Strategic Formulation of Ultra-High Performance Concrete Emphasizing Compressive Strength Analysis and Sustainability Evaluation

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Abstract. The rapid use of Ultra-High Performance Concrete (UHPC) has an aggressive environmental impact. Although UHPC has great performance in strength and durability, it has some limitations in achieving sustainability. The exploration of materials that balance environmental, economic, and social factors becomes significant as construction methods progress toward sustainability. There have been many studies focusing on the sustainable approach of UHPC materials. Many industrial wastes contribute as supplementary cementitious material (SCM) to achieve ultra-high strength in concrete. By using them as a substitute for cement, it can reduce environmental impact as well as the cost of production. This paper identifies the effects of the substitution of cement with different industrial wastes on UHPC properties, with a comprehensive assessment of sustainability in terms of environmental assessment of low carbon emission, economic consideration of overall cost efficiency, and social engagement without compromising its mechanical strength. Through a systematic evaluation process, a literature review was conducted from previous research publications by collecting data on different substitution elements and identifying different parameters (strength, carbon emission, and cost). The results indicated that the substitution of the percentage of cement led to an increase in mechanical properties with the reduction of carbon emission and cost of production. Moreover, Lime powder (LP) emerges as the optimal substitution for UHPC, as identified through the compressive strength and sustainability assessment among the selected SCMs. So, The use of LP as a substitution for cement can reduce environmental impact without compromising the strength of UHPC. Furthermore, the LP-based UHPC can lower production costs, which indicates its imminent practical application.

Keywords: Ultra-high performance concrete, economic assessment, supplementary cementitious materials, sustainability, low carbon emission

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1 Introduction

A crucial development in concrete technology is Ultra-High Performance Concrete (UHPC), also known as Reactive Powder Concrete (RPC). UHPC has outstanding mechanical and durability attributes, such as a compressive strength greater than 150 MPa and outstanding tensile strength, toughness, and ductility. Furthermore, its exceptional water and chloride permeability resistance provides outstanding durability [2].

Unquestionably, UHPC can revolutionize the construction industry by enabling the building of structures that defy conventional design constraints. However, the challenges are mostly caused by the expensive and constrained supply of materials, the lack of comprehensive design standards, and the complex manufacturing and curing process. UHPC's need for a significant amount of Portland cement, which has negative environmental effects, is one of its shortcomings. One viable approach to solve these issues is to reduce the amount of cement in UHPC by replacing some percentage of the cement with supplementary cementitious materials (SCMs)[5]. From the previous studies, it was found that Metakaolin (MK) and industrial wastes (fly ash, silica fume, and slag) are used to produce low carbon emission UHPC in the ternary binder system using only 35–65% cement without sacrificing mechanical performance [1]. With a low cement content of 560 kg/m^3 and a 28-day compressive strength of 153 MPa, UHPC can lower embedded CO_2 emissions by 47% and save costs by adding the recommended optimal limestone powder concentration of 50% volume [6]. The mechanical performance, durability analysis, and environmental effect of UHPC of cement-based materials have demonstrated higher performance when using rice husk ash (RHA) as a mineral additive [10]. At the 90-day curing age, a mixture containing 15% MK had the highest compressive, flexural, and splitting strengths, increasing by 3.16%, 4.57%, and 5.37%, respectively, in comparison to the control mix [1]. Additionally, UHPC's potential durability performance is enhanced by adding metakaolin up to 20% into concrete [11]. In the process of making UHPC, quarry stone powder is used in place of 22.2% to 44.4% cement to reduce environmental impact [7]. Furthermore, Low carbon emission UHPC can be prepared with only 20–25% cement in the entire binder system by using multi-scale reactive mineral powders, such as fly ash, slag, silica fume, and nano-SiO_2 [12].

This paper offers an overview of the emergence of UHPC and considers cement-like substances made from industrial waste as potential replacements for its expensive binder. It takes into account that concrete made using these SCMs might not meet conventional UHPC's exact quality standards. In the context of UHPC, the paper explores the effects of these waste materials on workability, compressive strength, flexural strength, split tensile strength, and their environmental effects. The paper also introduces a strategy for determining each waste material's suitability, placing a spotlight on a thorough assessment of sustainability. This evaluation takes into account social engagement, economic factors regarding overall cost efficiency, and ecological considerations with a focus on low carbon emissions.

2 Methodology

For this comprehensive assessment, Searches across multiple databases, including Web of Science, Scopus, and Google Scholar, were conducted to gather research on UHPC incorporating waste material (Fig. 1). Due to its extensive usage and accessibility of research papers, Google Scholar was the main database searched. To conduct the research, a list of relevant search terms was compiled, such as low carbon emissions, sustainability, industrial wastes, compressive strength, ultra-high-performance concrete, and supplementary cementitious materials. Only articles published in English were included in the search. Further refining, only research relevant to industrial wastes or supplemental cementitious materials (SCMs) in ultra-high-performance concrete (UHPC) was chosen, resulting in a selection of more than 100 papers. Then, the abstract was selected and screened to ascertain its applicability to the study.

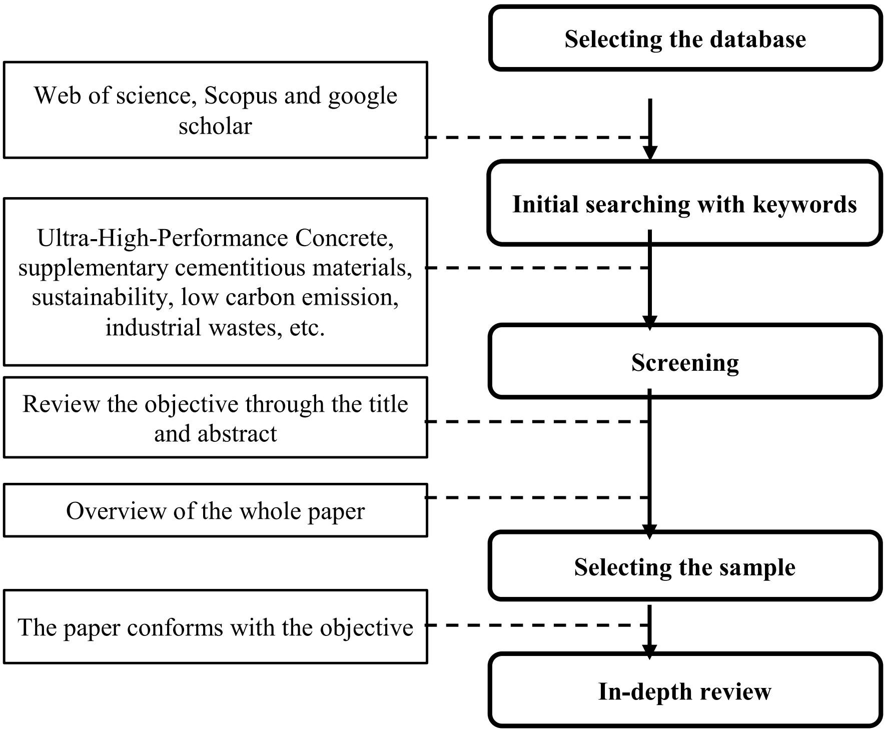

Fig. 1. The five-step workflow for reviewing the literature

A study regarding different SCMs used as replacements for cement to produce sustainable UHPC in terms of environmental impact, cost analysis, and social acceptability without compromising its compressive strength. After screening and choosing 10 articles, analysis and review were conducted by taking into account the different kinds of waste from industries known as SCMs that were utilized in UHPC. Furthermore, all the chosen articles that were examined were part of the peer-reviewed literature and were discussed in the final set.

Tables 1 and 2 present data encapsulating the physical and chemical properties sourced from various scholarly papers on UHPC where cement is substituted with SCMs. A thorough review of these tables reveals significant similarities between the physical and chemical compositions of SCMs and traditional cement.

Table 1. Physical properties

SCMs	Specific Gravity	Particle size (μm)	Reference
GGBS	2.88	0.5-800	[1]
FA	2.29	0.1-250	[1]
MK	2.57	0.1-850	[1]
GGP	2.5	0.01-1000	[3]
LS	2.46	0.1-280	[13]
LP	2.7	20	[6]
CSS	3.65	22.25	[8]
BP	2.8	22	[14, 15]

Table 3 shows the mix proportions of various UHPC mixes. The mixes are derived from the mix proportion table of various papers in which cement is replaced to achieve the best mechanical properties and sustainability criteria. In those tables, cement has been replaced at various percentages, but we have chosen the optimum replacements with the highest compressive strength. A concise overview of the optimal mixes is presented in Table 4, establishing the relationship between the optimum replacement percentages and the superior attributes defining these UHPC blends with SCMs.

Compressive strength is the primary standard for evaluating the resistance of concrete under high stress in many structural designs. The comparative results of the compressive strengths at 28 days of several UHPC mixtures in varying levels of SCM addition are displayed in Fig. 2. The main factors that influence concrete's compressive strength are the amount of cement, aggregate types, and the SCM used.

Table 2. Chemical properties

SCMs	CaO	SiO_2	Al_2O_3	Fe_2O_3	SO_3	Na_2O	K_2O	MgO	P_2O_5	MnO	TiO_2	L.O.I	Reference
GGBS	45.88	30.38	9.05	3.82	1.78	0.52	0.31	5.39	-	-	-	1.4	[1]
FA	7.5	46.44	38.01	3.12	0.69	0.330	0.88	0.23	0.76	0.11	1.17	-	[1]
MK	0.78	53.3	30.0	4.33	-	0.26	0.62	0.16	-	-	-	0.98	[1]
GGP	2.31	83.21	2.02	.1.76	-	4.72	3.39	0.54	-	-	-	-	[3]
LS	10.11	53.22	17.11	1.48	7.15	.33	0.53	0.41	-	-	-	-	[4]
LP	71.39	8.2	1.53	0.96	-	-	-	1.27		16.18	-	-	[6]
BP	9.57	43.74	13.80	16.05	0.08	2.84	0.91	4.77	0.49	-	3.78	3.87	[7]
CSS	41.55	11.47	2.24	31.35	0.03			3.78	1.30	4.78	1.56	0.72	[8]
PS	46.73	42.77	3.34	0.51	0.6	0.25	0.64	2.27	1.81		0.14	0.47	[9]

The increasing recognition of global warming has prompted researchers to investigate substitute binders to minimize reliance on cement as the principal binder in concrete, as cement produces 10% of worldwide carbon emissions [16]. This paper compares nine different SCMs, which will undoubtedly lower concrete's overall embodied CO_2 emissions. For this, it used the eco-strength efficiency of concrete, a metric applied to the environmental impact assessment for evaluation. It is called the CO_2 intensity [17], and it is the amount of CO_2 emissions produced per unit of performance. It was determined using formula (1) & (2).

$$C_i = CO_2/C_s \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (1)$$

$$E_f = (E\text{-}Energy)/f_c \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (2)$$

Table 3. Mix proportion of UHPC

SCMs	SCMs quan-tity	Cement	Sand	SP	Water	QP	FA	SF	Steel Fiber	Ref
GGBS	450	450	1271	24	166	180	-	135	156	[1]
FA	270	630	1271	24	166	180	-	135	156	[1]
MK	225	675	1271	24	166	180	-	135	156	[1]
BP	320	400	970	25	182	-	280	140	-	[7]
CSS	155.5	786.3	1316.2		177.2					[8]
PS	300	450	990	34	182		200	144		[9]
LS	112	896	1013		202			112		[4]
LP	407.5	664.3	914	15.2	240.5					[6]
GGP	70.1	631.4	820.8	17.5	164.2	259.6			156	[3]

Where f_c is the compressive strength for 28 days, C_i is the eco-strength efficiency, or the intensity of CO_2, E_f is the embodied energy parameter, CO_2 is the embodied carbon dioxide emissions, and E-energy is embodied energy of concrete by the concrete mixes, as calculated using Table 5 and Table 6. The lower values of E_f and C_i mean better sustainability.

Table 4. Literature on the use of different waste as cement replacement in UHPC

SCMs	Replace-ment	Optimum replace-ment	w/b ratio	Other materials	Cement type	SP kg/m^3	Reference
GGBS	30-50%	50%	0.16	-	PC	24	[1]
FA	20-30%	30%	0.16	-	PC	24	[1]
MK	15-25%	25%	0.16	-	PC	24	[1]
GGP	5%, 10%, 15%, 20% 25%	10%	0.22	-	OPC (grade 42.5)	17.5	[3]
LS	5%, 10%, 15%	10%	0.18	SF	PC (P.I52.5)	18.8	[4]
LP	20%-80%	40%	0.15		CEM I		[6]
BP	22%, 44%	44%	0.15	SF, FA	PC	25	[7]
CSS	15-45%, 60%	15%	0.16		CEM I 52.5 R	27.8	[8]
PS	10-50%	40%	0.3-0.6	SF, FA, PCE	CEM I		[9]

3 Results and Discussion

3.1 Assessment of Compressive Strength

The study shows the compressive strength of UHPC mixtures of replacement with MK, GGBS, and FA at different percentages, and 50% GGBS was the optimum mixture [1]. Another study shows the compressive strength with GGP, where the optimum was 10% [3]; with LS, the optimum was 10% [4]; with CSS, the optimum was 15% [8]; with PS, the optimum was 40% [9]; with BP, the optimum was 44% [7], and with LP, the optimum was 40% [6].

The highest compressive strength achieved was 162 MPa in 15% CSS. The compressive strengths showed a value of 158 MPa for samples LP (40%) and GGP (10%). In comparison with 15% CSS, the compressive strength is reduced by 44.44%, 33.33%, 25.93%, 2.47%, 8.64%, 2.47%, 30.25%, and 21.3% for GGBS, FA, MK, RH, LS, LP, BP and PS, respectively. Without SCM, other components of the mixtures were not at a constant rate. Silica fume, fly ash, and admixtures were added to some of the mixtures.

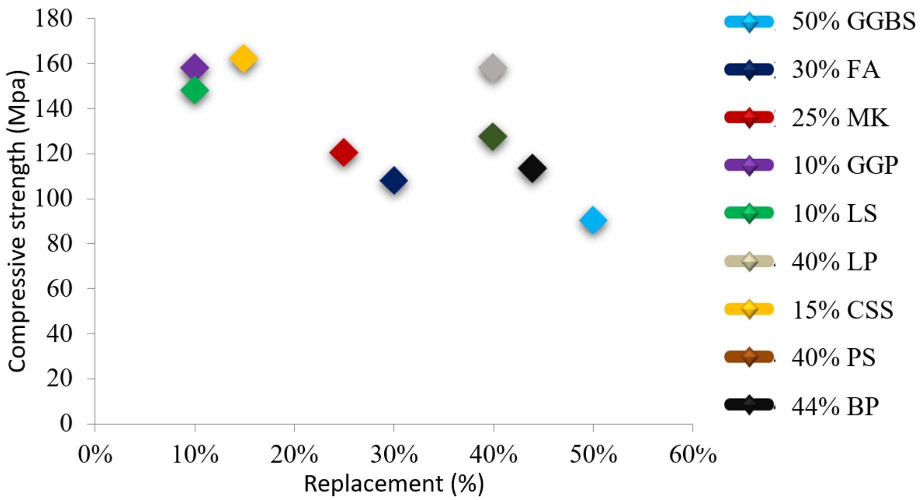

Fig. 2. Effect of cement replacement on compressive strength

3.2 Sustainability Assessment

Environmental Impact. According to Table 6 amount all the mixes BP (3.76 kg-CO_2/m^3/MPa & 24.38 MJ/m^3/MPa), CSS (4.24 kg-CO_2/m^3/MPa & 24.79 MJ/m^3/MPa), PS (3.61 kg-CO_2/m^3/MPa & 25.31 MJ/m^3/MPa) and, LP (4.14 kg-CO_2/m^3/MPa & 25.75 MJ/m^3/MPa) have the lowest efficiency and embodied energy parameter respectively. Fig. 3 illustrates a relationship between compressive strength and eco-strength efficiency (C_i) of different mixes where lower values of Ci indicate high compressive strength and low CO_2 emission into the environment. Similarly, a lower value of E_f coupled with high compressive strength refers to reduced environmental impact (Fig. 4). Furthermore, lower values of both E_f and C_i denote enhanced sustainability. However, the maximum compressive strength is observed for CSS (162MPa), LP (158MPa), PS (127.5MPa), and BP (113MPa). So, in terms of these parameters, CSS and LP have gained priority. On the contrary, BP and PS have better eco-strength efficiency but significantly decreased compressive strength compared to the previous two mixes.

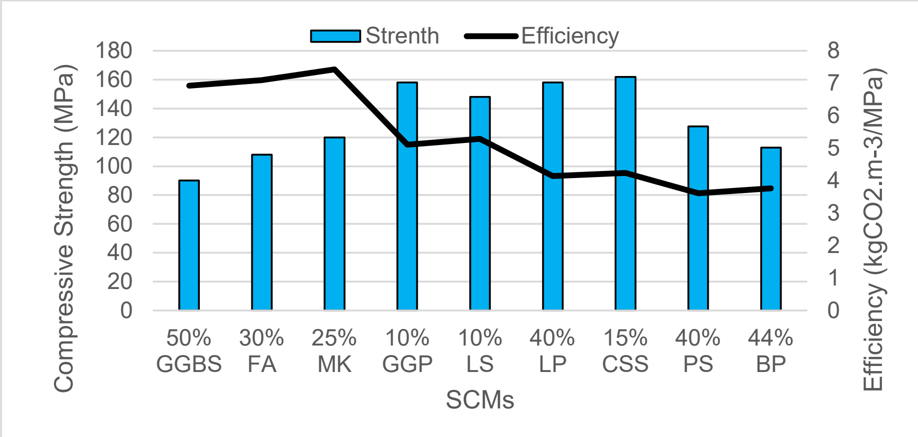

Fig. 3. Eco-strength efficiency with respect to the compressive strength

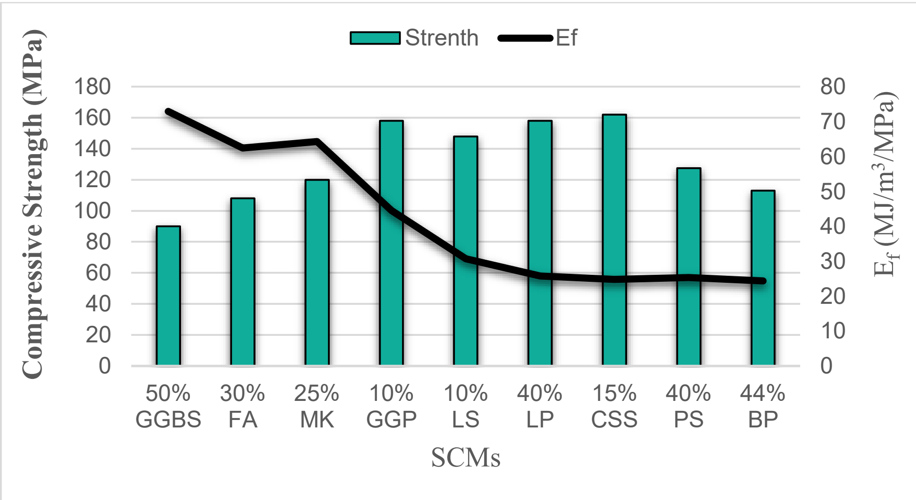

Fig. 4. E_f (MJ/m^3/MPa) with respect to the compressive strength

Cost–Benefit Assessment. From Table 6, it was identified that the production cost of different mixes of UHPC. Among the previous four mixes described in the environmental impact analysis, PS and BP have higher production costs, although their eco-strength efficiency is lesser. On the other hand, LP and CSS have lower production costs compared to them and have high compressive strength and low eco-strength efficiency. So, LP and CSS are the mixes that provide sustainable UHPC production in terms of environmental impact and cost assessment. Between these two, LP must be given priority in terms of low environmental impact and low production cost compared to CSS, as they have almost similar compressive strength.

Table 5. Material embodied energy and cost at the production stage

SCMs	E-CO_2 (kg/kg)	E. energy (MJ/kg)	Production Cost (tk/kg)	Reference
Cement	0.83	4.8	11	[1]
SF	0.0140	0.1	34.75	[1]
Sand	0.001	0.022	2.23	[1]
Water	0.0002	0.01	0.088	[1]
Steel fiber	1.49	20.59	93.62	[1]
QP	0.02	0.0008	1.85	[18]
PCE	0.75	18	237.6	[9]
Admixture	0.0022	0.0058	100	[19]
HRWR	0.25	18.1	352.47	[1]
GGBS	0.019	1.588	3.7	[1]
FA	0.0090	0.1	4.41	[1]
MK	0.40	3.48	39.6	[1]
GGP	0.64	11.0	6.3	[20]
LS	0.321	1.906	22	[4]
LP	0.241	1.427	3.3	[6]
BP	0.312	1.0	110	[7]
CSS	0.215	1.362	110	[8]
PS	0.190	1.325	66	[9]

Table 6. Summary of total eCO_2 emission and production cost of concrete mixes

SCMs	ECO_2 (kg-CO_2/m^3)	E. energy (MJ/m^3)	Compressive Strength, f_c (Mpa)	C_i (E-CO_2/f_c)	E_f (EE/f_c)	Mixture production cost (tk/m^3)
GGBS	623.86	6568.12	90	6.93	72.97	37553
FA	767.14	6744.52	108	7.10	62.45	39058
MK	892.06	7716.52	120	7.43	64.30	47273
GGP	807.45	7033.87	158	5.11	44.52	26067
LS	782.25	4549.78	148	5.29	30.74	18489
LP	654.34	4067.78	158	4.14	25.75	12232
BP	425	2755.16	113	3.76	24.38	50379
CSS	687.41	4016.76	162	4.24	24.79	28706
PS	460.84	3227.5	127.5	3.61	25.31	40939

4 Conclusion

This paper provides an extensive review of the use of various industrial wastes as cement substitutes in the production of sustainable and universally applicable UHPC in the construction industry.

- The result presents a comparison of alternative SCM replacements, with each mix representing an optimal combination within various UHPC research studies. Certain SCM mixes exhibit superiority over others in terms of compressive strength, environmental impact, and cost-benefit assessment.
- The CSS mix shows the highest compressive strength among all the mixes. The second highest has been seen in LP, where the replacement rate of cement is higher than CSS.
- CSS and LP take precedence for their low eco-strength efficiency with the highest compressive strength of UHPC. Also, the PS mix exhibits the lowest eco-strength efficiency with a compressive strength of 127.5 MPa, surpassing the UHPC strength limit.
- Between LP and CSS, LP demonstrates the lowest production cost alongside other favorable criteria. Furthermore, LP has a high cement replacement rate. So, In terms of low environmental effect and low production cost, LP should be prioritized over CSS because they have nearly identical compressive strength.

Abbreviations

GGBS Ground granulated blast furnace slag
FA Fly ash
MK Metakaolin
GGP Ground granite powder

LS	Lithium slag
LP	Lime powder
CSS	Carbonated steel slag
PS	Phosphorus slag
BP	Basalt powder
SF	Silica fume
QP	Quartz powder
PCE	Polycarboxylate ethers admixture
HRWR	High Range Water Reducer
SP	Superplasticizer

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References

1. Abdellatief, M., AL-Tam, S.M., Elemam, W.E., Alanazi, H., Elgendy, G.M., and Tahwia, A.M., Development of ultra-high-performance concrete with low environmental impact integrated with metakaolin and industrial wastes. Case Studies in Construction Materials, 2023. 18: p. e01724.
2. Park, S., Wu, S., Liu, Z., and Pyo, S., The role of supplementary cementitious materials (SCMs) in ultra high performance concrete (UHPC): A review. Materials, 2021. 14(6): p. 1472.
3. Zhang, H., Ji, T., He, B., and He, L., Performance of ultra-high performance concrete (UHPC) with cement partially replaced by ground granite powder (GGP) under different curing conditions. Construction and Building Materials, 2019. 213: p. 469-482.
4. He, Z.-h., Du, S.-g., and Chen, D., Microstructure of ultra high performance concrete containing lithium slag. Journal of hazardous materials, 2018. 353: p. 35-43.
5. Kashem, A., Karim, R., Malo, S.C., Das, P., Datta, S.D., and Alharthai, M., Hybrid data-driven approaches to predicting the compressive strength of ultra-high-performance concrete using SHAP and PDP analyses. Case Studies in Construction Materials, 2024. 20: p. e02991 DOI: https://doi.org/10.1016/j.cscm.2024.e02991.
6. Li, P.P., Brouwers, H., Chen, W., and Yu, Q., Optimization and characterization of high-volume limestone powder in sustainable ultra-high performance concrete. Construction and Building Materials, 2020. 242: p. 118112.
7. Yang, R., Yu, R., Shui, Z., Gao, X., Han, J., Lin, G., Qian, D., Liu, Z., and He, Y., Environmental and economical friendly ultra-high performance-concrete incorporating appropriate quarry-stone powders. Journal of Cleaner Production, 2020. 260: p. 121112.

8. Liu, G., Schollbach, K., Li, P., and Brouwers, H., Valorization of converter steel slag into eco-friendly ultra-high performance concrete by ambient CO2 pre-treatment. Construction and Building Materials, 2021. 280: p. 122580.
9. Yang, R., Yu, R., Shui, Z., Gao, X., Xiao, X., Zhang, X., Wang, Y., and He, Y., Low carbon design of an Ultra-High Performance Concrete (UHPC) incorporating phosphorous slag. Journal of Cleaner Production, 2019. 240: p. 118157.
10. Hu, L., He, Z., and Zhang, S., Sustainable use of rice husk ash in cement-based materials: Environmental evaluation and performance improvement. Journal of Cleaner Production, 2020. 264: p. 121744.
11. Bakera, A.T. and Alexander, M.G., Use of metakaolin as supplementary cementitious material in concrete, with focus on durability properties. RILEM Technical Letters, 2019. 4: p. 89-102.
12. Shi, Y., Long, G., Ma, C., Xie, Y., and He, J., Design and preparation of ultra-high performance concrete with low environmental impact. Journal of Cleaner Production, 2019. 214: p. 633-643.
13. Rahman, S.A., Dodd, A., Khair, S., Shaikh, F.U.A., Sarker, P.K., and Hosan, A., Assessment of lithium slag as a supplementary cementitious material: Pozzolanic activity and microstructure development. Cement and Concrete Composites, 2023. 143: p. 105262.
14. Aghamelu, O., Odoh, B., and Egboka, B., A geotechnical investigation on the structural failures of building projects in parts of Awka, southeastern Nigeria. Indian journal of science and technology, 2011. 4(9): p. 1119-1124.
15. Yılmaz, A., Engineering properties of basalt aggregates in terms of use in granular layers of flexible pavements. Case Studies in Construction Materials, 2022. 17: p. e01182.
16. Kumar, R., Shafiq, N., Kumar, A., and Jhatial, A.A., Investigating embodied carbon, mechanical properties, and durability of high-performance concrete using ternary and quaternary blends of metakaolin, nano-silica, and fly ash. Environmental Science and Pollution Research, 2021. 28: p. 49074-49088.
17. Damineli, B.L., Kemeid, F.M., Aguiar, P.S., and John, V.M., Measuring the eco-efficiency of cement use. Cement and Concrete Composites, 2010. 32(8): p. 555-562.
18. Chen, J., Ng, P.-L., Jaskulski, R., and Kubissa, W., Use of quartz sand to produce low embodied energy and carbon footprint plaster. Journal of Sustainable Architecture and Civil Engineering, 2017. 21(4): p. 75-81.
19. Sobuz, M.H.R., Datta, S.D., Akid, A.S.M., Tam, V.W., Islam, S., Rana, M.J., Aslani, F., Yalçınkaya, Ç., and Sutan, N.M., Evaluating the effects of recycled concrete aggregate size and concentration on properties of high-strength sustainable concrete. Journal of King Saud University-Engineering Sciences, 2022.
20. Hammond, G., Jones, C., Lowrie, E.F., and Tse, P., Embodied carbon. The inventory of carbon and energy (ICE). Version (2.0), 2011.