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Life-cycle Assessment and Multi-criteria Decision-Making of Two-Generation High-Performance Recycled Aggregate Concrete

Doctoral Theses

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1. BOUNDARY CONDITIONS AND LIMITATIONS

The boundary conditions used in this study include the processes associated with the production of concrete in two generations (standard and alternative, fourteen mixtures) using a specific ratio of fly ash and/or silica fume (20%, 12%, respectively) for each particular mixture together will all major flows of raw materials, emission factors, and transportation.

The experimental part only includes the processing of the concrete mixtures (casting and mixing), fresh properties, compressive strength, flexural strength, splitting strength, and water absorption results. However, the experiments were carried out only to check the strength and water absorption of the fourteen mixtures to make sure that the strength of all mixtures is over 55 MPa at three ages of test (28, 90 and 180 days).

While the life cycle assessment required only one concrete strength (compressive strength results at three ages 28, 90, and 180 days) as one of selected criteria beside carbon emission, human health, ecosystem quality, resources, climate change, volume of material, and cost. However, the transportation costs are also included for better reliability of the presented results, and to avoid overrepresentation of environmental benefits.

The last part of this research was the selection of best alternative among the fourteen mixtures by choosing five multi criteria decision making (TOPSIS, EDAS, VIKOR, WSM, and WPM) and for better reliability two weighted methods were also included in this work (entropy method and equal performance method) and compare all the results of all technique together.

2. THE AIM OF DISSERTATION

These goals were accomplished by the following aims:

1- To improve the proportioning and process of the HPC mixture to achieve concrete strength class C55/67.
2- To determine the maximum replacement possibility of cement by fly ash and silica fume.
3- Defining the minimal dosage of superplasticizer and the potential replacement quantity for recycled concrete aggregate/ multi recycled concrete aggregate in the high-performance concrete 's workability.
4- Studying the possibility of multiple utilisations of multi recycled aggregate concrete in real construction.
5- Life cycle assessment is being used to assess the environmental impact of using end-of-life concrete as a replacement for coarse aggregate in the multi-life cycle dimension.
6- Choosing the best alternative among all mixtures using five multi criteria decision making and comparing the results obtained from all the used techniques.

3. METHODOLOGY

This research has been conducted in 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, multi recycled aggregate concrete. The four stages prioritize the technical, environmental, and economic perspectives. The proposed research methodology is summarized in Figure 1.

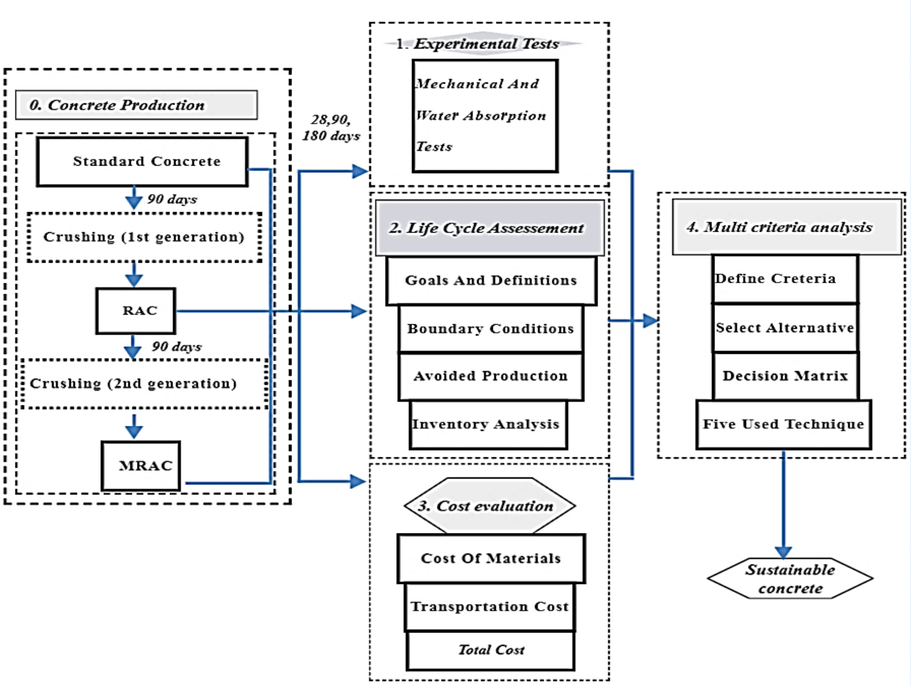


Figure 1. Theses stag

3.1. Concrete production and experimental testing

Two generations of recycling concrete were prepared and tested at both fresh and hardened states. After producing the standard concrete, the first generation was produced by using the rubble of standard concrete after testing as recycled coarse aggregate with different proportions to produce recycled aggregate concrete. While the second generation was produced by using the rubble of recycled aggregate concrete that was produced in the first generation after testing as the multi recycled coarse aggregate with different proportions to produce multi recycled aggregate concrete. In total, fourteen concrete mixtures were produced in three phases: the first phase (standard concrete), where only natural aggregate was used as a coarse aggregate. In the second phase (first generation), recycled coarse aggregate was replaced natural aggregate partially (30% or 70%). While in the last phase (second generation) the natural aggregate was replaced partially (30% or 70%) with multi recycled coarse aggregate. Table 1. Showed the fourteen concrete proportions.

Table 1. Concrete mixtures and material proportions

Mixture name	Classification	Cement, kg/m³	FA, kg/m³	SF, kg/m³	Fine aggregate, kg/m³	NA, kg/m³	RCA, kg/m³	MRCA, kg/m³	Superplasticizer, kg/m³	Water, kg/m³
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

CC: control concrete; 20F: concrete with 20% fly ash; 12S: concrete contain 12% silica fume; 20F-12S: concrete with 20% fly ash and 12% silica fume; R30: concrete with 30% recycled coarse aggregate; R70: concrete with 70% recycled coarse aggregate; RR30/30: concrete with 30% multi recycled coarse aggregate (R30); RR30/70: concrete with 70% multi recycled coarse aggregate (R30); RR70/30: concrete with 30% multi recycled coarse aggregate (R70); RR70/70: concrete with 70% multi recycled coarse aggregate (R70).

In brief, standardized specimens of varying sizes were prepared using steel and plastic molds for testing. These specimens were immersed in lime-saturated water for seven days, following the MSZ EN 772-11:2011 standard [4], and then placed in a laboratory environment at 20±2°C until the testing periods at 28, 90, and 180 days. A total of 210 cubes, 168 prisms, and 168 cylinders were manufactured for testing. Mechanical properties such as compressive strength, flexural strength, and splitting strength were assessed in accordance with established standards [5][6][7]. Additionally, a water absorption test was performed at the 90-day, and the consistency of the fresh mixtures was determined using a slump flow table test.

3.2. Life cycle assessment

This part included two approaches. 1) The obtained data were 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 1. 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 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 (GW), Ionizing radiation (IA), 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 global warming 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). 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 SimaPro 9.0.

2) The second approach is the using of weighted equation; the results involve the quantification of carbon dioxide emissions and material volumes.

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 (5) carbon dioxide values of all the materials used in concrete production can be summarized.

$$CO_{2,total} = \sum_{j=1}^{m} (W_i \times CO_{2,j}) \qquad \text{Eq. (5)}$$

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, Wi is the total amount of each j material in kg, CO2,j is the CO_2 emission value of each j material in $kgCO_2/kg$.

3.3. Cost evaluation

The recycled coarse aggregate and multi recycled coarse aggregate 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 both types of recycled aggregate 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 [10][11][12][13][14]. Whereas all materials were purchased and carried to the laboratory together from the location with a total price of 20 km/ 2800 FT.

3.4. Multi criteria decision making

The technique, namely TOPSIS, is a useful and effective technique for selecting and classifying options based on distance measurements. In essence[15], 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, relative closeness coefficient (RCC) determines the best and worst alternatives, as the highest relative closeness coefficient value is the best alternative.

The VICOR technique is an effective method for compensating for multi criteria decision making and is used to address issues brought on by erroneous and unsuitable criteria [16]. 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. The best and worst values for each criterion are then determined the indicator (Qj) is calculated in the end. The best option has the lowest value of such a variable.

The EDAS technique 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 concrete[17]. In addition, the usefulness of the EDAS as an multi criteria decision making 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. WSM tends to be employed for computations based on real-world criterion values, particularly in one-dimensional scenarios. When A alternatives and 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. Finally, WPM, it 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 [18].

4. NEW SCIENTIFIC RESULTS

High performance 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 analysis that was carried out:

4.1. 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.

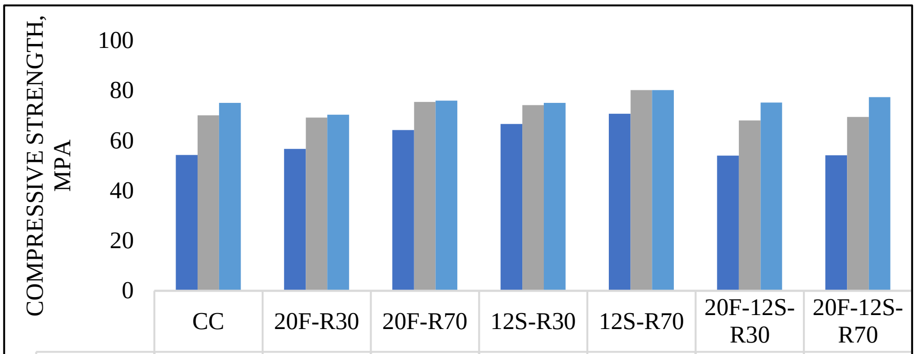
The pressing need to use the coarse recycled concrete aggregates originates from the widespread issue of the enormous volumes of building and demolition debris because of wars and natural catastrophes in certain parts of the world, not to mention the scarcity of natural resources in other areas. The 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 by 3% and 2.79%, respectively. This behavior may be explained by the recycled concrete aggregate's high porosity, roughness, and unique surface, which improved the RCA's interconnection with the new mortar.

In general, when compared to control concrete (Figure 2.), all compressive strength values of recycled aggregate concrete mixtures are higher than concrete class (C55/67) at age of 28 days, which may be considered as a high-performance concrete (ACI Committee, 1997).



	CC	20F-R30	20F-R70	12S-R30	12S-R70	20F-12S-R30	20F-12S-R70
28 days	54,2	56,7	64,2	66,6	70,7	54	54,1
90 days	70,1	69,2	75,4	74,2	80,2	68	69,5
180 days	75	70,27	76	75,1	80,23	75,2	77,3

Figure 2. 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% (Figure 3.). 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-performance concrete employing cement with a strength used class.

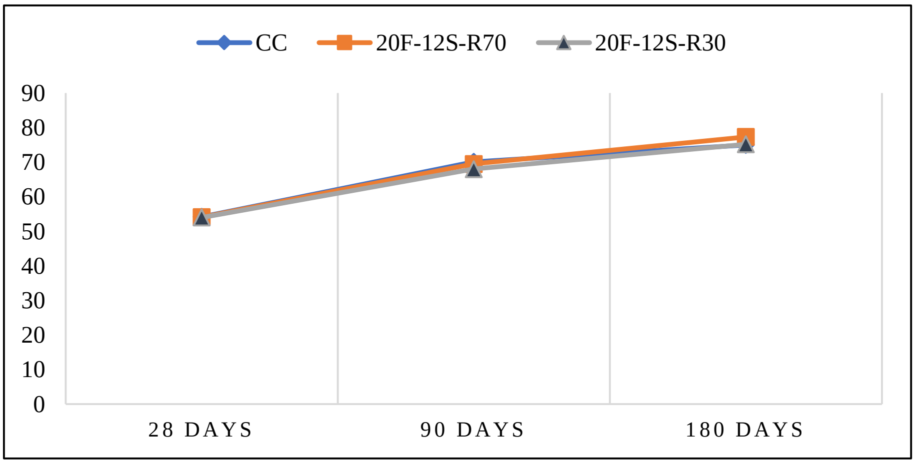


Figure 3. Comparation of compressive strength of control concrete and fly ash-silica fume-recycled concrete mixtures

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 CC 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.

4.2. 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 4.).

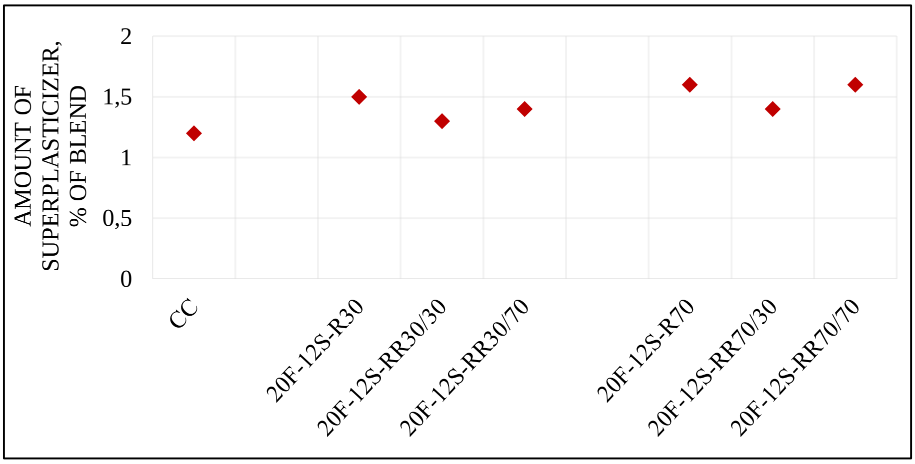
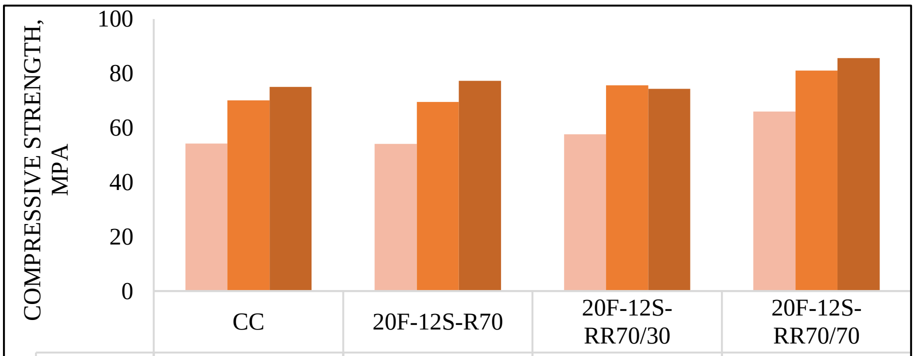


Figure 4. Superplasticizer amount of control concrete, fly ash-silica fume concrete with 30% recycled aggregate and fly ash-silica fume with 30% multi recycled aggregate concrete

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 5.). 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. However, another aspect influencing the multi recycled aggregate concrete improved compressive strength may be the usage of supplementary cementitious materials once more as a cement substitute in the second generation.



	CC	20F-12S-R70	20F-12S-RR70/30	20F-12S-RR70/70
28 days	54,2	54,1	57,7	66
90 days	70,1	69,5	75,7	81
180 days	75	77,3	74,3	85,6

Figure 5. Comparation of compressive strength of control concrete, fly ash-silica fume-recycled concrete mixtures and fly ash-silica fume-multi recycled aggregate concrete mixtures

My publications [3], [4], and [5] are part of this thesis group.

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**.**

4.3. 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 alternative) 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 (Sima Pro SW) was the program used to calculate the total environmental load. 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 second generation of 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/F. 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 6.). 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.

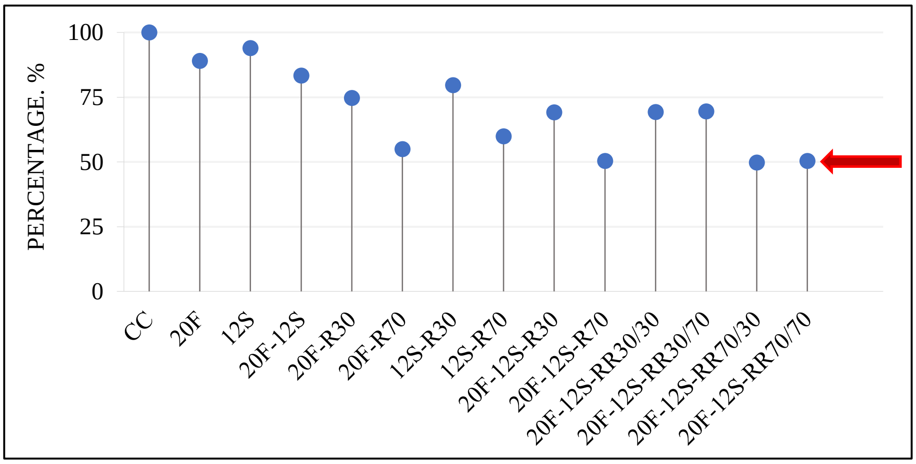


Figure 6. Land occupation midpoint category

III/B. Figure 7. 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.

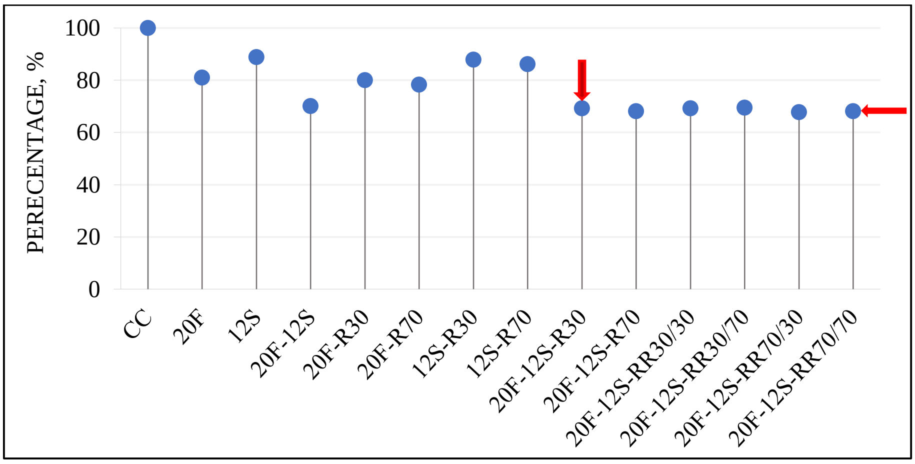


Figure 7. Global warming potential midpoint category results

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 8).

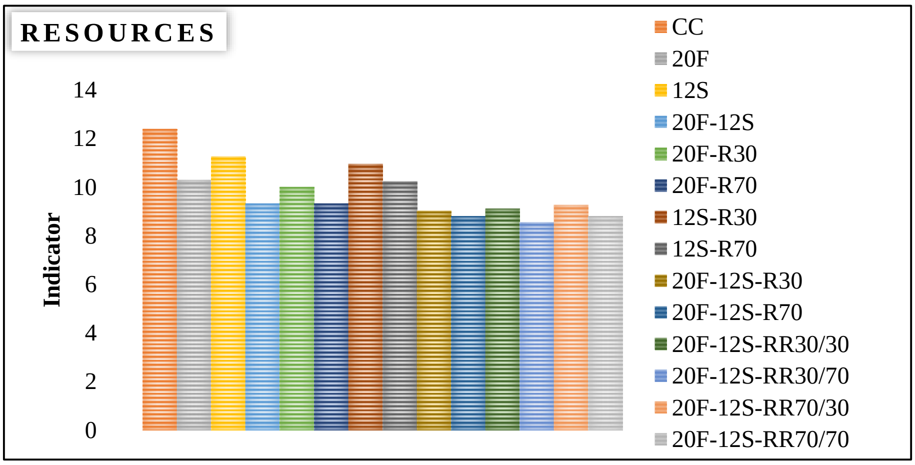


Figure 8. Resources values of fourteen examined mixtures

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 9).

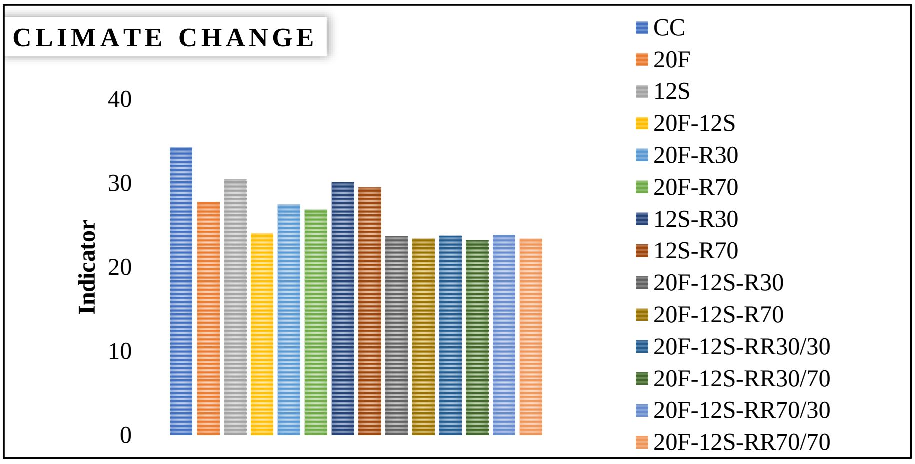


Figure 9. Climate change values of fourteen examined mixtures

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 10).

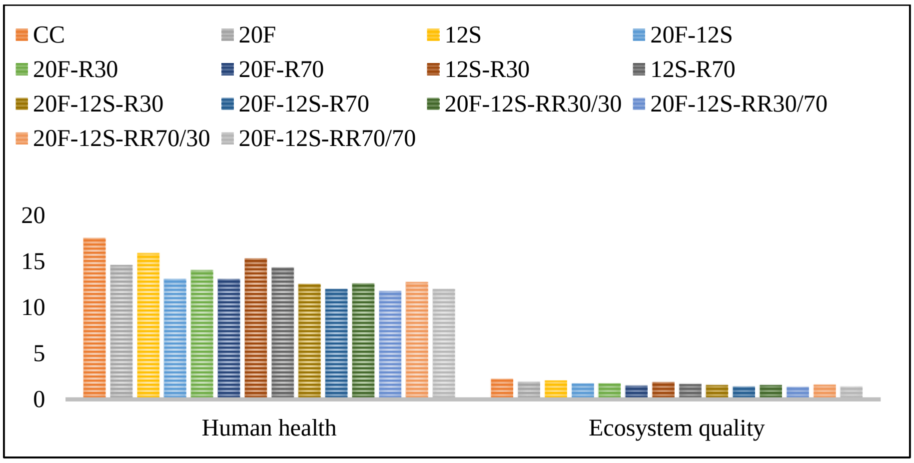


Figure 10. Human health and ecosystem quality values of fourteen examined mixtures

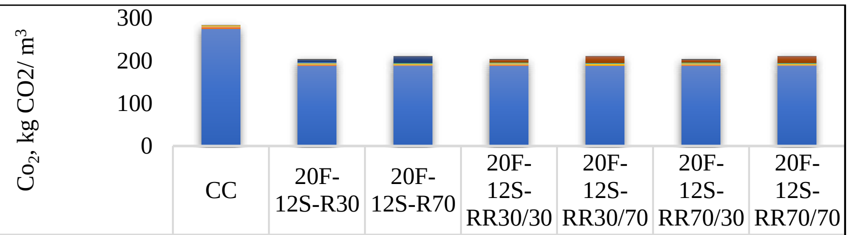
The environmental burden presented in this thesis was calculated using SimaPro 9.0 software, as previously mentioned. However, prior to using the software, the results were obtained through a different approach, implying the quantification of carbon dioxide emissions and material volumes. These results were already published in two impact factor journals and constitute a section of this thesis, organized into the following groups:

III/D. 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. (a) carbon dioxide values of all the materials used in concrete production can be summarized.

$$CO_{2,total} = \sum_{j=1}^{m}(W_i \times CO_{2,j}) \text{...Eq. (a)}$$

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 $kgCO_2/kg$.

III/E. 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 (Figure 11).



	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 11. CO_2 emission values of control concrete, recycled aggregate concrete (two replacement ratios of cement), multi recycled aggregate concrete

III/F. 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 12).

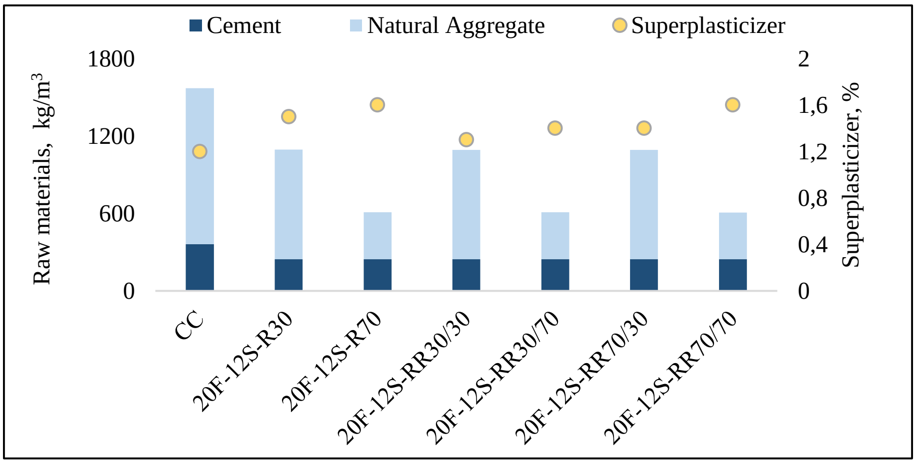


Figure 12. Volume of materials of control concrete, fly ash-silica fume-recycled concrete mixtures and fly ash-silica fume-multi recycled aggregate concrete mixtures

My publications [1], [2] and [3] are part of this thesis group.

4.4. Thesis IV

This thesis is related to the cost of the materials.

The reused 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.

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/20Km, 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 13).

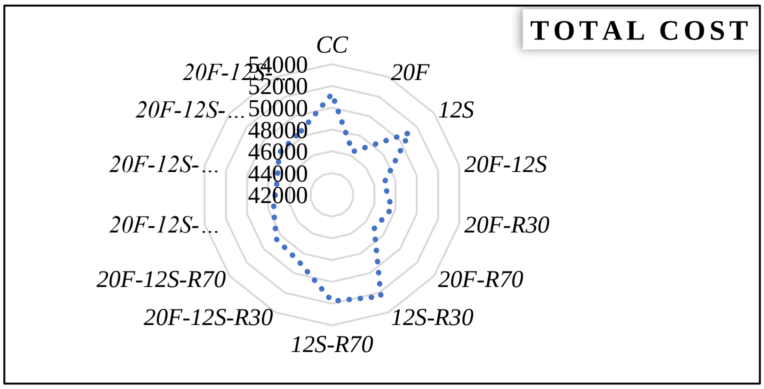


Figure 13. Cost of materials

4.5. Thesis V

This thesis is related to the multi criteria decision making. Which used in the first time with choosing alternatives from multi recycled aggregate concrete, which can be considered as a novelty approach in this dissertation. (My publications [1], [2] and [3] are part of this thesis group).

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 14).

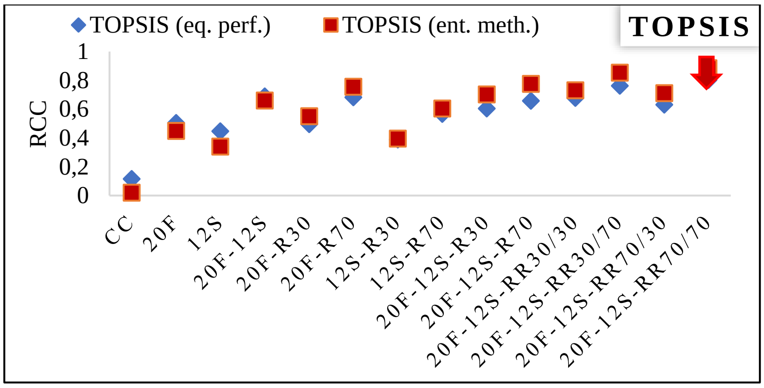


Figure 14. TOPSIS technique results

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 15).

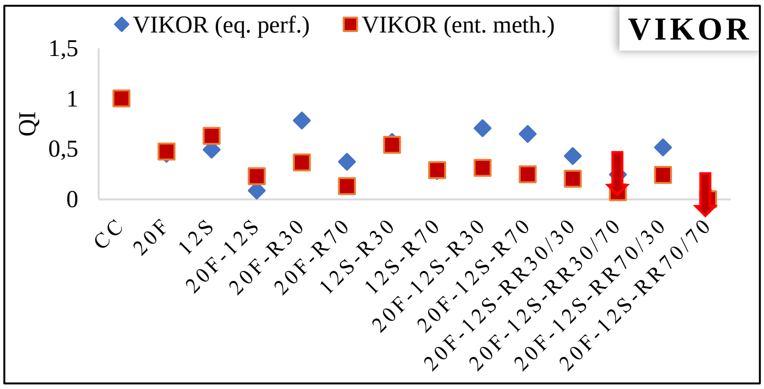


Figure 15. VIKOR technique results

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 16).

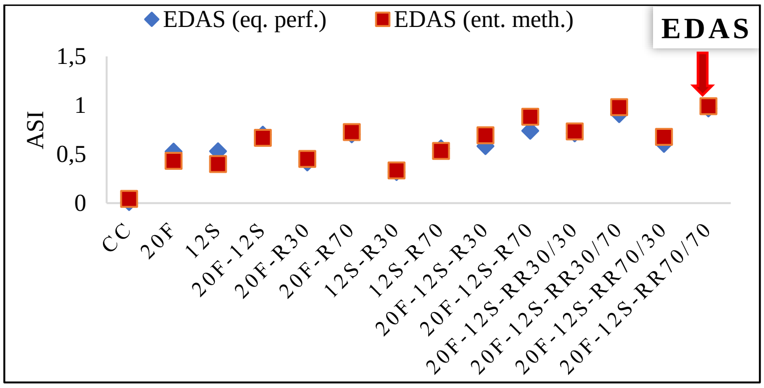


Figure 16. EDAS technique results

V/D. Once more, the results obtained through both WSM and WPM techniques align with those generated by TOPSIS, VIKOR, and EDAS. The highest SWSM values and SWPM 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 17).

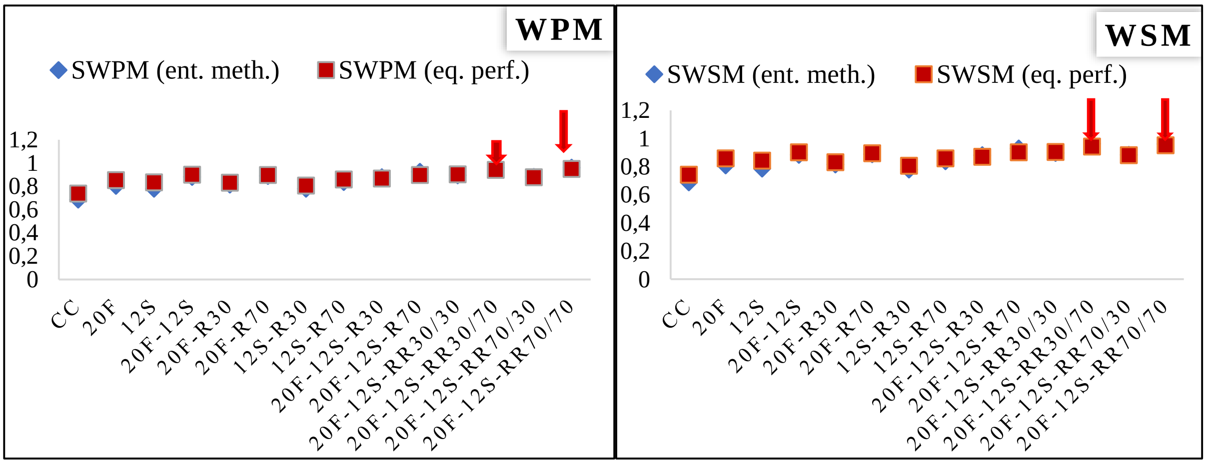


Figure 17. WPM and WSM techniques' results

5. CONCLOUSIONS

The following conclusions are given according to experimental and analytical parts:

1) Experimental conclusions

- Series II, in the case of 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 recycled concrete aggregate 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, high performance concrete was produced with a particular ratio of supplementary cementitious materials, which already boosted flexural strength.
- The water absorption values increased in all mixtures. Especially, when silica fume added to 70% recycled concrete aggregate, 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 fly ash's particles are superior to silica fume particles in filling the pores inside the concrete.
- Series III, the optimal replacement amount of cement by supplementary cementitious materials 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 control concrete), 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 control concrete 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 control concrete (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 life cycle assessment 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 control 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 (weighted equation) 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 control concrete 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.

In the second stage, and after calculating the life cycle assessment and cost of materials, the selection of the best concrete mixture, using 5 multi criteria decision making 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 Qi 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 ASi 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 control concrete or first-generation mixtures.
- The highest SWSM 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.

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