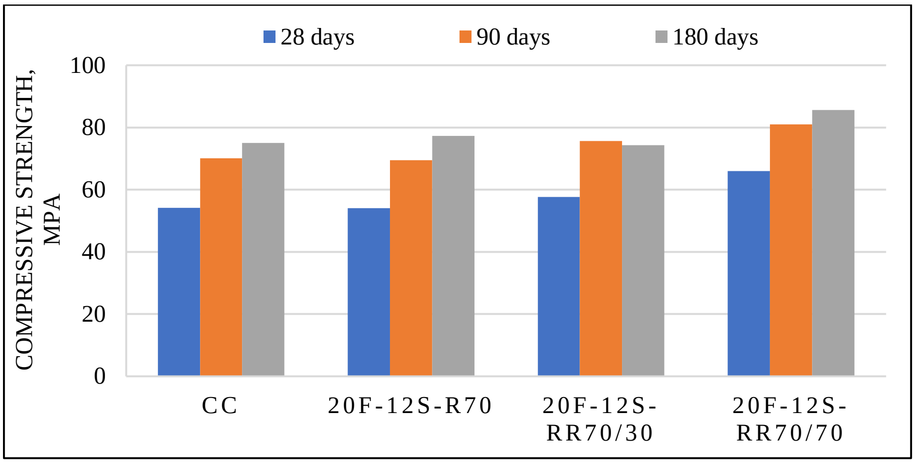


Figure 35. Comparation of compressive strength of control concrete,
fly ash, silica fume, recycled aggregate concrete mixtures,
and fly ash, silica fume, multi recycled aggregate concrete mixtures

The improvement due to the rough surface of multi recycled concrete aggregate, and the high number of fine particles. Moreover, the use of SCMs once again in the second generation as a cement replacement can be the third reason contributing to the multi recycled concrete aggregate's increased compressive strength.

6.3 Thesis group III

This group is related to life cycle assessment. The boundary conditions used in this thesis include the processes associated with the production of concrete (standard and alternatives) for each particular mixture together will all major flows of raw materials, emissions, and transportation.

To analyse the experimental findings in light of their potential effects on the environment. SimaPro 9.0 (SimaPro SW) and manual calculation were used in this research. The overall environmental load represented as a single score; the definition varies depending on the impact assessment technique being used to calculate the single score. Characterization, damage estimation, normalization, and weighting are all incorporated in this score.

III/A. I analytically proved that the land occupation category decreased 50% in the case of second-generation concrete, especially, in concrete contains 70% multi recycled concrete aggregate.

III/B. I analytically proved that the global warming potential category decreased 20% in the first generation (concrete contained both fly ash and silica fume with 70% recycled concrete

aggregate) and 25% in the second generation (concrete containing both fly ash and silica fume with 70% multi recycled concrete aggregate), compared to the control concrete.

III/C. By calculating the endpoint category showed that using the second-generation mixtures saved 27% of the resources, because of using two partial replacement materials (cement and natural aggregate).

III/D. I analytically proved that the climate change indicator reduced up to 31.28% by integrating muti recycled aggregate concrete compared to CC concrete.

III/E. I analytically proved that the human health and ecosystem quality indicators improved 29% and 34% by using 20% fly ash and 12% silica fume with 70% multi recycled aggregate concrete.

III/F. The cement obtained the highest value of total carbon dioxide by 98.3% in control concrete mixture. Additionally, I analytically approved that using fly ash and silica fume reduced the carbon dioxide by 28. 3% in concrete contained 30% multi recycled aggregate concrete. While the reduction of the total emission was up to 25.7% when the ratio reached 70%.

III/G. I analytically approved that the volume of raw materials of MRAC mixtures got parallel decrease as that in the first generation. Where the reductions were 30.4 %, 61.1 %, 30.4 %, and 61.3 % for 20F-12S-RR30/30, 20F-12S-RR30/70, 20F-12S-RR70/30, and 20F-12S-RR70/70, respectively, compared to control concrete.

III/A. The substitution of portland cement with 12% silica fume and 20% fly ash can indeed be viewed as a more prominent factor compared to the replacement of only natural coarse aggregate in concrete formulations, especially in 20% fly ash and 12% silica fume with 70% multi recycled concrete aggregate mixtures (Figure 36), where the control concrete's land occupation was 100%. Therefore, by addressing the replacement of both cement and aggregate, this research offers a fresh perspective and presents a sustainable alternative concrete mixture as compared to control concrete formulations.

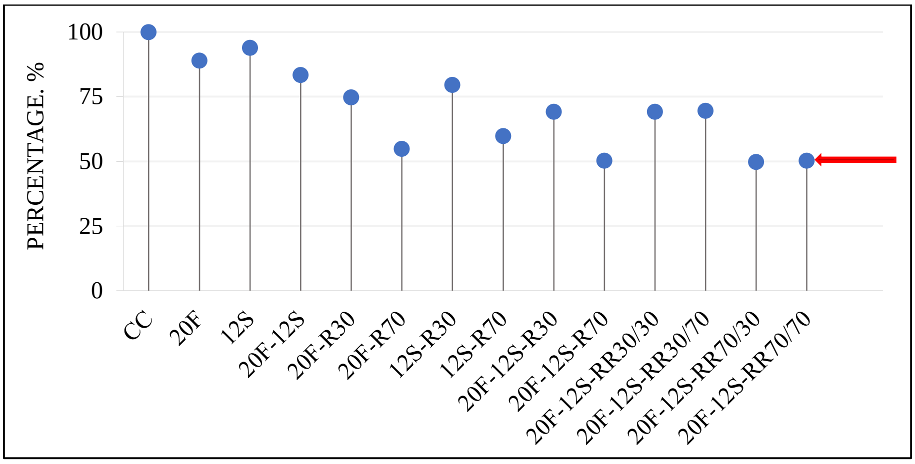


Figure 36. Land occupation midpoint category

III/B. Figure 37 demonstrates that the combined use of supplementary cementitious materials as a cement replacement has the most positive significant impact on the overall environmental score. This reaffirms that cement production has the most substantial negative environmental impact. However, the use of recycled concrete aggregate or multi-recycled concrete aggregate has shown a substantial reduction in environmental impact values, this reduction is particularly pronounced when 70% of multi-recycled concrete aggregate is used.

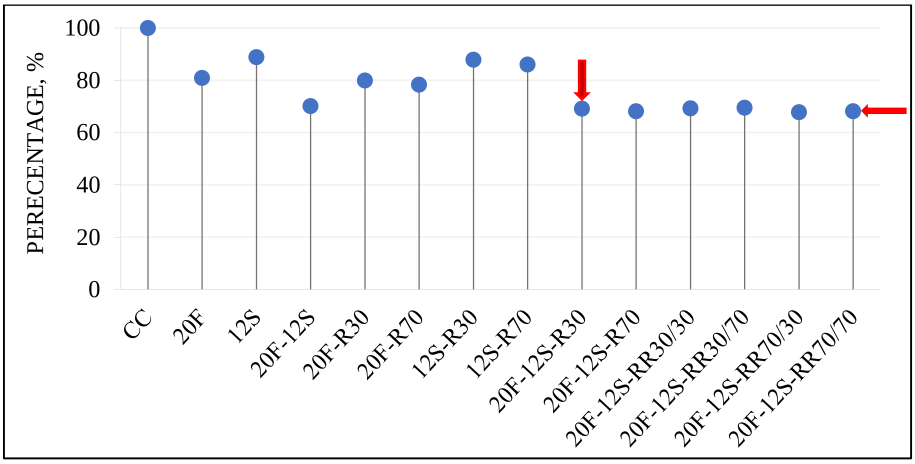


Figure 37. Global warming potential midpoint category results

III/C. By using two replacement materials of natural aggregate and cement the resources indicator reduced significantly in the second-generation concrete, compared to the control concrete. Showing that the importance of saving raw materials (Figure 38).

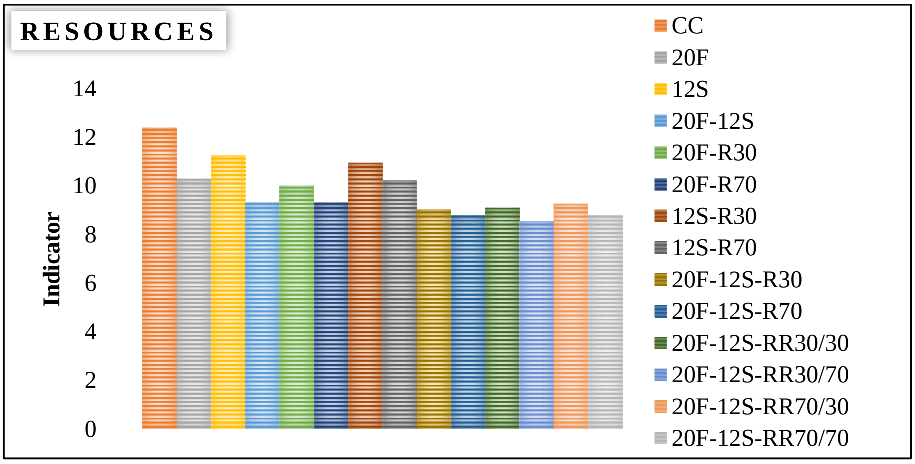


Figure 38. resources values of fourteen examined mixtures

III/D. This is because incorporating multi recycled concrete aggregate reduced the demand for natural aggregates, thereby decreasing the energy consumption and emissions associated with their extraction and transportation. Additionally, the inclusion of fly ash and silica fume further reduces the carbon footprint by utilizing industrial by-products. Overall, this sustainable approach to concrete production helps mitigate climate change by lowering greenhouse gas emissions and conserving natural resources (Figure 39).

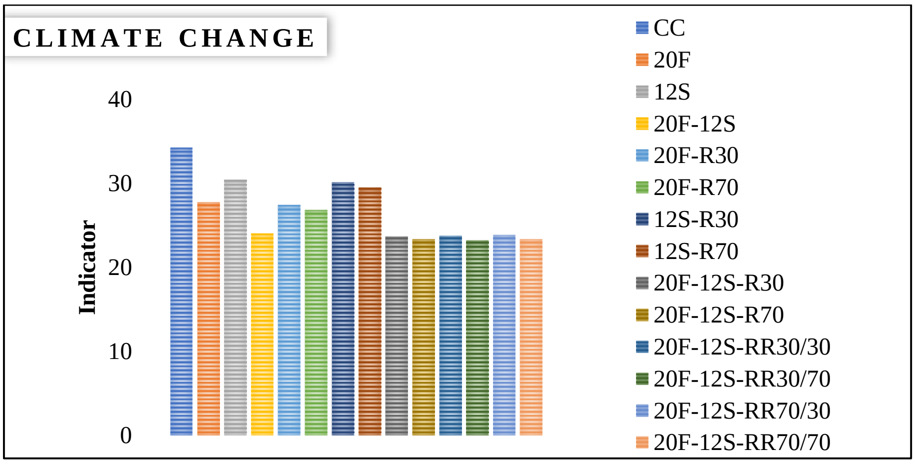


Figure 39. Climate change values of fourteen examined mixtures

III/E. This is achieved by reducing the extraction of natural resources and minimizing the release of harmful pollutants associated with traditional concrete production. The utilization of industrial by-products like fly ash and silica fume further diminishes the environmental impact by diverting waste from landfills and decreasing emissions. Consequently, this sustainable approach enhances air and water quality, safeguarding both human health and ecosystem integrity (Figure 40).

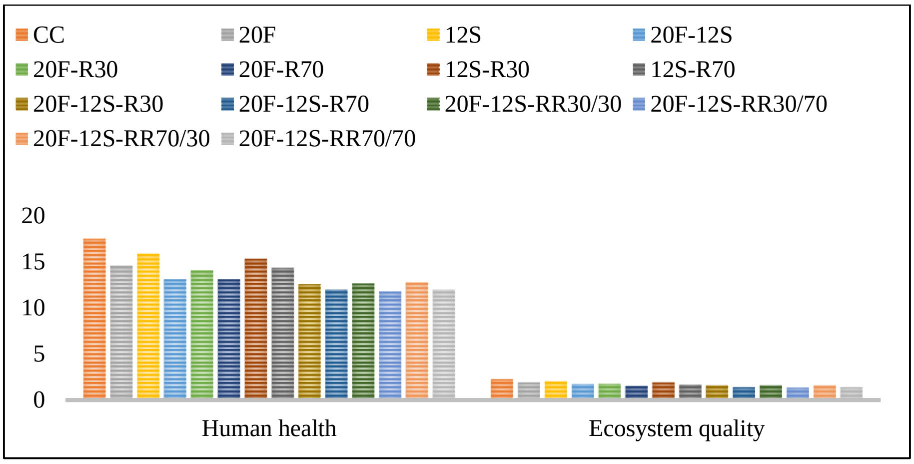


Figure 40. Human health and ecosystem quality values of fourteen examined mixtures

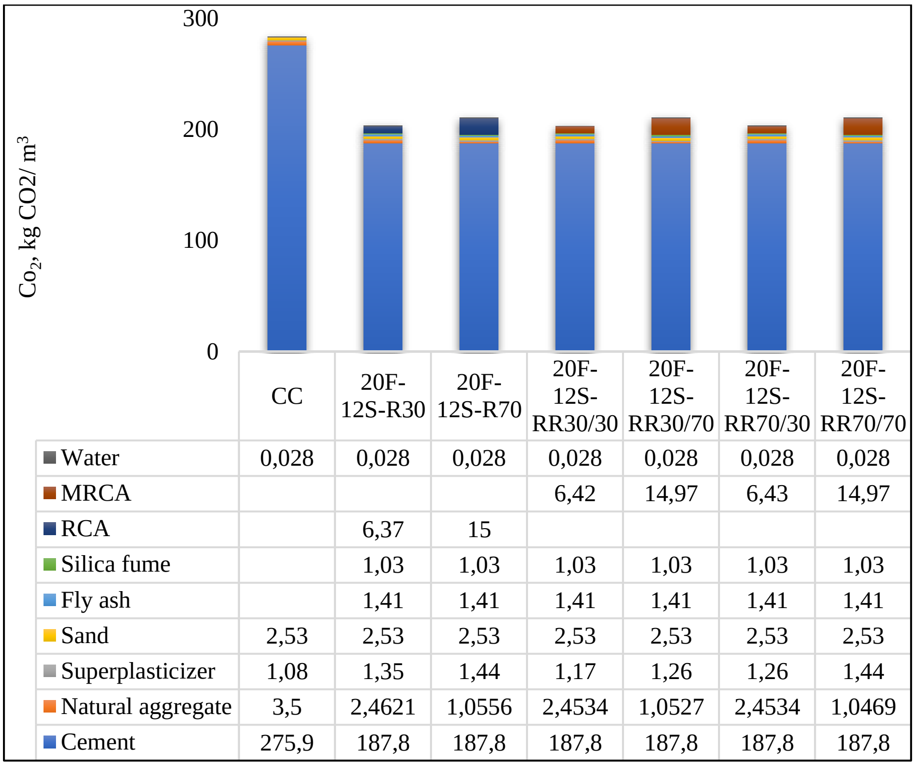
III/F. The environmental burden presented in this thesis was calculated using SimaPro software, as previously mentioned. However, prior to using the software, the results were obtained through a different approach, involving the quantification of carbon dioxide emissions and material volumes. These results were already published in two impact factor journals and constitute a section of this thesis, organized into the following groups:

The total carbon dioxide emissions of each concrete mixture are evaluated by calculating the carbon dioxide emission of cement, natural coarse aggregate and superplasticizers, as these materials are changing in the case of different concrete types. By applying Equation (18) carbon dioxide values of all the materials used in concrete production can be summarized.

$$\mathrm{CO}_{2,\mathrm{total}} = \sum_{j=1}^{m}(W_i \times \mathrm{CO}_{2,j}) \qquad \text{Eq. (18)}$$

Where, $CO_{2,total}$ is the total CO_2 emission of concrete in $kgCO_2/kg$, m is the total raw material used in the calculation, W_i is the total amount of each j material in kg, $CO_{2,j}$ is the CO_2 emission value of each j material in $kgCO_2/kg$.

This can be attributed to two factors: the significant carbon dioxide emissions of cement manufacture, which could be lowered by employing fly ash and silica fume. The manual crushing for creating recycled concrete aggregate and multi recycled concrete aggregate was the second cause for this decrease.



	CC	20F-12S-R30	20F-12S-R70	20F-12S-RR30/30	20F-12S-RR30/70	20F-12S-RR70/30	20F-12S-RR70/70
Water	0,028	0,028	0,028	0,028	0,028	0,028	0,028
MRCA				6,42	14,97	6,43	14,97
RCA		6,37	15				
Silica fume		1,03	1,03	1,03	1,03	1,03	1,03
Fly ash		1,41	1,41	1,41	1,41	1,41	1,41
Sand	2,53	2,53	2,53	2,53	2,53	2,53	2,53
Superplasticizer	1,08	1,35	1,44	1,17	1,26	1,26	1,44
Natural aggregate	3,5	2,4621	1,0556	2,4534	1,0527	2,4534	1,0469
Cement	275,9	187,8	187,8	187,8	187,8	187,8	187,8

Figure 41. CO$_2$ emission values of control concrete, recycled aggregate concrete (two replacement ratios of cement), multi recycled aggregate concrete

III/G. The reduction in raw materials is also notable due to the replacement of natural aggregate with recycled concrete aggregate. However, in the first and second generations, this reduction was attributed not only to aggregate replacement but also to the utilization of fly ash and silica fume as supplementary materials in place of cement. Furthermore, the percentage of superplasticizer required was balanced due to the incorporation of fly ash and silica fume in one mixture, even with a 70% multi-recycled concrete aggregate content (Figure 40).

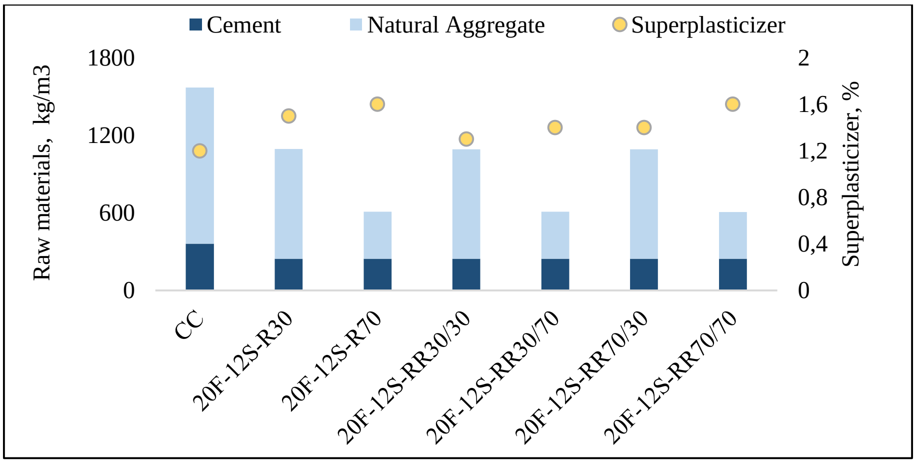


Figure 42. Volume of materials of control concrete,
fly ash, silica fume, recycled aggregate concrete mixtures,
and fly ash, silica fume, multi recycled aggregate concrete mixtures

6.4 Thesis IV

This thesis is related to the cost of the materials.

The reuse of concrete as a second generation of recycling concrete reduced the cost by approximately 6.68%, 3%, compared to the control concrete and series II's mixtures, respectively. Due to lower cost of transportation, crushing cost and used materials.

In series I, using fly ash and/or silica fume in one mixture reduces overall cost of concrete by 10% in concrete contained 20% fly ash compared to control concrete, due to the lower price of the fly ash. Additionally, using them with recycled concrete aggregate or multi recycled concrete aggregate reduced the cost of mixing concrete (multi recycled concrete aggregate supply is less expensive than natural aggregate because of the lower transportation distances, the cost of natural aggregate's transportation was 2800 Ft for 20 km, the absence of aggregate crushing costs, and the low cost of virgin material). The recycled concrete aggregate or multi recycled concrete aggregate utilized in this investigation were manually crushed in the university's laboratory, therefore there were no transportation costs. Yet, when comparing the first- and second-generation mixtures, the results showed that using supplementary cementitious materials and multi recycled concrete aggregate in place of cement and natural aggregate resulted in a significant cost savings benefit. As a result, when compared to control concrete, the prices of the four mixtures in the second generation are the lowest, falling by 7.32%, 8%, 6%, and 5.38 %, respectively (Figure 43).

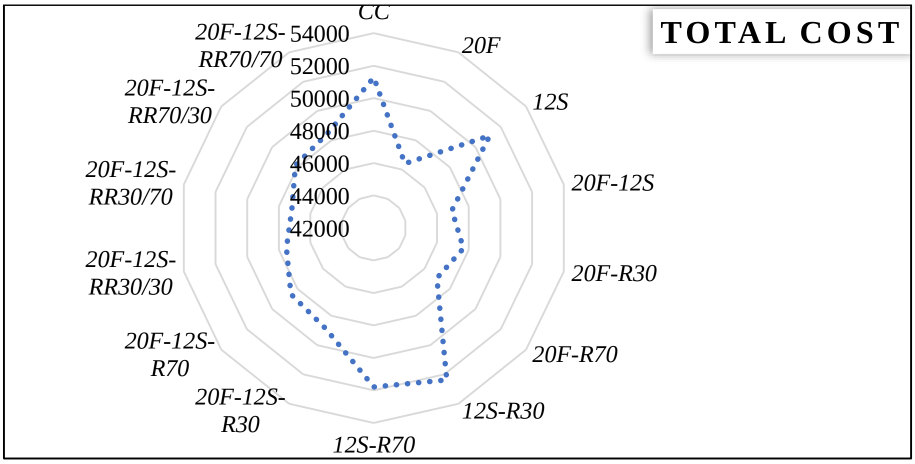


Figure 43. Cost of materials

6.5 Thesis V

This thesis limitation is related to use of the multi criteria decision making with multi recycled aggregate concrete . Which used in the first time with choosing alternatives from multi recycled aggregate concrete.

V/A. I analytically approved that according to TOPSIS technique the second-generation mixtures had the highest RCC values, while the CC mixture having the lowest value and 20F-12S-RC70/70 being deemed the best option among the alternatives based on the specified criteria. Due to the two replacement materials (cement and natural aggregate).

V/B. I analytically approved using VIKOR technique that the top two possibilities out of the fourteen mixtures were 20F-12S-RR70/70 and 20F-12S-RR30/30, with the second-generation mixtures having the top five lowest Qi values confirm again the importance of using multi recycled concrete aggregate (up to 70%) with supplementary materials, providing a new concrete for the practical construction.

V/C. I analytically approved that 20F-12S-RR70/70 and 20F-12S-RR30/70 mixtures, showed the highest ASi indicator among all the mixture variations using EDAS technique.

V/D. I analytically approved that the highest Swsm and Swpm values using both equal performance and entropy method was consistently observed in the second-generation mixtures, specifically 20F-12S-RR70/70 and 20F-12S30/70. Which consists of other used techniques results.

V/A. The indicator RCC of the TOPSIS technique highlighted the superiority of second-generation mixtures over control concrete and identifying a specific mixture (20F-12S-RR70/70) as the optimal choice based on the established criteria, largely due to the inclusion of replacement materials (Figure 44.)

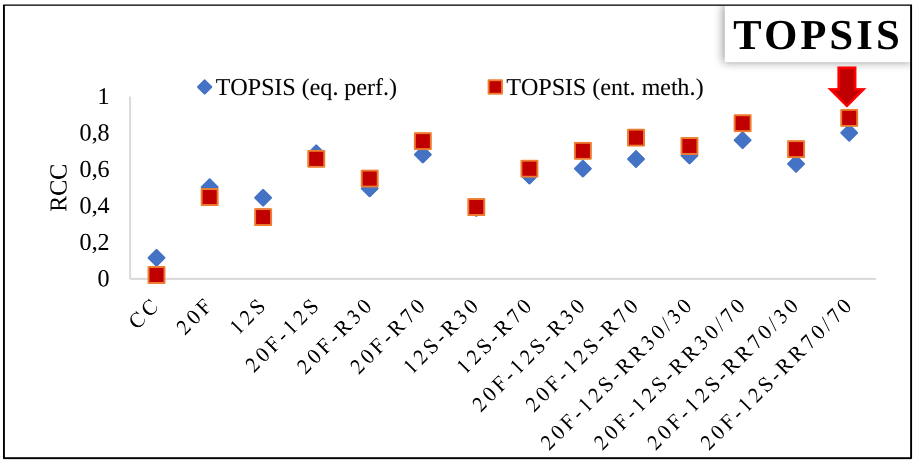


Figure 44. TOPSIS technique results

V/B. Even when different technique like VIKOR technique was used, which it's indicator (Qi) seeking for the lowest value (best one) the results were very similar to TOPSIS results with both weighted methods. It provided valuable insights into the optimal composition of concrete mixtures, emphasizing the significance of incorporating multi recycled aggregate and supplementary materials for sustainable and effective construction practices (Figure 45).

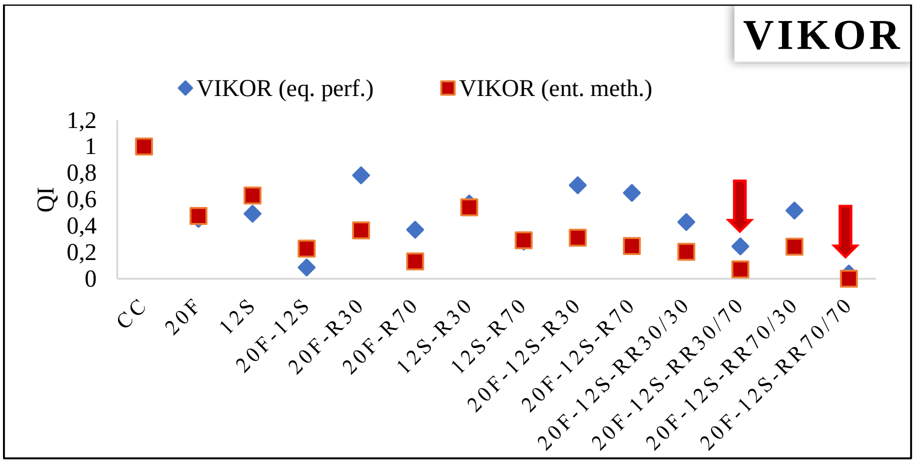


Figure 45. VIKOR technique results

V/C. The ASi indicator reflects the sustainability performance of concrete mixtures, considering the mentioned criteria. The higher ASi values obtained for the second-generation mixtures indicate that they outperformed other variations in terms of sustainability. Illustrated that the two replacement materials (aggregate and cement) played significance role in concrete production (Figure 46).

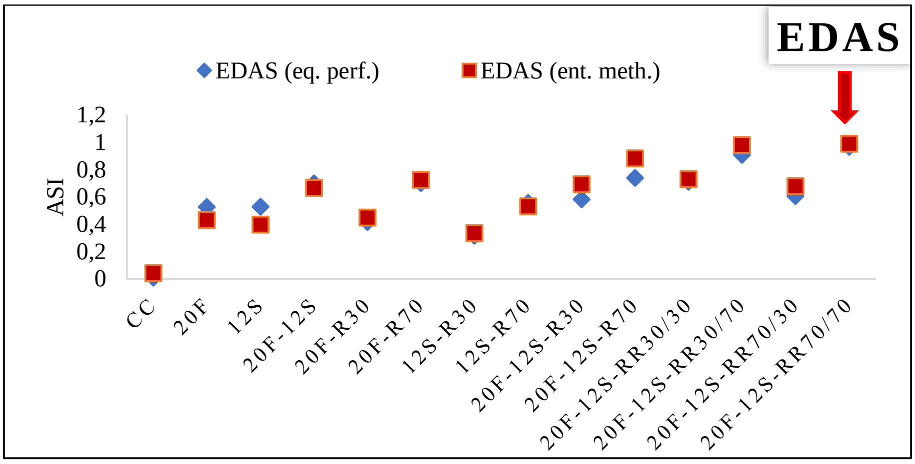


Figure 46. EDAS technique results

V/D. Once more, the results obtained through both WSM and WPM techniques align with those generated by TOPSIS, VIKOR, and EDAS. The highest S_{WSM} values and S_{WPM} were consistently observed in the second-generation mixtures, specifically mixtures (20F-12S-RR70/70 and 20F-12S30/70). This underscores the imperative of utilizing MRAC as a construction material, compared to control concrete (Figure 47).

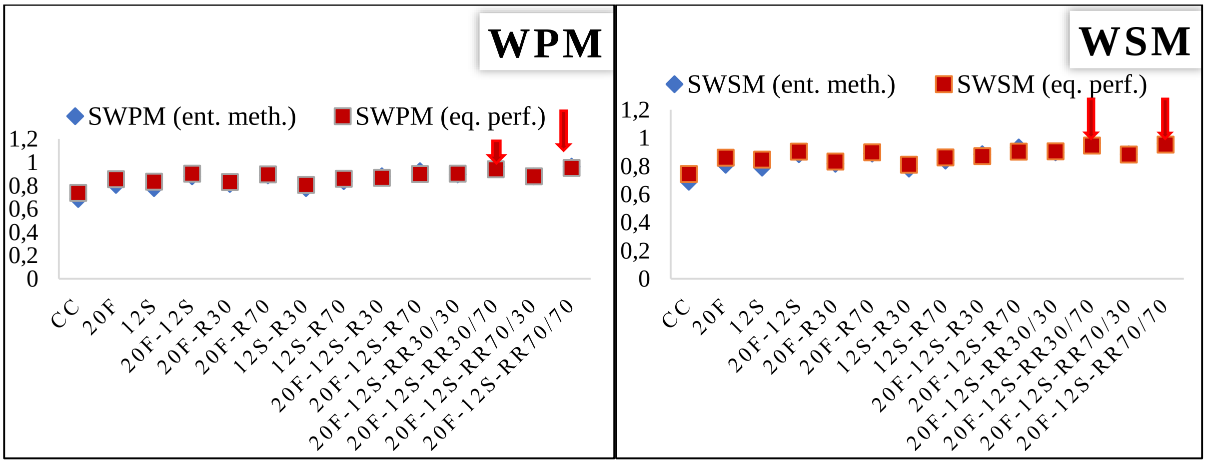


Figure 47. WPM and WSM techniques' results

CHAPTER 7: FUTURE RESEARCH

Applying LCA with multi criteria analysis techniques to have a sustainable version of HPC, which is a useful way to introduce various SCMs, is introduced in this work. It is critical to research MRCA in the Middle East since there are continual conflict in many locations, such as Syria and the Gaza Strip, where a lot of debris was left behind by demolished structures. Future benefits encompass the utilization of substantial amounts of waste construction materials to construct new buildings, offering an environmentally friendly, cost-effective, and high-strength solution. Implementing a dual replacement ratio strategy for both cement and aggregate holds the potential to create practical sustainable concrete, effectively curbing the consumption of natural resources. This is particularly significant in the construction and building sector. However, researcher can also use this work as a cornerstone for new additional researcher by:

- Implementing a forward-thinking approach involves the utilization of new SCMs with unique ratios, such as those derived from eggshells or glass. These materials, readily available in various regions, presenting a promising opportunity to enhance the performance of both MRAC and HPC. By strategically incorporating mentioned SCMs.
- Delving into an in-depth examination of additional properties of RAC, with a particular focus on durability, notably in the context of HPC.
- Undertaking a comprehensive investigation into the various properties of MRAC, with a specific emphasis on durability, particularly concerning HPC. This thorough examination seeks to provide insights into the long-term performance and sustainability of MRAC, especially in the context of high-strength applications.
- Additional tools can be utilized to assess the environmental friendliness of the new concrete mixtures. Integrated new LCA software and multi criteria decision-making techniques will be future framework to determine the most eco-friendly concrete among the new concrete mixtures.

LIST OF RELATED OWN PUBLICATIONS

Shmlls, M., Bozsaky, D., Horváth, T. The Analysis of Lifecycle and Multi-Criteria Decision-Making for Three-Generation High-Strength Recycled Aggregate Concrete. Chemical engineering transactions. Vol. 107, (2023).

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