ESTIDAMAA
Vol. (2024), 2024, pp. 7-14
ISSN: 3078-428X

Research Article

A Review on the Impact of Fly Ash on the Resistance of Ultra-High Performance Concrete to Acid and Sulfate Attacks

Asal M. Hamad [1,*], Hussein M. Hamada [2], Ali Mohammed Saleh [1,3], Noah Mohammed Saleh [1,4], Raed A. Hasan [5], Azil Bahari Alias [3], Jafar Keighobadi [4], Rodhan Abdullah Salih [1], Hussein M. Issa [1], Idan I. Ghdhban [1]

[1] *Al-Hawija technical institute, Northern technical university, Mosul, Iraq.*

[2] *College of engineering, American university of Sharjah, Sharjah, UAE.*

[3] *School of chemical engineering University Technology Mara, Shah Alam, Selangor, Malaysia.*

[4] *Faculty of Mechanical Engineering University of Tabriz, Iran.*

[5] *Renewable Energy Research Unit, Northern Technical University, Mosul, Iraq.*

ARTICLE INFO

Article History
Received 1 Nov 2023
Revised: 16 Des 2023
Accepted 15 Jan 2024
Published 5 Feb 2024

Keywords
Fly ash ,
environment pollution ,
ultra-high performance concrete,
carbon dioxide,
durability of concrete .

ABSTRACT

A huge amount of fly ash (FA) was generated every year and dumped in landfills in large quantities and leading to environmental pollution issues. The use of FA in normal concrete and ultra-high performance concrete (UHPC) can reduce pollution in both cases, namely, reduce the accumulation of FA as waste material in landfills and reduce the cement production that generates around 7% of total carbon dioxide (CO2) emissions. This study is a comprehensive review to find out the effect of FA on some durability properties of UHPC, namely acid and sulfate attacks. The results indicate that the use of FA has a positive effect on the increase in the resistance of UHPC samples against acid and sulfate attacks. It is recommended to use nano-FA in the treatment of corrosion and carbonation of UHPC.

1. INTRODUCTION

The increase in the population of the world over time continues, thus resulting in the construction of numerous new buildings and important infrastructure projects such as highway bridges, tunnels, airports, hospitals, residential and commercial high-rise buildings, and so on [1]. These infrastructure projects require a special type of concrete that has a high compressive strength and an ability to be durable in different aggressive environments, called ultra-high-performance concrete (UHPC). Mehta et al. [2] expected that the request for concrete will increase to 18 billion tons by the year 2050. The primary role of engineering is to transform waste into valuable resources. Cement is the main constituent in concrete components, at the same time is one of the highest contributors to the release of high amounts of CO_2 emissions that lead to environmental pollution [3, 4]. Therefore, the researchers and scientists focus their efforts to find sustainable construction materials to replace cement without effect on the concrete properties and reducing the cement's harm to the environment.
Currently, UHPC is required by numerous significant construction projects because of its performance related to durability and mechanical properties [5, 6]. UHPC usually consists of a large quantity of cement, fine aggregate, low water-cement ratio, admixture, superplasticizer, and fiber reinforcements [7, 8]. The compressive strength of UHPC samples is very high that is more than 150 MPa and mainly depends on the handling method and materials that constitute [9, 10]. The cement and silica fume content used in UHPC in huge quantities about more than 900 kg/m^3 and 150 kg/m^3, respectively [11, 12]. The benefits of sustainable concrete materials from waste materials not only include reducing the emissions of CO_2 into the atmosphere, moreover have other benefits such as reducing the accumulation of this waste in landfills area and reusing

*Corresponding author email: a.hamad82@gmail.com
DOI: https://doi.org/10.70470/ESTIDAMAA/2024/002

it in cement production [13, 14]. Therefore, the use of agriculture and industrial wastes as cementitious materials can reduce cement production and thus reduce its harmful effects on the environment [15, 16]. Furthermore, reducing the final cost of concrete production by reducing the area of the landfills and their maintenance as well as reducing the cement content that is considered as the most expensive among the concrete components [17, 18].

Fly ash (FA) is one industrial waste (by-product) that is produced in huge quantities in power plants and other factories that generate electric worldwide [19, 20]. FA has a chemical composition similar to cement, therefore it was used with cement in more construction applications [21]. Numerous studies investigated the effect of FA as a cement replacement in improving the mechanical strength of concrete [22-24]. Other studies investigated the potential use of the huge amount of FA in producing concrete with a focus on reducing the CO_2 emissions into the atmosphere [25, 26]. While, the use of FA in improving of the UHPC against acid and sulfate attacks has not been investigated in more detail [27, 28]. Therefore, this study will focus on the potential use of FA as cement replacement in improving the resistance of UHPC against acid and sulfate attacks and maintaining high-durability concrete in different aggressive environments.

1.1 Significant of study

The purpose of this study is mostly to review the previous studies related to the effect of FA on the sulfate and acid attacks as a chemical and aggressive environment in UHPC samples. As well as, to show the effect of FA on the shape, appearance, weight, and compressive strength of UHPC samples, and to be a strong knowledge base for researchers and academics when they want to design UHPC in aggressive and chemical environments to get better durability characteristics of UHPC in sustainable construction materials. The cost of raw materials is the key issue for increasing UHPC price [29] Currently, this study focused on the effect of FA as low cost compared to cement on the sulfate and acid attacks of UHPC.

For reducing the final cost of UHPC, it is important to know the effect of the other renewable and sustainable materials that can be used as cement binder materials instead of cement on the concrete properties. FA is one of these sustainable materials that was used as cementitious materials in numerous studies to reduce the cement content in concrete mixtures. Usually, the quantity of cementitious material to produce UHPC is ranging between 800 and 1000 kg/m^3 [30, 31]. Consequently, researchers focused their work on investigating how to decrease the quantity of natural cement without effect on the concrete properties. For that reason, many studies have used waste materials such as FA as cement replacement partially to attain double benefits, namely reducing cement production and reducing the accumulation of these wastes from landfills, thus saving the environment from pollution due to CO_2 emissions [32].

2. FLY ASH

The use of FA in the construction industry became necessary to fulfill meet the required concrete quantities with special requirements and to get eco-friendly concrete. The chemical composition and physical properties of FA differ from one country to another depending on the raw materials sources and treatment processes in the thermal power plants [33, 34]. Due to the FA nature with high pozzolanics made it widely used as cement replacement in more construction applications [35]. FA is an industrial product or by-product material generated from the thermal power plants that work in coal-fired [20, 36]. Fig. 1 displays a general outline of a coal-burning in power plant and the formation of FA as predicted by Thomas [37].

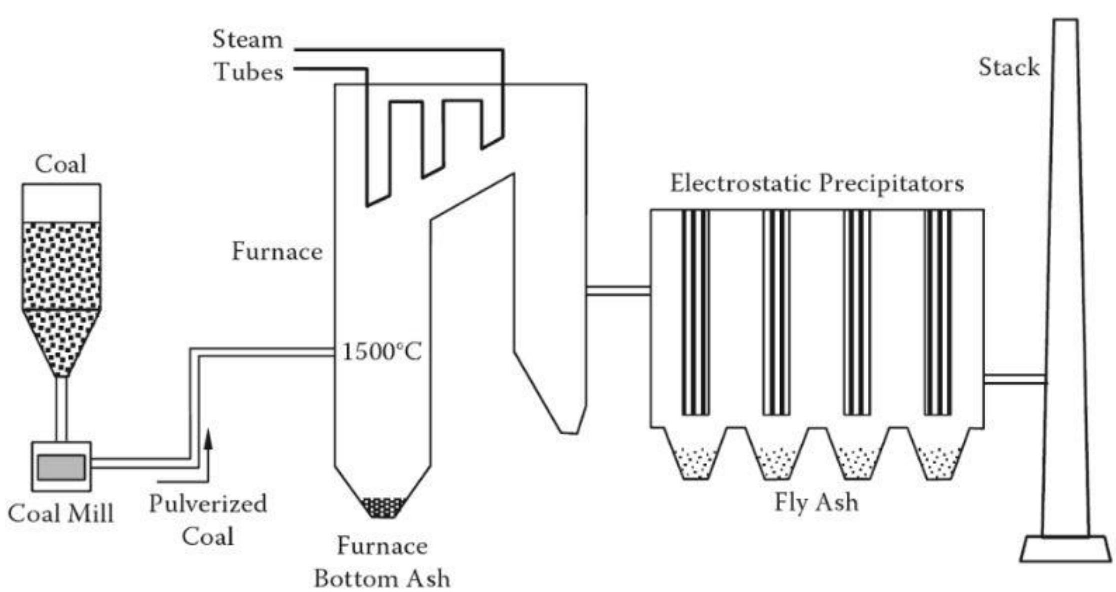

Fig. 1 Schematic layout of generation process of FA [37].

The FA particles can be classified into two kinds based on specifications of ASTM, namely class C and class F [38, 39]. FA Class C is the FA generated from lignite combustion and sub-bituminous coal. It comprises higher calcium than class F FA. Therefore, the concrete comprising this type has higher compressive strength than that of class F FA [40, 41]. The class F FA is a byproduct of the combustion of bituminous. Even though the alumina, silica, and iron content of class F FA is higher than that of Class C FA, however, the Class F FA has lower calcium content than that of Class C FA, that is necessary for reactions, thus it needs either lime or cement to activate [40, 42].

2.1 Chemical composition of FA

The chemical composition of FA can be examined using XRF test. The chemical composition of FA depends on the functioning parameters of boilers and sources of coal. Table 1 show the chemical composition of FA from difference sources.

TABLE I CHEMICAL COMPOSITION OF FA USED IN THE PRODUCTION OF UHPC.

References	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	K_2O	Na_2O	P_2O_5	SO_3	TiO_2	LOI
Tahwia et al., [43]	50.14	18.12	7.34	6.31	1.56	2.19	1.11	0.42	---	0.85	0.29
Ali et al., [44]	56.4	25.5	3.4	2.5	0.9	2.2	0.4	--	---	---	7.1
Danish and Mosaberpanah [45]	50.01	30.8	11.05	3.88	1.5	0.67	0.31	---	0.29	1.76	--
Sata et al., [46]	38.7	20.7	15.3	16.6	1.5	2.7	1.2	0.2	2.6	0.4	0.1
Ali et al., [47]	61.0	28.4	3.4	4.3	---	---	---	---	---	---	1.4

2.2 Physical properties of FA

Danish and Mosaberpanah [45] used small particle sizes of FA, it was ranging between 0.3 mm and 0.075 mm that can be supporting the microstructure through increasing density matrix and reducing voids. Table 2 show the physical properties of FA used in concrete by the previous studies.

TABLE II PHYSICAL PROPERTIES OF FA USED IN THE PRODUCTION OF UHPC

References	Source of FA	Specific gravity (kg/m^3)	Bulk density (kg/m^3)	Specific surface area (m^2/kg)	Water absorption %	Median particle size d_{50} (μm)
Ali et al., [44]	Pakistan	2.34	1130	265		
Sata et al., [46]	Thailand	2.51		210		37. 1

3. DURABILITY OF UHPC

3.1 Resistance of Sulfate attacks

Sulfate attack is one important issue that reduces concrete durability over time, thus resulting in cracks and expansion in concrete structures [48]. The expansion in the concrete structures occurs owing to the creation of gypsum and ettringite [49, 50]. The high pozzolanic in FA can enhance the resistance against sulfate attacks because of pozzolanic reactions can increase C-S-H gels and reduce the quantity of CH [51]. Tahwia et al., [43] examined the effect of FA on the sulfate attack of UHPC with different replacement levels of 0%, 30%, and 50% on total cement weight and used three concentrations of Na_2SO_4 solutions as illustrated in Table 3.

TABLE III EFFECT OF FA AS CEMENT REPLACEMENT ON THE COMPRESSIVE STRENGTH OF UHPC [43].

Replacement levels %	Compressive strength of High concentration of Na_2SO_4 (MPa)		Compressive strength of Low concentration of Na_2SO_4 (MPa).		Compressive strength of control concrete samples (MPa).	
	90 days	180 day	90 days	180 days	90 days	180 days
0	169.7	160.8	184.5	189.7	184.5	190.3
30	179.8	169.9	193.7	199.5	193.7	199.7
50	166.8	157.4	181.7	186.5	181.7	187.4

As shown in table 3, the high concentration of sodium sulfate (Na_2SO_4) leads to reduce the compressive strength of UHPC containing FA compared to the control concrete sample. While, the low concentration of sulfate solution, the compressive strength for all replacement levels did not affect by the sulfate, and had a similar compressive strength to the control UHPC sample. The entrance of sulfate ions to inside concretes results to occur numerous reactions inside the concrete body, which cause damage to the concrete structure with time [52]. However, there are numerous factors effects on the resistance of external sulfate attacks of concrete, such as sulfate concentration, sulfate type, curing conditions, water binder ratio (w/b), and binder type [53-55]. Liu et al. [56] informed that the use of FA as cement replacement considerably improved the resistance against sulfate attacks due to their pozzolanic reactions. Another study reported that the addition of 10% FA into concrete mixture leads to reduce expansion to be lower than that of control concrete samples exposed to 4.2 % $MgSO_4$ and 5 % Na_2SO_4solutions [57].

Another study by Irassar et al., [58] reported that the SEM/EDS show the important results of sulfate aggression were ettringite and gypsum inside the inward and surface parts, respectively, which was expected with the inspection carried out. Consequently, gypsum is more probable to be created over the crystallization process in the surface part due to the existence of high concentrations of sulfate materials. Liu et al. [59] stated that the addition of 40 % FA as cement replacement in concrete production resulted in to increase in the resistance against sulfate attacks due to its containing high pozzolanic material.

3.2 Resistance against acid attacks

The use of FA as cement replacement in concrete production has no significant impact in preventing acid-type deterioration, including softening and scaling of the mortar with low solution PH. Whereas, the formed expansion resulting from sulfate was significantly decreased due to adding more than 30% FA as cement replacement in concrete production. In another study by Uthaman et al., [60], reported that the filling effect and formation of further C-S-H gels of FA leads to improving the density and microstructure of concrete to be high resistance against sulfate attacks. Sujay et al., [61] studied the influence of ultrafine FA and nano-silica as cement replacements on the proportion of weight loss in UHPC samples. They observed that the strength and weight loss were increased due to an increase in the FA percentage, as shown in Fig. 2. Thus, the FA has superior resistance against acid attacks as compared to the control sample.

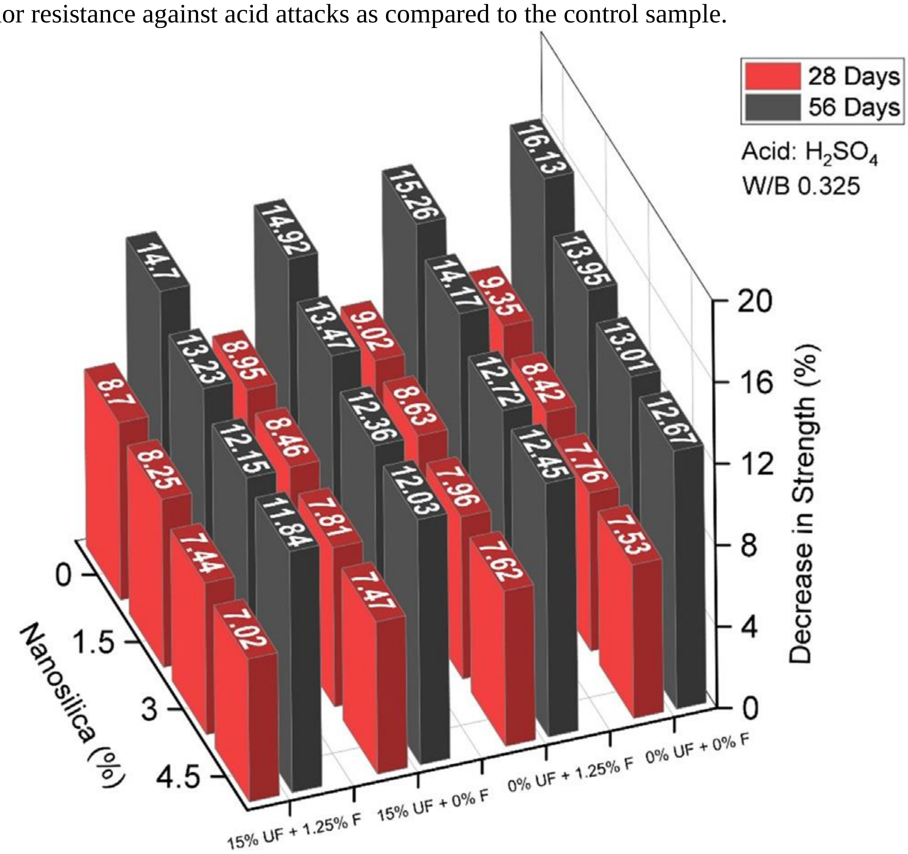

Fig. 2 Proportion strength loss owing to inundation in H_2SO_4 with W/B of 0.325 [61].

The test of acid attacks was conducted by Danish and Mosaberpanah [45] on the samples to find out their performance in an acid environment such as H2SO4. They used a concentration of 5% H_2SO_4 and that concentration was checked every ten days. The samples were weighed and tested the compressive strength at 3, 7, and 30 days, to identify the percentage loss in weight and compressive strength due to immersion in acid attacks. They observed that the acid attack spreads owing to the reaction of calcium hydroxide, thus resulting in the creation of highly soluble salts such as gypsum. A recent study by Patil et al., [62], concluded that the incorporation of 5% FA and 5% SF as cement replacement has increased the resistance against acid attacks especially MgSO4 and HCL as compared to the control concrete sample. The 90 days-compressive strength of concrete containing 5% FA and 5% SF was reduced by 16.25%, while the 90 days-compressive strength of the control concrete sample was reduced by 22.09%. Therefore, we can conclude that the addition of FA as cement replacement in the concrete mixture has a positive effect on the improvement of resistance against acid attacks.

The immersion of concrete samples (cubes) in an acid solution such as sulfuric acid (H_2SO_4) has a significant effect on visual observation. The sulfuric solution led to the deterioration of concrete cubes. The deterioration started with corners falling off, then other parts started to fall. The main cause behind losing weight is the high water-binder ratio of concrete mix that makes numerous porous voids enter acids into the concrete body. Barbhuiya and Kumala[63] used a 3% sulfuric acid (H_2SO_4) solution for curing concrete samples containing fly ash (FA) and ultra-fine fly ash (UFFA) as partial cement replacement. They observed that the loss in compressive strength of concrete in the acid environments recorded the lowest value, especially concrete samples made of 30% FA and 10% UFFA compared to the control concrete samples without

FA. This mix also displayed the lowest effect in appearance and mass when exposed to the environment's acid, as shown in Fig. 3.

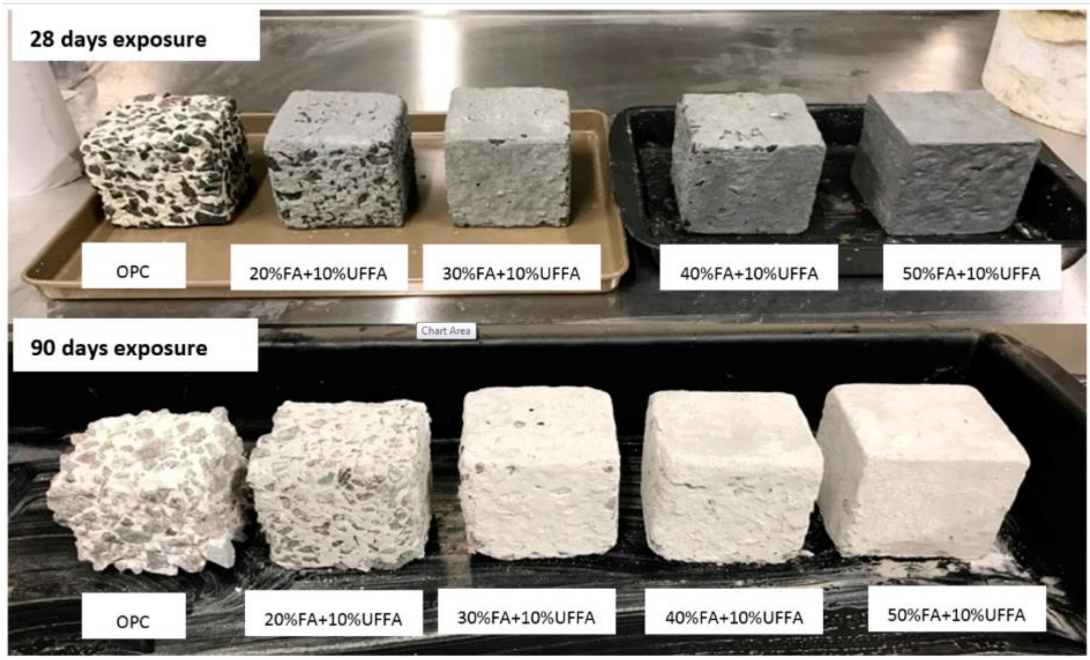

Fig. 3 Effect of acid attacks on the concrete samples with 3% H_2SO_4 solution [63].

4. DISCUSSION OF RESULTS

The use of FA as a cementitious material in partial cement replacement in the production of UHPC and its effect on the acid and sulfate attacks is a significant matter and should be investigated in more detail. This research addressed the results obtained from previous studies related to the use of FA as cementitious material and its role in the resistance against acid and sulfate attacks of UHPC samples. UHPC structures exposed to the oceanic environment effect by chemical attacks, like chlorides, acid, and sulfates, resulting in spalling and corrosion in reinforcement concrete. Due to the incorporation of FA in UHPC mix, thus getting high-density UHPC, thus chemical attack signs take more time to appear as compared with other concrete types [64]. Also, as reported in the previous studies, FA in cement mixtures positively affected the increase of resistance against acid and sulfate attacks [65].

5. CONCLUSIONS

Cement production consumes high energy and generates huge quantities of CO2 emissions. The researchers tried several times to reduce the negative impact of cement production on the environment and concrete properties. They used several types of waste materials to solve this issue and FA is one of these wastes. In this study, the results from previous studies about the effect of FA as partial cement replacement on the sulfate and acid attacks of UHPC were reviewed and discussed in detail and can be drawn some conclusions as following points:

1. FA is one of the industrial wastes (by-products) generated from the thermal power plants that work coal-fired.
2. FA particles have different chemical composition depending on the raw materials source and production condition, and silica oxide (SiO2) constitute the highest content among its components.
3. The FA particles can be used as partial cement replacement and has both advantages in terms of economic and environmental point.
4. The results obtained from using FA as cement replacement indicate the use of FA in a small amount can achieve better UHPC performance as compared to the normal UHPC.
5. The high pozzolanic reactions in FA can produce C-S-H gels, essential to improve the strength and microstructure of UHPC.
6. The FA with high pozzolanic reactions in the concrete mix has a significant influence on the improvement of water absorption, captivity, and resistance against acid and sulfate attacks due to the potential to produce further C-S-H gels and decrease the amount of CH, thus enhancing the UHPC durability.

For future studies, it is better to use different treatments on the FA particles such as different techniques in preparing nano-FA and using it to treat the corrosion and carbonation resistance of UHPC, thus reducing the cement content in UHPC mixtures.

Funding:

The authors declare that no specific financial aid or sponsorship was received from governmental, private, or commercial entities to support this study. The research was solely financed by the authors' own contributions.

Conflicts of Interest:

The authors declare that there are no conflicts of interest in this study.

Acknowledgment:

The authors express their heartfelt appreciation to their institutions for the essential support and motivation provided throughout the research period

References

[1] L. S. Pheng, L. S. Hou, "The economy and the construction industry," Construction Quality and the Economy: A Study at the Firm Level, pp. 21-54, 2019.
[2] P. K. Mehta, "Greening of the concrete industry for sustainable development," Concrete International, vol. 24, pp. 23-28, 2002.
[3] R. I. C. Juarez and S. Finnegan, "The environmental impact of cement production in Europe: A holistic review of existing EPDs," Cleaner Environmental Systems, vol. 3, p. 100053, 2021.
[4] M. Rangrazian, R. Madandoust, R. Mahjoub, and M. Raftari, "Reduction of CO2 environmental pollution from concrete, by adding local mineral pozzolan as a part of cement replacement in concrete: a case study on engineering properties," Nanotechnology for Environmental Engineering, pp. 1-16, 2022.
[5] A. K. Akhnoukh and C. Buckhalter, "Ultra-high-performance concrete: Constituents, mechanical properties, applications and current challenges," Case Studies in Construction Materials, vol. 15, p. e00559, 2021.
[6] M. H. Akeed et al., "Ultra-high-performance fiber-reinforced concrete. Part IV: Durability properties, cost assessment, applications, and challenges," Case Studies in Construction Materials, p. e01271, 2022.
[7] M. Nodehi and S. E. Nodehi, "Ultra high performance concrete (UHPC): Reactive powder concrete, slurry infiltrated fiber concrete and superabsorbent polymer concrete," Innovative Infrastructure Solutions, vol. 7, p. 39, 2022.
[8] M. H. Akeed et al., "Ultra-high-performance fiber-reinforced concrete. Part I: Developments, principles, raw materials," Case Studies in Construction Materials, vol. 17, p. e01290, 2022.
[9] M. Amin, A. M. Zeyad, B. A. Tayeh, and I. S. Agwa, "Effect of ferrosilicon and silica fume on mechanical, durability, and microstructure characteristics of ultra high-performance concrete," Construction and Building Materials, vol. 320, p. 126233, 2022.
[10] A. Arora et al., "Material design of economical ultra-high performance concrete (UHPC) and evaluation of their properties," Cement and Concrete Composites, vol. 104, p. 103346, 2019.
[11] A. El-Mir, S. G. Nehme, and J. J. Assaad, "Effect of binder content and sand type on mechanical characteristics of ultra-high performance concrete," Arabian Journal for Science and Engineering, vol. 47, pp. 13021-13034, 2022.
[12] S. H. Yeo et al., "Properties of cementitious repair materials for concrete pavement," Advances in Materials Science and Engineering, vol. 2022, 2022.
[13] R. Islam et al., "An empirical study of construction and demolition waste generation and implication of recycling," Waste Management, vol. 95, pp. 10-21, 2019.
[14] M. Tejaswini et al., "A comprehensive review on integrative approach for sustainable management of plastic waste and its associated externalities," Science of the Total Environment, p. 153973, 2022.
[15] H. M. Hamada et al., "Sustainable use of palm oil fuel ash as a supplementary cementitious material: A comprehensive review," Journal of Building Engineering, vol. 40, p. 102286, 2021.
[16] N. Bheel, F. A. Memon, and S. L. Meghwar, "Study of fresh and hardened properties of concrete using cement with modified blend of millet husk ash as secondary cementitious material," Silicon, vol. 13, pp. 4641-4652, 2021.
[17] C. O. Nwankwo et al., "High volume Portland cement replacement: A review," Construction and Building Materials, vol. 260, p. 120445, 2020.
[18] A. Pandey and B. Kumar, "Utilization of agricultural and industrial waste as replacement of cement in pavement quality concrete: a review," Environmental Science and Pollution Research, vol. 29, pp. 24504-24546, 2022.
[19] A. K. Dan et al., "Prospective utilization of coal fly ash for making advanced materials," in Clean Coal Technologies: Beneficiation, Utilization, Transport Phenomena and Prospective, Springer, 2021, pp. 511-531.
[20] M. Mathapati et al., "A review on fly ash utilization," Materials Today: Proceedings, vol. 50, pp. 1535-1540, 2022.
[21] B. Kipkemboi et al., "Effect of C3S content of clinker on properties of fly ash cement concrete," Construction and Building Materials, vol. 240, p. 117840, 2020.
[22] Y. Wei et al., "Effect of fly ash on mechanical properties and microstructure of cellulose fiber-reinforced concrete under sulfate dry–wet cycle attack," Construction and Building Materials, vol. 302, p. 124207, 2021.
[23] M. A. Nawaz et al., "Effect of sulfate activator on mechanical and durability properties of concrete incorporating low calcium fly ash," Case Studies in Construction Materials, vol. 13, p. e00407, 2020.
[24] F. Mustapha et al., "The effect of fly ash and silica fume on self-compacting high-performance concrete," Materials Today: Proceedings, vol. 39, pp. 965-969, 2021.

[25] Y. Deng et al., "Preparation and mechanical characterization of engineered cementitious composites with high-volume fly ash and waste glass powder," Journal of Cleaner Production, vol. 333, p. 130222, 2022.

[26] E. R. Teixeira et al., "Synergetic effect of biomass fly ash on improvement of high-volume coal fly ash concrete properties," Construction and Building Materials, vol. 314, p. 125680, 2022.

[27] S. H. Lessly et al., "Durability properties of modified ultra-high performance concrete with varying cement content and curing regime," Materials Today: Proceedings, vol. 45, pp. 6426-6432, 2021.

[28] H. Zeng et al., "Effect of limestone powder and fly ash on the pH evolution coefficient of concrete in a sulfate-freeze–thaw environment," Journal of Materials Research and Technology, vol. 16, pp. 1889-1903, 2022.

[29] M. Bajaber and I. Hakeem, "UHPC evolution, development, and utilization in construction: A review," Journal of Materials Research and Technology, vol. 10, pp. 1058-1074, 2021.

[30] M. Song et al., "Mechanical performance and microstructure of ultra-high-performance concrete modified by calcium sulfoaluminate cement," Advances in Civil Engineering, vol. 2021, pp. 1-9, 2021.

[31] F. Dingqiang et al., "Development and applications of ultra-high performance concrete in bridge engineering," in IOP Conference Series: Earth and Environmental Science, 2018, p. 022038.

[32] C. M. Grădinaru et al., "When agricultural waste transforms into an environmentally friendly material: The case of green concrete as alternative to natural resources depletion," Journal of Agricultural and Environmental Ethics, vol. 32, pp. 77-93, 2019.

[33] V. K. Yadav et al., "Status of Coal-Based Thermal Power Plants, Coal Fly Ash Production, Utilization in India and Their Emerging Applications," Minerals, vol. 12, p. 1503, 2022.

[34] B. Krasnyi et al., "Fly ash as technogenic raw material for producing refractory and insulating ceramic materials," Glass and Ceramics, vol. 78, pp. 48-56, 2021.

[35] M. Amran et al., "Fly ash-based eco-friendly geopolymer concrete: A critical review of the long-term durability properties," Construction and Building Materials, vol. 270, p. 121857, 2021.

[36] S. Verma et al., "Exploring brine sludge and fly ash waste for making nontoxic radiation shielding materials," in Advanced Materials from Recycled Waste, pp. 27-44, 2023.

[37] M. Thomas, Supplementary cementing materials in concrete, CRC Press, 2013.

[38] S. K. Mondal et al., "Effect of Class C and Class F Fly Ash on Early-Age and Mature-Age Properties of Calcium Sulfoaluminate Cement Paste," Sustainability, vol. 15, p. 2501, 2023.

[39] P. Yoosuk et al., "Properties of polypropylene fiber reinforced cellular lightweight high calcium fly ash geopolymer mortar," Case Studies in Construction Materials, vol. 15, p. e00730, 2021.

[40] S. Al-Shmaisani et al., "Assessment of blended coal source fly ashes and blended fly ashes," Construction and Building Materials, vol. 342, p. 127918, 2022.

[41] A. Oner, S. Akyuz, and R. Yildiz, "An experimental study on strength development of concrete containing fly ash and optimum usage of fly ash in concrete," Cement and Concrete Research, vol. 35, pp. 1165-1171, 2005.

[42] A. Bhatt, S. Priyadarshini, A. A. Mohanakrishnan, A. Abri, M. Sattler, and S. Techapaphawit, "Physical, chemical, and geotechnical properties of coal fly ash: A global review," Case Studies in Construction Materials, vol. 11, p. e00263, 2019.

[43] A. M. Tahwia, G. M. Elgendy, and M. Amin, "Durability and microstructure of eco-efficient ultra-high-performance concrete," Construction and Building Materials, vol. 303, p. 124491, 2021.

[44] B. Ali, M. A. Gulzar, and A. Raza, "Effect of sulfate activation of fly ash on mechanical and durability properties of recycled aggregate concrete," Construction and Building Materials, vol. 277, p. 122329, 2021.

[45] A. Danish and M. A. Mosaberpanah, "Influence of cenospheres and fly ash on the mechanical and durability properties of high-performance cement mortar under different curing regimes," Construction and Building Materials, vol. 279, p. 122458, 2021.

[46] V. Sata, A. Sathonsaowaphak, and P. Chindaprasirt, "Resistance of lignite bottom ash geopolymer mortar to sulfate and sulfuric acid attack," Cement and Concrete Composites, vol. 34, pp. 700-708, 2012.

[47] B. Ali et al., "The durability of high-strength concrete containing waste tire steel fiber and coal fly ash," Advances in Materials Science and Engineering, vol. 2021, pp. 1-19, 2021.

[48] Z. Zhang, J. Zhou, J. Yang, Y. Zou, and Z. Wang, "Understanding of the deterioration characteristic of concrete exposed to external sulfate attack: Insight into mesoscopic pore structures," Construction and Building Materials, vol. 260, p. 119932, 2020.

[49] J. Cao et al., "Influence of hoop restraint on microstructure and phase composite of cement paste filled steel tube under external sulfate attack," Construction and Building Materials, vol. 366, p. 130195, 2023.

[50] F. Xu et al., "Experimental investigation on the effect of sulfate attack on chloride diffusivity of cracked concrete subjected to composite solution," Construction and Building Materials, vol. 237, p. 117643, 2020.

[51] X. Han, J. Feng, Y. Shao, and R. Hong, "Influence of a steel slag powder-ground fly ash composite supplementary cementitious material on the chloride and sulphate resistance of mass concrete," Powder Technology, vol. 370, pp. 176-183, 2020.

[52] J. Skalny, J. Marchand, and I. Odler, Sulfate Attack on Concrete. Taylor & Francis, 2003.

[53] N. M. Al-Akhras, "Durability of metakaolin concrete to sulfate attack," Cement and Concrete Research, vol. 36, pp. 1727-1734, 2006.

[54] Z. Zhang, X. Jin, and W. Luo, "Long-term behaviors of concrete under low-concentration sulfate attack subjected to natural variation of environmental climate conditions," Cement and Concrete Research, vol. 116, pp. 217-230, 2019.

[55] A. M. Tahwia et al., "Long-Term Performance of Concrete Made with Different Types of Cement under Severe Sulfate Exposure," Materials, vol. 16, p. 240, 2023.

[56] M. Liu, H. Tan, and X. He, "Effects of nano-SiO2 on early strength and microstructure of steam-cured high volume fly ash cement system," Construction and Building Materials, vol. 194, pp. 350-359, 2019.

[57] A. Mardani-Aghabaglou, G. İ. Sezer, and K. Ramyar, "Comparison of fly ash, silica fume and metakaolin from mechanical properties and durability performance of mortar mixtures view point," Construction and Building Materials, vol. 70, pp. 17-25, 2014.

[58] E. Irassar, V. Bonavetti, and M. González, "Microstructural study of sulfate attack on ordinary and limestone Portland cements at ambient temperature," Cement and Concrete Research, vol. 33, pp. 31-41, 2003.

[59] Y. Liu and F. Presuel-Moreno, "Effect of Elevated Temperature Curing on Compressive Strength and Electrical Resistivity of Concrete with Fly Ash and Ground-Granulated Blast-Furnace Slag," ACI Materials Journal, vol. 111, 2014.

[60] S. Uthaman et al., "Enhancement of strength and durability of fly ash concrete in seawater environments: Synergistic effect of nanoparticles," Construction and Building Materials, vol. 187, pp. 448-459, 2018.

[61] H. Sujay, N. A. Nair, H. S. Rao, and V. Sairam, "Experimental study on durability characteristics of composite fiber reinforced high-performance concrete incorporating nanosilica and ultra fine fly ash," Construction and Building Materials, vol. 262, p. 120738, 2020.

[62] S. Patil et al., "Durability and micro-structure studies on fly ash and silica fume based composite fiber reinforced high-performance concrete," Materials Today: Proceedings, vol. 49, pp. 1511-1520, 2022.

[63] S. Barbhuiya and D. Kumala, "Behaviour of a sustainable concrete in acidic environment," Sustainability, vol. 9, p. 1556, 2017.

[64] J. Li, Z. Wu, C. Shi, Q. Yuan, and Z. Zhang, "Durability of ultra-high performance concrete–A review," Construction and Building Materials, vol. 255, p. 119296, 2020.

[65] C. Herath et al., "Performance of high volume fly ash concrete incorporating additives: A systematic literature review," Construction and Building Materials, vol. 258, p. 120606, 2020.

[66] D. T. Doan, A. GhaffarianHoseini, N. Naismith, T. Zhang, and J. Tookey, "A critical comparison of green building rating systems," Building and Environment, vol. 123, pp. 243-260, 2017.

[67] S. Petter, W. DeLone, and E. McLean, "Measuring information systems success: Models, dimensions, measures, and interrelationships," European Journal of Information Systems, vol. 17, no. 3, pp. 236-263, 2008.

[68] A. H. Ali et al., "Big data classification based on improved parallel k-nearest neighbor," TELKOMNIKA (Telecommunication Computing Electronics and Control), vol. 21, no. 1, pp. 235-246, 2023.

[69] R. A. Hasan, H. W. Abdulwahid, and A. S. Abdalzahra, "Using ideal time horizon for energy cost determination," Iraqi Journal For Computer Science and Mathematics, vol. 2, no. 1, pp. 9-13, 2021.

[70] R. A. Hasan, T. Sutikno, and M. A. Ismail, "A review on big data sentiment analysis techniques," Mesopotamian Journal of Big Data, vol. 2021, pp. 6-13, 2021.

[71] R. A. Hasan, M. M. Akawee, and T. Sutikno, "Improved GIS-T model for finding the shortest paths in graphs," Babylonian Journal of Machine Learning, vol. 2023, pp. 7-16, 2023.

[72] M. A. Mohammed et al., "The effectiveness of big data classification control based on principal component analysis," Bulletin of Electrical Engineering and Informatics, vol. 12, no. 1, pp. 427-434, 2023.