

VOL. 107, 2023



DOI: 10.3303/CET23107039

Guest Editors: Petar S. Varbanov, Bohong Wang, Petro Kapustenko Copyright © 2023, AIDIC Servizi S.r.l. ISBN 979-12-81206-07-6; ISSN 2283-9216

The Analysis of Lifecycle and Multi-Criteria Decision-Making for Three-Generation High-Strength Recycled Aggregate Concrete

Maysam Shmlls*, Dávid Bozsaky, Tamás Horváth

Department of Architecture and Building Construction, Faculty of Architecture, Civil Engineering and Transport Sciences, Széchenyi Istvan University, Gyor, Hungary maysamshmlls@gmail.com

The paper encompasses a comprehensive analysis of the life cycle of high-strength concrete (HSC), as well as a work on how HSC is made. Recycled concrete aggregate and multi-recycled concrete aggregate were utilized to partially replace natural aggregate (NA) in the production of the HSCs, while fly ash and silica fume were employed in place of cement. Firstly, the fresh state examination included a flow table test and compressive strength was tested at 28, 90, and 180 days. Moreover, the other aspects (cost and environmental life cycle) were considered to fulfill the sustainability of HSC, which might fit many applications in the building industry. The application of multi-criteria decision-making (MCDM) techniques can help in the development of sustainable concrete by identifying the best choice among multiple alternatives. Therefore, life cycle assessment (LCA) and MCDM technique, namely TOPSIS, were employed to select the best concrete mixture regardless of its generation. The output of the LCA is distributed as input for the TOPSIS technique. The results showed that the third generation of concrete, when compared to the first or second generation of recycled concrete, offers a more favorable alternative with acceptable technical performance, lower environmental impact, and less budget.

1. Introduction

The production of significant amounts of waste and the rapid expansion of resource utilization present substantial challenges to today's society. One industry that demands careful waste control and resource conservation is construction. The vast volume of construction debris and demolition rubble continues to expand drastically as a result of frequent building destruction. A building's construction, utilization, repair, and end-of-life phases must all consider environmental concerns to reduce its environmental impact (EI). However, combining LCA and MCDM techniques is essential for success in low EI structure building if more than one aspect needs to be considered. The many tasks, goals, and activities that make up construction processes and procedures require a variety of resources and considerations. The concrete production included cement, aggregate, sand, and water. However, cement consumption has topped 4400 x 10⁶ t, resulting in more than 5 % of global CO₂ emissions (CSI, 2017). The weight of concrete is composed mostly of aggregates, which make up about two / three of its weight (Rehman et al., 2020).

One of the most efficient strategies to reduce EI and CO₂ emissions from concrete buildings is to use alternative materials for its key components. For instance, replacing NA and/or cement with recycled coarse aggregate/multi recycled coarse aggregate and additional cementitious materials. The effects of replacing cement with up to 30 % fly ash in recycled aggregate concrete (RAC) were examined by Sunayana et al. (2017). The results demonstrated that 20 % fly ash increased the compressive strength of RAC when compared to traditional concrete or RAC+ 30 % fly ash. According to Thilakarathna et al. (2020), using fly ash and silica fume in place of cement results in a considerable reduction in CO₂ emissions. Furthermore, using recycled coarse aggregate instead of NA in just one mixture will result in an additional doubling decrease in CO₂ emissions. But whether RAC comes from ready-made concrete or real concrete, it will eventually reach the end of its useful life. Examples include the worldwide rejected precast concrete made with recycled coarse aggregate or RAC structures that were destroyed in wars or unexpected events (Barroqueiro et al., 2019). A huge amount of waste

Paper Received: 15 April 2023; Revised: 29 June 2023; Accepted: 24 October 2023

Please cite this article as: Shmlls M., Bozsaky D., Horváth T., 2023, The Analysis of Lifecycle and Multi-Criteria Decision-Making for Three-Generation High-Strength Recycled Aggregate Concrete, Chemical Engineering Transactions, 107, 229-234 DOI:10.3303/CET23107039

230

made from recently recycled materials will be produced while this is happening, and if it is crushed, multi recycled coarse aggregate will be the result. The application of multi recycled coarse aggregate will develop in new MRAC. Huda and Alam, (2014) studied the mechanical properties of multi recycled aggregate concrete (MRAC) in different ages with 20 % fly ash, the results showed that although compressive strength was claimed to be lowered by up to 100 % substitution, MRAC may perform at least 25 % higher than the required strength. In general, when energy-related issues and the effects of global warming become more complex, applying MCDM techniques can provide solutions. The replacement ranges for recycled coarse aggregate and multi recycled coarse aggregate were found to be 30 % and 70 % of NA by mass, respectively, based on a literature study. Silica fume and fly ash, which were used to substitute cement, had respective mass ratios of 12 % and 20 %. The authors of this study developed a novel strategy (TOPSIS, technique for order performance by similarity to ideal solution) to select the best concrete mixture among 14 alternatives, three generations, based on high performance, EI, and cost to address all the aspects. They contained not only recycled coarse aggregate but also varying amounts of multi recycled coarse aggregate as a replacement for NA, fly ash, and silica fume as a replacement for cement. Various conditions (cost, strength, and EI) were taken into account while using the previously mentioned technique for various concrete mixtures for that reason. Finally, the testing of many applications seeks to show the reliability of the recommended method in any situation and application within the upcoming building sector.

2. Methodology

2.1 Materials and paper stages

The present research was conducted in four stages. The technological, environmental, and economic perspectives are given primacy throughout the four stages. Three generations of concrete were prepared and tested in the first stage for both fresh and compressive strength. After creating the first generation of concrete, recycled coarse aggregate-tested rubble was mixed in second-generation concrete in two replacement ratios, 30 % and 70 %, in different ratios to create RAC. In contrast, the third generation was produced by using RAC rubble (two replacement ratios, 30 % and 70 %) that were left over from the previous generations' testing as the multi recycled coarse aggregate and generating MRAC in different ratios. The cement used was CEM I 52.5 N, which has a specific gravity of 3.130 g/cm³. Additionally, fly ash and silica fume were utilized in place of cement and have specific gravities of 2.19 and 2.49 g/cm³, respectively. However, for the manufacturing of soft plastic concrete, a superplasticizer known as Sika ViscoCrete-5-500 is used. The superplasticizer had a 1.069 g/cm³ specific gravity. The proportions of each concrete mixture are shown in Table 1.

Mixture name	Classification	Portland cement, kg/m ³	Sand, kg/m³	Aggregate, kg/m³	Recycled aggregate, kg/m³	Multi recycled aggregate, kg/m ³	Superplasticizer, kg/m³	Water, kg/m³	Fly ash, kg/m³	Silica fume, kg/m³
SC	_	360	687	1208	0	-	4.32	145	0	0
FA-SC	j.	288	687	1208	0	-	3.60	145	72	0
S-SC		317	687	1208	0	-	4.32	145	0	43
FA-S-SC	1 st	245	687	1208	0	-	3.96	145	72	43
FA-R30		288	687	847	361	-	4.68	145	72	0
FA-R70		288	687	361	847	-	4.86	145	72	0
S-R30	_	317	687	847	363	-	5.40	145	0	43
S-R70	ţ.	317	687	365	845	-	5.62	145	0	43
FA-S-R30		245	687	848	361	-	5.40	145	72	43
FA-S-R70		245	687	365	848	-	5.76	145	72	43
FA-S-R30-R30		245	687	847	-	362	4.68	145	72	43
FA-S-R30-R70	ţ.	245	687	363	-	846	5.04	145	72	43
FA-S-R70-R30	era	245	687	846	-	363	5.04	145	72	43
FA-S-R70-R70	P da	245	687	361	-	846	5.76	145	72	43

Whereas (FA) refers to fly ash, (SF) refers to silica fume, (R-) refers to the recycled aggregate percentage %, (R-R-) refers to the multi recycled coarse aggregate percentage %.

The tests were carried out in compliance with the relevant Hungarian standards (MSZ EN 12390-3, 2019), which are comparable to European specifications. The flow table test (MSZ EN 12350-5, 2019) was initially used to evaluate the workability of each combination. Twelve cube-shaped samples, each 150 x 150 x 150 mm in size, were used for assessing compressive strength. Figure 1 depicts the sieve analysis of all the aggregate used in concrete.



Figure 1: Sieve analysis of all aggregate used in concrete

One of the boundaries that needs to be examined during the second stage (LCA), is the manufacturing of individual concrete components for two generations. Since the manufacturing processes are the same for each material, generation, and consumption stage, processing concrete mixes was avoided in the study. Boundary specifications are displayed in Figure 2. The data gathered was altered to correspond with the functional unit and loaded into Simapro LCA software 9.0. Mixing ratios in Table 3 were utilized to compute the quantities of each component.



Figure 2: Boundary condition of designed mixtures

The basis for the environmental advantages evaluated in the current work, however, is the avoided creation of NA in the second and third generations of planned concrete. All generations of planned concrete also take into account the partial substitution of fly ash and silica fume for Portland cement in addition to the substitution of crushed the final stages of life concrete for NA. Regulations related to European standards for LCA analysis (ISO 14040, 2006) exclude the prevention of landfilling old concrete as advantageous. Our manual aggregate crushing was in the lab, however, the assumption of triturated concrete waste was 0.015 MJ/kg. Simapro LCA software 9.0 was used to include the data collected, modify it for the functional unit, and use the mixture proportions shown in Table 1 as stated in the software. The Impact 2002 + approach (version 3.5) in Simapro 9.0 was selected for the present research in order to analyze both midpoint impact categories and endpoint indicators and permit a single score for MCDM.

Depending on the PSI of the cement, the price per cubic meter for transport and pouring concrete ranges from \$ 118.9 to \$ 146.9 generally (Home Guide, 2022). However, it would be prudent to promote the use of multi recycled coarse aggregate if its direct and transportation costs are lower than those of NA and its production costs are lower than those of ordinary concrete. As a result, this research concentrates on evaluating the direct costs of three aggregation types. As recycled coarse aggregate and multi recycled coarse aggregate were manually crushed at the university lab, transportation was not involved. The cost of each material is shown in Table 2.

Table 2. The price of each single material.										
Component	Cement	Silica fume	Fly ash	Sand	NA	Superplasticizer	RCA			
Price (Euro/kg)	0.183	0.454	0.227	0.01	0.01	4.83	0.004			

Finally, six criteria were used in the last phase to assess each concrete mixture: human health, ecosystem quality, climate, resources, material price, and strength of concrete across all mixtures. Two methods were used to weight the used criteria (Equal performance and Entropy method), the evaluation of the weight function was conducted on the assumption that all criteria were significant at the same scale and each criterion was given equal weight. TOPSIS presupposes that the chosen option is as far away from the worst-case scenario as feasible while being as near to the optimistic ideal solution as possible. TOPSIS starts with the formation of a decision matrix, which is then normalized to create a normalized matrix with non-dimensional identities that bring together the alternatives and the criteria (Shmlls et al., 2022). The alternatives are idealized by determining the best (A+) and worst (A-) ideal solutions that prioritize all of these criteria. The following stage is to calculate the positive (D+) and negative (D-) separation matrices, which help to determine the relative closeness coefficient (RCC) for each choice. The greatest RCC value is the best alternative, and RCC decides which options are better and which are worse. Figure 3 shows the TOPSIS method's workflow.



Figure 3: TOPSIS technique

3. Results and Discussion

3.1 Compressive strength

The major focus was on reaching the target strength of 70-90 MPa and guaranteeing the highest allowed usage of waste/recycled materials by estimating the material proportions. High-strength concrete was classified as having a compressive strength of 55 MPa or more (ACI Committee, 1997). However, the proportions of superplasticizer were modified to reach the same level of workability in all blends. The slump flow table test, which aimed for a range of 420 to 480 mm, was used to establish the workability class. Physical examinations, such as the slump flow table test, were used to confirm the mixes' viability. According to the results of this investigation, silica fume-containing mixtures often required more superplasticizer than those that simply included fly ash. As expected, the inclusion of recycled coarse aggregate resulted in reduced workability of the concrete and increased water absorption (Padmini et al., 2009). However, the use of MRAC, which is the third generation of recycling, required a lower amount of superplasticizer compared to RAC mixtures, aligning with the findings of (Abed et al., 2020), Figure 4 clearly indicates that the addition of recycled coarse aggregate had a minimal impact on the compressive strength. Specifically, the FA-S-R30 mixture exhibited a strength comparable to SC. The higher strength observed in the recycled mixtures can be attributed to their increased specific roughness, as mentioned in (Abed et al., 2020). However, adding silica fume to the RAC increased its strength more than adding fly ash, demonstrating the silica fume particles' remarkable capacity to withstand compression. Furthermore, the compressive strength of FA-S-R30-R30 was 7.3 %, 14.2 %, and 8.78 % higher than FA-S-R30 at 28, 90, and 180 days, respectively. Additionally, Figure 4 demonstrates that a higher dosage of multi recycled coarse aggregate also improved the compressive strength of the concrete when compared to RAC. For example, at the same test ages, the compressive strength of FA-S-R70R70 was 11 %, 16.55 %, and 22 % higher than FA-S-R70.

232



Figure 4: Compressive strength findings

3.2. Finding of LCA and price of materials

The findings indicate that climate change, followed by detrimental effects on human health and extraction of resources, is mostly responsible for the environmental burden. The quality of the ecology has just a slight influence. According to the results of (Abed et al., 2022a), the ecological burden of the SC mixture is significantly greater than that of the third or second generation. emphasizing the advantages of using recycled coarse aggregate or multi recycled coarse aggregate. They used in this investigation were physically crushed in the laboratory, which prevented the need for transportation. The same findings were obtained by (Singh et al., 2023), who discovered that the high EI lowered when local waste materials were used. In comparison to SC, using recycled or multi coarse aggregate with supplemental components (fly ash and/or silica fume) is much more effective at improving sustainability performance. These results agreed with those in (Xing et al., 2022). Consequently, the third generation's mixtures are the cheapest and least expensive, with savings of 9.34 %, 12.62 %, 8.13 %, and 9.37 %, respectively, for FA-S-R30-R30, FA-S-R30-R70, FA-S-R70-R30, and FA-S-R70-R70, when compared to SC. The findings of the LCA and the cost of materials are shown in Table 3 (Shmlls, 2023).

3.3. Finding of TOPSIS

The weighted decision matrix for each of the fourteen alternative concrete mixtures with different proportions, as determined by the TOPSIS technique, is shown in Table 4 (Shmlls, 2023). Equal performance and the entropy approach were used to establish the ideal weights for each criterion prior to creating the choice matrix. These techniques are frequently used in decision-making to evaluate the dispersion of values. Figure 5 illustrates that, according to the specified criteria, the FA-S-R70-R70 combination was judged to be the best option among the alternatives and had the highest RCC values, while the SC mixture had the lowest values. The third-generation mixtures had the highest RCC values overall. This shows how using multi recycled coarse aggregate while taking into account environmental impact, economics, and technical requirements has positive consequences. Additionally, the entropy approach revealed that the third generation had the top five highest RCC values, demonstrating the relevance of this type of aggregate in the building and construction industries. This finding agreed with those of (Abed et al., 2022b).



Figure 5: TOPSIS selection findings

4. Conclusion

Recycling cycles offer a long-term, cost-effective option for all nations, which can have an impact on the environment and the global economy. In this paper, a complete LCA of three generations of recycling concrete was done, considering the benefits of appropriate amounts of fly ash and silica fume. A TOPSIS was a novel technique used to find the optimum alternative of 14 HSC's concrete mixtures produced in three generations that best satisfies the input requirements while considering technical performance, human health, ecosystem quality, climate change, resources, and prices. However, Compressive strength, the measured qualities in the first generation, only slightly dropped but still maintained a reasonable level. MRAC, on the other hand, maintained mechanical compatibility with SC even after 180 days. Secondly, LCA, the combined effect of replacing cement and NA, led to an average savings of 20 % when using recycled materials in the second and third generations. Additionally, several advantages are observed in terms of reducing the total EI. Finally, TOPSIS concluded that the third generation of recycled concrete is a more advantageous choice, providing adequate technical performance while demonstrating decreased EI and costs compared to the first generation or the second generation of concrete.

Acknowledgments

Huge gratitude to the laboratory staff and the aforementioned authors from Széchenyi István University.

References

- Abed M., Fort J., Rashid K., 2022a, Multicriterial life cycle assessment of eco-efficient self-compacting concrete modified by waste perlite powder and/or recycled concrete aggregate, Construction and Building Materials, 348, 128696.
- Abed M., Rashid K., Rehman M.U., Ju M., 2022b, Performance keys on self-compacting concrete using recycled aggregate with fly ash by multi-criteria analysis, Journal of Cleaner Production, 378, 134398.
- Abed M., Nemes R., Tayeh B.A., 2020, Properties of self-compacting high-strength concrete containing multiple use of recycled aggregate, Journal of King Saud University Engineering Sciences, 32,2,108-114.
- ACI Committee, 1997, State-of-the-Art Report on High-Strength Concrete, Am Concrete Institute, 92, 55. Barroqueiro T., da Silva P. R., de Brito J. D., 2019, Fresh-State and Mechanical Properties of High-Performance
- Self-Compacting Concrete with Recycled Aggregates from the Precast Industry, Materials, 12(21), 3565. CSI. 2017. CO₂ and Climate Protection. Cement Sustainability Initiative.
- Home Guide, 2022, How Much Does It Cost to Deliver Concrete Per Yard? https://homeguide.com/costs/concrete-prices, accessed 8.06.2022.
- Huda S.B., Alam M.S., 2014, Mechanical behavior of three generations of 100% repeated recycled coarse aggregate concrete, Construction and Building Material, 65, 574-582.
- ISO 14040, 2006, Environmental management, Life cycle assessment, Principles and framework.
- MSZ EN 12350-5, 2019, Testing Fresh Concrete. Part 5: Flow Table Test Hungarian Standard Committee.
- MSZ EN 12390-3,2019, Testing Hardened Concrete. Part 3: Compressive Strength of Test Specimen Hungarian Standard Committee.
- Padmini A.K., Ramamurthy K., Mathews M.S., 2009, Influence of parent concrete on the properties of recycled aggregate concrete, Construction and Building Materials Journal, 23(2), 829-836.
- Rehman M.U., Rashid K., Haq E.U., Hussain M., Shehzad N., 2020, Physico-mechanical performance and durability of artificial lightweight aggregates synthesized by cementing and geopolymerization, Construction and Building Materials, 232, 117290.
- Shmlls M., Abed M.A., Horvath T., Bozsaky D., 2022, Sustainability framework of recycled aggregate concrete produced with supplementary cementitious materials, Ain Shams Engineering Journal, 14(8), 102036.
- Shmlls M., 2023, Additional material file, Research gate, https://dx.doi.org/10.13140/RG.2.2.12992.10246
- Singh R.P., Vanapalli K.R., Cheela V.R.S., Sharma H.B., Mohanty B., 2023, Fly ash, GGBS, and silica fume based geopolymer concrete with recycled aggregates: Properties and environmental impacts, Construction and Building Materials, 378, 131168.
- Sunayana S., Barai S.V., 2017, Recycled aggregate concrete incorporating fly ash: comparative study on particle packing and conventional method, Construction and Building Materials, 156, 376–386.
- Thilakarathna P.S.M., Seo S., Baduge K.K.S., Lee H., Mendis P., Foliente G., 2020, Embodied carbon analysis and benchmarking emissions of high and ultra-high strength concrete using machine learning algorithms, Journal of Cleaner Production, 262, 121281.
- Xing W., Tam V.W., Le K.N., Hao J.L., Wang J., 2022, Life cycle assessment of recycled aggregate concrete on its environmental impacts: A critical review, Construction and Building Materials, 317, 125950.

234