A Review on the Mechanical Performance of High-Volume Fly Ash Light-Weight Concrete

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ABSTRACT

One of the most crucial ecological challenges is the removal of the ever increasing enormous quantities of Fly Ash (FA) generated from various industries and its reduction in landfill spaces. Light-Weight Aggregate Concrete (LWAC) is utilized in the construction industry as it can decrease the unit weight leading to lower dead load, thermos-insulation, and resistance against earthquakes. A number of researchers have implemented experimental programs on the use of large amounts of FA as a substitute for cement in various lightweight concrete mixtures. This study aims to present the recent efforts of adding attapulgite in LWAC and highlight its effects and the influence of its mixture with High Volume FA Light-Weight Concrete (HVFALC) in terms of compressibility resistance, tensile strength, and rupture resistance.

Keywords-light-weight aggregate; cement substitute; high volumes fly ash; attapulgite aggregate; mechanical performance

I. INTRODUCTION

The demand for LWAC in intelligent infrastructure is essential due to its ability to reduce dead loads and thermal insulation, especially in tall buildings. The American Concrete Institute (ACI) committee recommends that LWAC have a unit weight between 1120 and 1920 kg/m^3 and a compressive strength of more than 17 MPa [1-3]. The global LWAC market reached around 37.3 billion USD in 2018 while the estimated value in 2026 is around 56.8 billion USD indicating the escalating global demand for LWAC [4]. To meet this growing need for infrastructure, innovative methods for producing LWAC must be explored, potentially leading to an increase in cement and natural aggregate usage. The manufacturing of concrete produces a significant amount of CO_2, contributing to global warming [5-7]. A formula can estimate the carbon dioxide emissions produced by concrete, considering emissions from its components and processes like mixing and transportation [8]. For example, it is reported that manufacturing 1 m^3 of concrete with standard components results in approximately 287 kg of CO_2 emissions [9]. Portland cement represents the most significant contribution to energy consumption in concrete [10]. Utilizing pozzolanic materials as a replacement of cement leads to the reduction of CO_2 emissions [11]. Additionally, manufacturing by-products, such as FA, as a high-volume substitute for cement can offer substantial benefits in terms of cost, energy production, environmental sustainability, and durability [12, 13]. Approximately 777 million tons of FA were generated in 2008 globally, with only 54% of them being utilized [14]. The disposal of such a large quantity of FA poses environmental risks, including dust and air pollution [15, 16]. Annual FA production is about 900 million tons, with only about 55% of this amount being currently used [17], leading to significant disposal issues as the excess ash is often discarded in landfills or the ocean [18, 19]. This method increases the risk of air and water pollution through leaching, which can be mitigated by utilizing specific percentages of FA as a cement substitute, with substitution rates reaching up to 50% [20-22]. This approach contributes to the growth of HVFALC aiming to mitigate environmental impacts while addressing the challenges of FA disposal and contributing to the sustainability of construction materials.

The current research aims to assess the key mechanical characteristics of LWAC. Additionally, it offers a comprehensive review of the existing literature on the use of HVFALC in the production of LWAC.

II. TYPES OF LIGHT-WEIGHT AGGREGATE CONCRETE

Light-weight materials are employed as substitutes for traditional fine or coarse aggregates in the production of LWAC [23, 24]. There are two principal categories of LWACs: organic and inorganic [25]. Organic LWACs encompass materials, such as attapulgite, pumice, rice-husk, oil palm, and coconut shells, whereas inorganic LWACs contain expanded clays and sintered FA [26-29]. Typically, LWAC possesses a unit weight of less than 2000 kg/m^3, in contrast to the 2400 kg/m^3 standard for Regular Conventional Weight Concrete (RCWC). LWAC finds application in construction as prefabricated walls, precast elements, and building blocks due to its reduced unit weight, which leads to a lower dead load on structures, thereby diminishing shipping and handling costs. Additionally, the reduced unit weight of LWAC enhances thermal insulation and eliminates the risk of earthquake damage. Finally, LWAC offers protection against corrosion for steel reinforcements [30-32].

III. ATTAPULGITE LIGHT-WEIGHT AGGREGATE CONCRETE

Attapulgite Aggregate (AA), a crystalline hydrated compound $Al_2Mg_2O_{15}Si_5$, possesses a distinct chemical structure that endows it with exclusive supportive characteristics. It represents the utmost prevalent form of ground, a term denoting a series of highly absorbent clays [33, 34]. Several research efforts have been performed into attapulgite, a natural clay mineral in Iraq, initiated by developing mineral admixtures using natural materials sourced from the Al-Najaf tar area. A study conducted in 2014 explored the viability of utilizing clays located at the southwest of Iraq as a gravel. This investigation was segmented into two phases: the first focused on producing light-weight coarse aggregate and identifying the optimal calcination rate, while the second aimed at creating LWAC using the produced aggregate. At an optimal firing temperature of 800 °C, the density of the Attapulgite Light-Weight Aggregate Concrete (ALWAC) was recorded to be 808 kg/m^3, with a dry specific gravity of 1.45 at a higher calcination above 1000 °C [35, 36].

Certain methods have been proposed to produce AA from Iraqi attapulgite, subsequently designing an ALWAC mixture. The process is initiated with the collection of raw material from the Tar Al-Najaf region in Iraq, which is then pulverized to a fine powder through milling. The crucial step is the estimation of the optimal firing temperature, which should not exceed 1100 °C for more than 30 minutes. Reducing the grain size positively contributes to the quality of the produced mixture [37].

The use of attapulgite as a highly reactive mineral admixture can help develop compressive strength by 12.2, 12.6, and 16.3% accompanied with a relative reduction in water absorption by 4%, 4.8%, and 4.9% at 1, 4, and 8 weeks, respectively [38]. Moreover, the Ultrasonic Pulse Velocity (UPV) measurements proved to be an improvement in densifying the ALWAC. Another study utilized a locally Iraqi attapulgite as a replacement of coarse LWAC in making Light-Weight Concrete (LWC) with self-consolidating properties and the produced mixture was aligned with the criteria of EFNARC for self-consolidating concrete [39].

Furthermore, an experimental research assessed the performance of reinforced beams casted using ALWAC. The cylindrical compressive strength of LWAC is around 50% lower than the strength of Normal-Weight Aggregate Concrete (NWAC). Furthermore, a weight reduction of 20.6% in LWAC beams is observed in comparison to NWAC. The failure stress of LWAC beams is only 5% lower than that for/of NWAC and under the two-point bending test and a decrease in ductility and toughness [40].

A study proposed producing LWAC with a density of 1.668 ton/m^3 and a compressive strength of 21.8 MPa by adding AA composed of 50% fine LWAC, 100% coarse LWAC, and 10% of pozzolanic material. This mix design resulted in two types of insulating LWAC. The first sample had a density of 1.38 ton/m^3 and a thermal conductivity of 0.37 W/m.K for AA with 100% fine and 100% coarse aggregate. On the other hand, the second type's density was 1.432 ton/m^3 and its thermal conductivity was 0.41 W/m.K for AA with 100% fine, 100% coarse aggregate, and 10% of pozzolanic material [41].

Another study researched the relation between the particle size of AA and the content of Micro Steel Fiber (MSF) corresponding to the resulted engineering characteristics of Light-Weight Self-Consolidated Concrete (LWSCC). The sampling of the LWSCC included two mix designs depending on maximum particle sizes, 12.5 mm and 19 mm, and three MSF contents, 0.5%, 1%, and 1.5%, for each type. An inverse correlation is observed when utilizing the higher limit of particle size. Specifically, it indicates an improvement in fresh properties and a weakness in hardening properties [42]. Additionally, incorporating MSFs negatively impacts the fresh properties, especially at higher MSF contents and at larger AA particle sizes. Moreover, a study produced light-weight coarse attapulgite gravel from a natural material by calcining it at 1100 °C for half an hour and treating it with a 6% concentration of NaOCl for one day. It explored the influence of using silica fume ratios from 10 to 20% of the cement's/by cement weight, with steel fiber ratio of 0.5 and 1% of the total volume. The research demonstrated that treating attapulgite with NaOCl enhanced the concrete's compressive strength by approximately 18%. Furthermore, the use of silica fume and steel fibers significantly improved the engineering characteristics of LWAC. A considerable percentage of failure was noted for the designed beams, reaching 80% on the failure stress post-cracking [43].

An additional experimental research produced LWC using AA and examined the shear performance of LWSCC beams under axial and flexural loads. Flexural loads were applied at two points progressively until beam failure. Beam samples with advancing/declining ratios of 2.5, 2.75, and 3, were also prepared by being subjected to various axial loads of 100 KN and 150 KN. It was discovered that beam samples with lower advancing/declining ratios failed at minor bending levels compared to other samples. Applied axial loads delayed the failure of LWSCC beams and altered the failure mechanism from shearing to compressive and crushing, due to the compressive stresses at the top of the beams [44].

The use of 10% High Reactivity Attapulgite (HRA) in the concrete mix increased the compressive strength by 6, 7, 12, and 9% at a curing age of 1, 2, 4, and 13 weeks [45].

Finally, a study investigated the impact of using 5 and 10% of reactive attapulgite as a cement substitute on the compressive strength and permeability of the reinforced concrete. The results revealed that an increase of 10% does not greatly affect the permeability of the concrete, but the compressive strength is reduced by 10% [46].

IV. MECHANICAL FEATURES OF LWA CONCRETE

An experimental program investigated the use of Oil Palm Shell Aggregate (OPSA) as a replacement for gravel in the making of LWAC to evaluate its strength and behavior. The use of a high replacement percentage of OPSA results in a range of 34 to 55 MPa regarding compressive strength. Furthermore, the range flexural strength received values from 5 to 6 MPa highlighting the/OPSA suitability in various construction works [47, 48]. Expanded Glass Aggregate (EGA) can be added instead of gravel to produce LWAC suggesting an enhancement in the compressive and flexural characteristics [49].

The compressive strength of LWAC with EGA is relatively steady compared to that of the normal concrete. On the same manner, the Light-Weight Expanded Clay Aggregate (LWECA) reduced the unit weight by 23% compared to the normal concrete. A research endeavor examined the impact of LWECA grain size on the elasticity modulus of LWAC [50-52]. Increasing the LWECA grain size led to a decrease in the elasticity modulus. Thus, the conventional methods deployed for determining the modulus of elasticity are not applicable for LWAC using a fine grain size of LWECA [53]. Another study revealed a strong relation between the elastic modulus and grain size, with an R^2 value of 0.96, highlighting the subtle influence of aggregate properties on LWAC mechanics [54]. Replacing aggregate with thermocol in combination with FA reduced density significantly, while the compressive strength remained steady [55]. Particularly, using 1590 kg of FA per 15 cm^3 as a filler maintained the compressive strength of LWAC with thermocol [46].

V. HIGH-VOLUME FLY ASH IN LIGHT-WEIGHT AGGREGATE CONCRETE

High Volume Fly Ash Concrete (HVFAC) has gained a great attention recently due to its promising results in terms of cost-effectiveness, durability, and sustainability. Employing concrete with significant quantities of FA has led to creating review articles on the existing research of HVFAC [56, 57]. The incorporation of high amounts of FA in LWC, includes the latter's manufacturing using light-weight FA aggregate to substitute the conventional aggregate in high volumes [58]. Although numerous review articles exist on the topic of light-weight FA aggregate, a gap remains in the literature regarding comprehensive reviews or comparisons of studies focusing on LWC that contains high proportions of FA as a cement substitute [59-61].

VI. COMPRESSIBILITY RESISTANCE OF HIGH VOLUMES OF FA LWC

Several researchers have explored the impact of FA as a substitute of cement in the making of High FA Light-Weight Concrete (HVFALC), with substitution rates ranging from 50% to 80% [62]. Experimental studies have documented a drop in the peak compressive stress during the first weak of curing, when 50, 60, and 70% of cement was substituted with high-calcium FA [63]. Utilizing 50% of FA as a replacement, at a ratio of 0.45 water to binder resulted in a decrease of 58.6% and 48.5% at 4 and 13 weeks, respectively [64]. Another study exhibited a growth of 11% in the compressive strength of LWC in comparison to the free from FA concrete by replacing the total coarse aggregate with FA coarse aggregate [65]. The optimal strength of LWC can be received by replacing the conventional coarse aggregate with 50% of sintered FA coarse aggregate and replacing the fine aggregate with 75% of FA cenosphere [66]. The sintered FA aggregate presents higher strength values when using a concrete mix under dry conditions rather than under saturated conditions [67].

Furthermore, the compressive strength between High Volume FA Normal-Weight Concrete (HVFANWC) and HVFALC was compared using 50% FA as a cement substitute in both concrete types [60]. A higher reduction was detected in strength for HVFALC than for HVFANWC by about 64.7%, 58.6%, and 49.4% during the 1, 4, and 13 weeks of curing, respectively. Additionally, the impact of high FA volumes was investigated as a cement substitute in Light-Weight Mortar

(LWM) containing waste polyethylene terephthalate as an aggregate [61]. The specific study noted a decrease in compressive strength over the first, fourth, thirteenth, and twenty-sixth week of curing, with reductions of 51.9%, 34.1%, 19.7%, and 14.3%, respectively, when using 50% FA. A study attempted to identify the impact of substituting 50% of cement with FA on the UCS of OPSA high-resistance LWC, detecting reductions of 48.9%, 33.2%, and 29.2% in the first, fourth, and eighth week of curing, respectively [63].

The impact of high FA volumes on the UCS of Light-Weight Foamed Concrete (LWFC) was assessed during the first, second, and fourth week of curing, observing significant decreases in strength by 78.8%, 69.8%, and 62.4% for concrete samples containing 50% FA [64]. A different research study created an environmentally friendly LWC with a compressive strength exceeding 30 MPa, utilizing 60 and 80% of FA as a cement substitute and light-weight FA aggregate as a normal aggregate substitute [68]. 25% of expanded polystyrene with FA and glass powder as a filler were used in the optimal ratio to obtain compressive strength of 28 MPa at 28 days [69]. A comparison of the compressive strength between LWAC and HVFALC, using 50% FA as a cement substitute and OPSA as a gravel substitute in HVFALC, demonstrated a decrease in strength for HVFALC compared to LWAC of approximately 48.9%, 33.3%, 29.1, and 27.7% during the first, fourth, eighth, and thirteenth week of curing [70]. Moreover, an experiment was performed to investigate the compressive strength of LWSCC formation using OPSA and a high quantity of FA [71]. A decrease in strength was noted by 10%, 17.7%, and 11.6% during the first, fourth, and thirteenth week of curing, respectively.

Additionally, a comparative research was carried out on the compressive strength characteristics including Normal-Weight Foamed Concrete (NWFC) and LWFC [72]. In the LWFC samples, 50% of FA replaced the cementitious materials, and 50% of quarry dust substituted conventional sand. The results indicated a reduction in compressive strength for LWFC compared to NWFC by approximately 7.1%, 25.45%, and 29.7% at the first, second, and fourth week of curing, respectively. A study was conducted to assess the impact of replacing cement with FA at levels of 22%, 50%, and 75% on the compressive strength of LWFC across five different densities, 800, 1000, 1200, 1400, and 1600 kg/m3 [73]. A notable drop was observed in the UCS value with a rise in the FA percentage.

The impact of FA on the density and strength of geopolymer concrete by 15%, 22.5%, and 30% was explored [74]. The results implied that the 30% of FA showed a higher reduction in density with a value of 750 kg/m^3. However, a higher compressive strength and tensile strength was obtained when FA was mixed with percentages of 22.5% and 15%.

A research experiment characterized the UCS behavior of HVFALC using two forms of LWAC; Expanded Clay (EC) and Expanded Shale (ES) along with two types of FA, namely Class F and C [75]. FA was used to substitute cementitious materials in percentages of 50% and 70%, maintaining a steady water over binder ratio equal to 0.4. Despite the reduction in the UCS value associated with the use of either class of FA, all produced concrete mixes exhibited a compressive strength higher than 17 MPa in the fourth week. These results deem the mixture suitable for structural applications according to ACI 318 standards [76]. Additionally, the use of either class of FA delayed the initial development of strength and influenced its progression at later stages, a phenomenon corroborated by other similar studies [53, 56, 77]. The effect of using higher volumes of FA on the UCS of various concrete combinations, as reported in previous research, is summarized in Table I. The percentage of decrement in compressive strength was compared to the reference mixture without FA.

TABLE I. IMPACT OF HIGH QUANTITIES OF FA IN COMPRESSIBILITY RESISTANCE

Type of mixture	Type of substitution	FA (%)	Age (week)	Decrement in comp. resistance (%)	Ref.
LWAC	cementitious	50	4	58.6	[78]
			13	48.5	
LWAC	cementitious	50	1	64.7	[79]
			4	58.6	
			13	49.4	
LWM	cementitious	50	1	51.9	[80]
			4	34.1	
			13	19.7	
			26	14.3	
LWAC	cementitious	50	1	48.9	[81]
			4	33.2	
			8	29.2	
LWFC	cementitious	50	1	78.8	[61]
			2	69.8	
			4	62.4	
LWAC	cementitious	50	1	48.9	[63]
			4	33.3	
			8	29.1	
			13	27.7	
LESCC	cementitious	50	1	10	[64]
			4	17.7	
			13	11.6	
LWFC	cementitious	50	1	7.1	[68]
			2	25.45	
			4	29.7	
LWFC	cementitious	25	1	19.9	[70]
			4	10.4	
		50	1	29.3	
			4	20.7	
		75	1	48.7	
			4	32.3	
LWC (FA, HRA)	cementitious	20	26	5	[44]

VII. TENSILE SPLITTING RESISTANCE OF HVFALC

The majority of the authors mentioned above have documented the tensile strength for several types of HVFALC. To begin with, a significant reduction in tensile strength for HVFALC samples was observed when compared to HVFANWC, amounting to 49% at the thirteenth week of curing [59]. Regarding LWFC, a decrease in tensile strength was reported for samples containing 50% FA in comparison to those with no FA [63]. Similarly, comparing tensile strength between LWAC and HVFALC, a reduction of 38.4% in tensile strength was observed at the fourth week for HVFALC samples using OPSA compared to LWAC samples with normal aggregate [62]. In the case of LWSCC produced with OPSA and a high volume of FA, a decline in tensile strength of about 45.2%, 42.6%, and 27.1% was noted for samples containing 50% FA versus those without FA at the first, fourth, and thirteenth week of curing, respectively [70].

A significant decrease in tensile strength was detected between NWFC and LWFC [72]. Specifically, LWFC samples containing 50% of FA as a cement substitute and 50% of quarry dust aggregate as a sand substitute exhibited a decrease in tensile strength of approximately 45.8% and 34.1% at the first and fourth week, respectively, compared to NWFC samples with no FA and conventional sand. In another study, that employed EC or ES as LWAC with two types of FA, class F or C, substituting 50% of cement, a reduction in tensile strength was reported when utilizing either class of FA across all produced concretes [75]. An exception was noted for concrete containing 50% of FA Class C with EC aggregate, which exhibited an increase in tensile strength by about 26.2% at the fourth week compared to the Normal Weight Concrete (NWC) without FA. The impact of utilizing high quantities of FA on the tensile strength of various concrete mixtures, compared to prior research, is summarized in Table II.

TABLE II. IMPACT OF HIGH QUANTITIES OF FA IN TENSILE RESISTANCE

Type of mixture	Type of substitution	FA (%)	Age (week)	Decrement in tensile resistance (%)	Ref.
LWAC	cementitious	50	13	49	[79]
LWAC	cementitious	50	4	38.4	[63]
LWSCC	cementitious	50	1	45.2	[64]
			4	42.6	
			13	27.1	
LWFC	cementitious	50	1	45.8	[68]
			4	34.1	
LWAC	Aggregate by sintered FA aggregate	100	28	10.25	[82]

VIII. MODULUS OF RUPTURE OF HVFALC

LWM containing waste polyethylene terephthalate as a fabricated aggregate and a high quantity of FA leads to a decrease in the modulus of rupture [61]. Specifically, samples containing 50% FA presented reductions in rupture resistance of approximately 36.6%, 23.3%, 24.5%, and 25.9% at the first, fourth, thirteenth, and twenty-sixth week, respectively, compared to those being free of FA. Substituting cement with FA at 50% on the rupture resistance of high-resistance LWC using OPSA suggests a significant decrease by about 45.4% in the fourth week of curing as the FA content increased from 0 to 50% [63]. 25% bagasse of FA and fine sand substitute with 30% of cenospheres are the ideal values for flexural strength improvement [83].

Furthermore, investigating the rupture resistance of LWAC and HVFALC, a decrease of about 23.1% was observed in the former at the fourth week for HVFALC samples containing OPSA compared to LWAC samples with normal aggregate [70]. The use of EC or ES as LWAC aggregates considering two types of FA, class F or C, at 50% as cement substitutes, reported an improvement in rupture resistance [74]. Conversely, a decrease in rupture resistance was noted when either class of FA was utilized at 70% across all produced concretes. The impact of employing high quantities of FA on the rupture resistance of various concrete mixtures, as documented in prior research, is summarized in Table III.

TABLE III. HIGH QUANTITIES OF FA IMPACT ON THE RUPTURE RESISTANCE

Type of mixture	Type of substitution	FA (%)	Age (week)	Decrement in rupture resistance (%)	Ref.
LWM	cementitious	50	1	36.6	[80]
			4	23.3	
			13	24.5	
			26	25.9	
LWAC	cementitious	50	4	45.4	[81]
LWAC	cementitious	50	4	23.1	[63]
LWAC (50% FA aggregate)	cementitious	40	4	8.2	[84]

IX. CONCLUSION

This paper presents recent endeavors that assess the key mechanical characteristics of Light-Weight Aggregate Concrete (LWAC), as well as the effects of employing significant quantities, exceeding 45%, of Fly Ash (FA) in replacing the cementitious material in eco-friendly High Volume FA Light-Weight Concrete (HVFALC). This work aimed to elucidate the performance of LWAC and HVFALC mixtures considering characteristics, such as compressive strength, tensile strength, and rupture resistance. The key points of the research outcomes are:

- The use of certain types of LWAC, for example the expanded glass aggregate, results in the production of Light-Weight Concrete (LWC), whose mechanical characteristics are close to those of Normal-Weight Concrete (NWC) manufactured with conventional aggregates.
- The incorporation of substantial quantities of FA into various LWC mixtures, including LWAC, Light-Weight Mortar (LWM), Light-Weight Foam Concrete (LWFC), and Light-Weight Self-Consolidating Concrete (LWSCC), tends to diminish their compressive strength in comparison with equivalent concrete mixtures free of FA.
- Regarding tensile strength, analogous to the impact observed on compressive strength, the use of substantial quantities of FA in the aforementioned LWC mixtures similarly diminishes their tensile splitting resistance. Incorporating 50% of FA into a LWC mixture with expanded clay aggregate has been shown to enhance both tensile and rupture resistance.
- The addition of substantial quantities of FA into a variety of LWC mixtures, including Light-Weight Structural Concrete

(LWSC), LWM, LWFC, and LWSCC, results in a decrease in rupture resistance when compared to equivalent concrete mixtures without FA.

REFERENCES

[1] ACI Committee 213, *Guide for Structural Light-weight-Aggregate Concrete*, 1st ed., 38800 Country Club Drive Farmington Hills, MI, USA: American Concrete Comittee, 2014.

[2] M. Al-Daraji and N. Aljalawi, "The Effect of Kevlar Fibers on the Mechanical Properties of Light-weight Perlite Concrete", *Engineering, Technology & Applied Science Research,* vol. 14, no.1, pp. 12906–12910, Feb. 2024, https://doi.org/10.48084/etasr.6665.

[3] N. M. F. Aljalawi, "Production of Building Blocks BufferLight-weightConcrete," *TEST Engineering & Management*, vol. 83, Apr. 2020, Art. no. 13100.

[4] "Materials and Chemicals - Light-weight Aggregate Concrete Market, " Reports and Data. Accessed: Sep. 17, 2024.

[5] N. M. F. Aljalawi, "Quality Control of Production Light-weight Ferrocement Plate Using Sustainable Materials," *Key Engineering Materials*, vol. 857, pp. 10-20, Aug. 2020, https://doi.org/10.4028/www.scientific.net/KEM.857.10.

[6] E. Benhelal, G. Zahedi, E. Shamsaei, and A. Bahadori, "Global strategies and potentials to curb CO2 emissions in cement industry," *Journal of Cleaner Production*, vol. 51, pp. 142-161, Jul. 2013, https://doi.org/10.1016/j.jclepro.2012.10.049.

[7] M. A. Nomeli and A. Riaz, "The Potential for Carbon Dioxide Sequestration in Subsurface Geological Formations," in *Handbook of Clean Energy Systems*, John Wiley & Sons, Ltd, 2015, pp. 1–10, https://doi.org/10.1002/9781118991978.hces161.

[8] H. S. Lee and X. Y. Wang, "Evaluation of the Carbon Dioxide Uptake of Slag-Blended Concrete Structures, Considering the Effect of Carbonation," *Sustainability*, vol. 8, no. 4, Mar. 2016, Art. no. 4, https://doi.org/10.3390/su8040312.

[9] M. Davoodabadi, I. Vareli, M. Liebscher, L. Tzounis, M. Sgarzi, A. S. Paipetis, J. Yang, G. Cuniberti, and V. Mechtcherine, "Thermoelectric Energy Harvesting from Single-Walled Carbon Nanotube Alkali-Activated Nanocomposites Produced from Industrial Waste Materials," *Nanomaterials*, vol. 11, no. 5, Apr. 2021, Art. no. 1095, https://doi.org/10.3390/nano11051095.

[10] D. J. Kazem and N. M. Fawzi, "Effect of Sustainable Materials on Some Properties of Pervious Concrete", *Engineering, Technology & Applied Science Research*, vol. 14, no. 3, pp. 14039–14043, Jun. 2024, https://doi.org/10.48084/etasr.7193.

[11] L. Struble and J. Godfrey, "How sustainable is concrete," in *Proceedings of the International Workshop on Sustainable Development and Concrete Technology*, Beijing, China, May 2004.

[12] S. Sadati, M. Arezoumandi, K. H. Khayat, and J. S. Volz, "Shear performance of reinforced concrete beams incorporating recycled concrete aggregate and high-volume fly ash," *Journal of Cleaner Production*, vol. 115, pp. 284-293, Mar. 2016, https://doi.org/10.1016/j.jclepro.2015.12.017.

[13] M. Arezoumandi and J. S. Volz, "Effect of fly ash replacement level on the shear strength of high-volume fly ash concrete beams," *Journal of Cleaner Production*, vol. 59, pp. 120-130, Nov. 2013, https://doi.org/10.1016/j.jclepro.2013.06.043.

[14] J. Jow, Y. Dong, Y. Zhao, S. Ding, Q. Li, X. Wang, and S.Y. Lai, "Fly ash-based technologies and value-added products based on materials science," presented at the 2015 World of Coal Ash Conference, Nashville, TN, USA, May 2015.

[15] V. M. Malhotra, and P. K. Mehta, *High-performance, high-volume fly ash concrete: materials, mixture proportioning, properties, construction practice, and case histories*, 2nd ed. Ottawa, Canada: Supplementary Cementing Materials for Sustainable Development Inc., 2005.

[16] P. K. Mehta, "High-performance, high-volume fly ash concrete for sustainable development," presented at the International Workshop on Sustainable Development and Concrete Technology, University of California, Berkeley, CA, USA, Jan. 2004.

[17] C. Heidrich, H. J. Feuerborn, and A. Weir, "Coal combustion products - A global perspective," presented at the World of Coal Ash Conference, Lexington, KY, USA, Apr. 2013.

[18] N. M. F. Aljalawi, "Production of light weight high strength block by use of additive materials," presented at the Second Conference of Construction and Construction Engineering, Baghdad, Iraq, Mar. 2017.

[19] J. Wang, Q. Qin, S. Hu, and K. Wu, "A concrete material with waste coal gangue and fly ash used for farmland drainage in high groundwater level areas," *Journal of Cleaner Production*, vol. 112, pp. 631-638, Jan. 2016, https://doi.org/10.1016/j.jclepro.2015.07.138.

[20] A. Fernández-Jiménez, A. Palomo, and M. Criado, "Microstructure development of alkali-activated fly ash cement: a descriptive model," Cement and Concrete Research, vol. 35, no. 6, pp. 1204-1209, Jun. 2005.

[21] M. Ahmaruzzaman, "A review on the utilization of fly ash," *Progress in Energy and Combustion Science*, vol. 36, no. 3, pp. 327-363, Jun. 2010.

[22] N. M. F. Aljalawi, K. I. Aziz, and S. Hama, "Effect of Metakaolin on Properties of Light-weight Porcelinate Aggregate Concrete," Journal of Engineering Physics, vol. 19, no. 4, Apr. 2013, https://doi.org/10.31026/j.eng.2013.04.02.

[23] J. Kravchenko and H. K. Lyerly, "The Impact of Coal-Powered Electrical Plants and Coal Ash Impoundments on the Health of Residential Communities," *North Carolina Medical Journal*, vol. 79, no. 5, pp. 289-300, Sep. 2018, https://doi.org/10.18043/ncm.79.5.289.

[24] A. Gianoncelli, A. Zacco, R. P. W. J. Struis, L. Borgese, L. E. Depero, and E. Bontempi, "Fly Ash Pollutants, Treatment and Recycling," in *Pollutant Diseases, Remediation and Recycling*, E. Lichtfouse, J. Schwarzbauer, and D. Robert, Eds., Cham, Germany: Springer International Publishing, 2013, pp. 103–213, https://doi.org/10.1007/978-3-319-02387-8_3.

[25] S. K. Adhikary, D. K. Ashish, and Ž. Rudžionis, "Expanded glass as light-weight aggregate in concrete – A review," *Journal of Cleaner Production*, vol. 313, Sep. 2021, Art. no. 127848, https://doi.org/10.1016/j.jclepro.2021.127848.

[26] M. Najmudin, H. Bakar, S. A. Kudus, N. Mustaffa, A. Jamadin, H. Abbas, R. Hassan, and N. Kamaruddin, "Effect of rice-husk as replacement cement on mechanical properties of concrete," *Journal of Mechanical Engineering*, vol. 20, no. 2, pp. 91-104, Apr. 2023, https://doi.org/10.24191/jmeche.v20i2.22056.

[27] M. Hussein, N. Fawzi, and Z. R. A. Raouf, "Insulating light weight aggregate concrete," *Engineering and Technology Journal*, vol. 28, no. 13, pp. 678-691, 2010.

[28] S. İpek, O. Ayodele, and K. Mermerdaş, "Influence of artificial aggregate on mechanical properties, fracture parameters and bond strength of concretes," *Construction and Building Materials*, vol. 238, Mar. 2020, https://doi.org/10.1016/j.conbuildmat.2019.117756.

[29] E. Yasar, C. Atis, A. Kiliç, and H. Gulsen, "Strength properties of light-weight concrete made with basaltic pumice and fly ash," *Materials Letters*, vol. 57, pp. 2267-2270, Apr. 2003, https://doi.org/10.1016/S0167-577X(03)00146-0.

[30] D. L. C. Hao, R. Abd Razak, M. Kheimi, Z. Yahya, M. M. A. B. Abdullah, D. D. B. Nergis, H. Fansuri, R. Ediati, R. Mohamed, and A. Abdullah, "Artificial light-weight aggregates made from pozzolanic material: A review on the method, physical and mechanical properties, thermal and microstructure," *Materials* vol. 15, no. 11, Nov. 2022, Art. no. 3929, https://doi.org/10.3390/ma15113929.

[31] N. M. F. Al Jalawi, "Production of high performance light-weight plates by use of sustainability materials," presented at the Second Conference of Construction and Construction Engineering, Baghdad, Iraq, May 2017.

[32] D. J. L. Clarke, Ed., *Structural Light-weight Aggregate Concrete*. London, UK: CRC Press, 2014, https://doi.org/10.1201/9781482269307.

[33] S. Chandra and L. Berntsson, *Light-weight Aggregate Concrete-Science, Technology, and Applications*, William Andrew Publishing/Noyes, 2002.

[34] ACI Committee 213-03, *Guide for Structural Light Weight Concrete*, MI, USA, American Concrete Institure, 2003.

[35] W. L. Haden and I. A. Schwint, "Attapulgite: Its properties and applications," *Industrial & Engineering Chemistry*, vol. 59, no. 9, pp. 58-69, 1967, https://doi.org/10.1021/ie51403a012.

[36] Q. J. A. Hachim, and N. M. Fawzi, "The effect of different types of aggregate and additives on the properties of self-compacting light-weight concrete", *Journal of Engineering*, vol. 18, no. 8, pp. 875-888, 2012.

[37] Q. Frayyeh, W. A. Abbas, and M. Hussein, "Producing light-weight concrete aggregate from Iraqi attapulgite," in *Proceedings of International Structural Engineering and Construction*, vol. 1, Nov. 2014, https://doi.org /10.14455/ISEC.res.2014.132.

[38] Q. J. Frayyeh, W. A. Abbas, and A. Hassan, "The Combined Effect of Attapulgite High Reactive Mineral Admixture and Superplasticizer on Compressive Strength of Attapulgite Light-weight Aggregate Concrete," *Engineering & Technology Journal*, vol. 34, pp. 2181-2192, Jun. 2016, https://doi.org/10.30684/etj.34.12A.2.

[39] W. A. Abbas, Q. Frayyeh, and S. Alobaidy, "Fresh and Hardened Properties of Light-weight Self Compacting Concrete Containing Attapulgite," *Engineering & Technology Journal*, vol. 34, pp. 1767–1781, Apr. 2016, https://doi.org/10.30684/etj.34.9A.5.

[40] S. Badar, L. Rasheed, and S. Salih, "The Structural Characteristics of Light-weight Aggregate Concrete Beams," *Journal of University of Babylon for Engineering Sciences*, vol. 27, pp. 64–73, May 2019, https://doi.org/10.29196/jubes.v27i2.2293.

[41] H. H. Hammad, Z. M. Mohamed, and T. Rasheed, "Using Attapulgite as a Light-weight Aggregate to Produce Structural and Insulating Concrete," *Association of Arab Universities Journal of Engineering Sciences*, vol. 26, no. 2, pp. 131–139, Jun. 2019, https://doi.org/ 10.33261/jaaru.2019.26.2.016.

[42] S. Alobaidy, "The Effects of Maximum Attapulgite Aggregate Size and Steel Fibers Content on Fresh and Some Mechanical Properties of Light-weight Self Compacting Concrete," *Journal of Engineering*, vol. 26, pp. 172-190, May 2020, https://doi.org/10.31026/j.eng.2020.05.12.

[43] Z. A. Mirza and N. N. Khalid, "Flexural performance of reinforced concrete beams containing treated attapulgite as lightweight aggregate," *IOP Conference Series: Materials Science and Engineering*, vol. 988, no. 1, Sep. 2020, Art. no. 012049, https://doi.org/10.1088/1757-899X/ 988/1/012049.

[44] H. Qassim and W. AL-Saraj, "Shear compression failure in reinforced self-compacted light-weight concrete beams subjected to axial load," *Materials Today: Proceedings*, vol. 60, pp. 1179-1185, Aug. 2021, https://doi.org/10.1016/j.matpr.2021.08.035.

[45] S. Alobaidy, "The Synergic Effect of Fly Ash and High Reactivity Attapulgite in Ternary Blended Cement," *Engineering and Technology Journal*, vol. 37, pp. 528–535, Dec. 2019, https://doi.org/ 10.30684/etj.v37i12A.456.

[46] C. Verma, S. Chakradhari, A. Watti, and R. K. Singh, "Light-weight Concrete by using Thermocol and Fly Ash," *International Research Journal of Engineering and Technology*, vol. 9, no. 1, Jan. 2022.

[47] P. Shafigh, Z. Jumaat, H. Mahmud, and A. Hamid, "Light-weight concrete made from crushed oil palm shell: Tensile strength and effect of initial curing on compressive strength," *Construction and Building Materials*, vol. 27, pp. 252-258, Feb. 2012, https://doi.org/10.1016/j.conbuildmat.2011.07.051.

[48] J. Bogas, M. Gomes, and S. Real, "Bonding of steel reinforcement in structural expanded clay lightweight aggregate concrete: The influence of failure mechanism and concrete composition," *Construction and Building Materials*, vol. 65, pp. 350–359, Aug. 2014, https://doi.org/10.1016/10.1016/j.conbuildmat.2014.04.122.

[49] M. Laith, "Improvement some properties of concrete with internal curing by using lightweight aggregate," M.Sc. Thesis, University of Baghdad, Iraq, 2011.

[50] A. Ardakani and M. Yazdani, "The relation between particle density and static elastic moduli of lightweight expanded clay aggregates - ScienceDirect," *Applied Clay Science*, vol. 93–94, pp. 28–34, May 2014, https://doi.org/10.1016/j.clay.2014.02.017.

[51] B. Ayati, V. Ferrándiz-Mas, D. Newport, and C. Cheeseman, "Use of clay in the manufacture of lightweight aggregate," *Construction and Building Materials*, vol. 162, pp. 124–131, Feb. 2018, https://doi.org/ 10.1016/j.conbuildmat.2017.12.018.

[52] J. A. Bogas, A. Gomes, and M. F. C. Pereira, "Self-compacting lightweight concrete produced with expanded clay aggregate," *Construction and Building Materials*, vol. 35, pp. 1013–1022, Oct. 2012, https://doi.org/10.1016/j.conbuildmat.2012.04.111.

[53] H. S. Qassim and W. K. AL-Saraj, "Shear compression failure in reinforced self-compacted lightweight concrete beams subjected to axial load," *Materials Today: Proceedings*, vol. 60, no. 3, pp. 1179–1185, May 2022, https://doi.org/10.1016/j.matpr.2021.08.035.

[54] A. Gholampour and T. Ozbakkaloglu, "Performance of sustainable concretes containing very high volume Class-F fly ash and ground granulated blast furnace slag - ScienceDirect," *Journal of Cleaner Production*, vol. 162, pp. 1407–1417, Sep. 2017, https://doi.org/ 10.1016/j.jclepro.2017.06.087.

[55] M. M. Khan and A. Sachar, "Experimental Study on Light Weight Concrete by Partial Replacement of Cement by Flyash, Coarse Aggregate Pumice Stone and Thermocol Beads," *International Journal of Innovative Research in Computer Science & Technology*, vol. 10, no. 3, pp. 114–119, May 2022, https://doi.org/10.55524/ijircst.2022.10.3.19.

[56] T. Hemalatha and A. Ramaswamy, "A review on fly ash characteristics – Towards promoting high volume utilization in developing sustainable concrete," *Journal of Cleaner Production*, vol. 147, pp. 546–559, Feb. 2017, https://doi.org/10.1016/j.jclepro.2017.01.114.

[57] A. M. Rashad, "A brief on high-volume Class F fly ash as cement replacement – A guide for Civil Engineer," *International Journal of Sustainable Built Enviroment*, vol. 4, no. 2, pp. 278–306, Dec. 2015, https://doi.org/10.1016/j.ijsbe.2015.10.002.

[58] K. Křížová and M. Tomáš, "Lightweight Concrete with Agglomerated Aggregate Based on Fly Ash," *Materials Science Forum*, vol. 1070, pp. 217–222, 2022, https://doi.org/10.4028/p-4t4zs9.

[59] C. Herath, "Performance of high volume fly ash concrete incorporating additives: A systematic literature review," *Construction and Building Materials*, vol. 258, Oct. 2020, Art. no. 120606, https://doi.org/10.1016/j.conbuildmat.2020.120606.

[60] D. S. Babu, K. G. Babu, and T. H. Wee, "Properties of Light-weight Expanded Polystyrene Aggregate Concretes Containing Fly Ash," *Cement and Concrete Research*, vol. 35, no. 6, pp. 1218–1223, Jun. 2005.

[61] S. Akçaözoğlu and C. D. Atiş, "Effect of Granulated Blast Furnace Slag and fly ash addition on the strength properties of lightweight mortars containing waste PET aggregates," *Construction and Building Materials*, vol. 25, no. 10, pp. 4052–4058, Oct. 2011, https://doi.org/ 10.1016/j.conbuildmat.2011.04.042.

[62] A. P. Wibowo, M. Saidani, M. Khorami, and M. Tyrer, "Fly Ash and Silica in Expanded Polystyrene Concrete Finding the Research Gap (Preliminary Study)," in *Advances in Civil Engineering Materials*, Singapore, 2021, pp. 323–334, https://doi.org/10.1007/978-981-33-6560-5_32.

[63] P. Shafigh, U. J. Alengaram, H. B. Mahmud, and M. Z. Jumaat, "Engineering properties of oil palm shell lightweight concrete containing fly ash," *Materials & Design*, vol. 49, pp. 613–621, Aug. 2019, https://doi.org/10.1016/j.matdes.2013.02.004.

[64] A. O. Richard and M. Ramli, "Experimental Production of Sustainable Lightweight Foamed Concrete," *Current Journal of Applied Science and Technology*, vol. 3, no. 4, pp. 994–1005, Jul. 2013, https://doi.org/10.9734/BJAST/2013/4242.

[65] M. V. S. Reddy, M. C. Nataraja, K. Sindhu, V. Harani, and K. Madhuralalasa, "Performance of light weight concrete using fly ash pellets as coarse aggregate replacement," *International Journal of Engineering Research and Technology*, vol. 9, no. 2, pp. 95–104, 2016.

[66] H. P. Satpathy, S. K. Patel, and A. N. Nayak, "Development of sustainable lightweight concrete using fly ash cenosphere and sintered fly ash aggregate - ScienceDirect," *Construction and Building Materials*, vol. 202, pp. 636–655, Mar. 2019, https://doi.org/10.1016/j.conbuildmat. 2019.01.034.

[67] L. Domagała, "Durability of Structural Lightweight Concrete with Sintered Fly Ash Aggregate," *Materials*, vol. 13, no. 20, 2020, Art. no. 4565, https://doi.org/10.3390/ma13204565.

[68] F. Rivera, P. Martínez, J. Castro, and M. López, "'Massive volume fly-ash concrete: A more sustainable material with fly ash replacing cement and aggregates,'" *Cement and Concrete Composites*, vol. 63, pp. 104–112, Oct. 2015, https://doi.org/10.1016/j.cemconcomp.2015.08.001.

[69] M. M. Yassen and E. T. Dawood, "Production of lightweight concrete using expanded polystyrene with fly ash and glass powder," *AIP Conference Proceedings*, vol. 2862, no. 1, Dec. 2023, Art. no. 020007, https://doi.org/10.1063/5.0181338.

[70] P. Shafigh, M. A. Nomeli, U. J. Alengaram, H. B. Mahmud, and M. Z. Jumaat, "Engineering properties of lightweight aggregate concrete containing limestone powder and high volume fly ash," *Journal of Cleaner Production*, vol. 135, pp. 148–157, Nov. 2016, https://doi.org/10.1016/j.jclepro.2016.06.082.

[71] T. Z. H. Ting, M. E. Rahman, and H. H. Lau, "Sustainable lightweight self-compacting concrete using oil palm shell and fly as," *Construction and Building Materials*, vol. 264, Dec. 2020, Art. no. 120590, https://doi.org/10.1016/j.conbuildmat.2020.120590.

[72] R. Gopalakrishnan, V. Sounthararajan, A. Mohan, and M. Tholkapiyan, "The strength and durability of fly ash and quarry dust light weight foam concrete," *Materials Today: Proceedings*, vol. 22, no. 3, pp. 1117–1124, Feb. 2020, https://doi.org/10.1016/j.matpr.2019.11.317.

[73] A. S. Krishna, R. Siempu, and G. A. V. S. S. Kumar, "Study on the fresh and hardened properties of foam concrete incorporating fly ash - ScienceDirect," *Materials Today: Proceedings*, vol. 46, no. 17, pp. 8639–8644, Aug. 2021, https://doi.org/10.1016/j.matpr.2021.03.599

[74] N. Nikoloutsopoulos, A. Sotiropoulou, G. Kakali, and S. Tsivilis, "Physical and Mechanical Properties of Fly Ash Based Geopolymer Concrete Compared to Conventional Concrete," *Buildings*, vol. 11, no. 5, Apr. 2021, Art. no. 178, https://doi.org/10.3390/buildings11050178.

[75] T. Mohammed, F. Aguayo, M. Nodehi, and T. Ozbakkaloglu, "Engineering properties of structural lightweight concrete containing expanded shale and clay with high volume class F and class C fly ash," *Structural Concrete*, vol. 24, no. 3, pp. 4029–4046, Jun. 2023, https://doi.org/10.1002/suco.202200562.

[76] J. P. Moehle, "Key Changes in the 2019 Edition of the ACI Building Code (ACI 318-19)," *Concrete International*, vol. 41, no. 8, pp. 21–27, Aug. 2019.

[77] P. R. de Matos, M. Foiato, and L. R. Prudêncio Jr, "Ecological, fresh state and long-term mechanical properties of high-volume fly ash high-performance self-compacting concrete," *Construction and Building Materials*, vol. 203, pp. 282–293, Apr. 2019, https://doi.org/10.1016/j.conbuildmat.2019.01.074.

[78] M. S. Nadesan and P. Dinakar, "Structural concrete using sintered flyash lightweight aggregate: A review," *Construction and Building Materials*, vol. 154, pp. 928–944, 011 2017, https://doi.org/10.1016/j.conbuildmat.2017.08.005.

[79] S. Paknehad, H. Hasani, H. Paknehad, M. B. Azizi, and H. R. Nasseri, "Investigation the Properties of Foam Concrete: A review," in *Proceedings of the Conference on Concrete Innovations*, Tabriz, Azerbaijan, May 2022.

[80] T. R. Naik and S. S. Singh, "Superplasticized Structural Concrete Containing High Volume of Class C Fly Ash," *Journal of Energy Engineering*, vol. 117, no. 2, pp. 87–96, Aug. 1991, https://doi.org/10.1061/(ASCE)0733-9402(1991)117:2(87).

[81] K. G. Babu and D. S. Babu, "Performance of fly ash concretes containing lightweight EPS aggregates," *Cement and Concrete Composites*, vol. 26, no. 6, pp. 605–611, Aug. 2004, https://doi.org/10.1016/S0958-9465(03)00034-9.

[82] M. Rodacka, L. Domagała, and R. Szydłowski, "Assessment of Properties of Structural Lightweight Concrete with Sintered Fly Ash Aggregate in Terms of Its Suitability for Use in Prestressed Members," *Materials*, vol. 16, no. 15, Aug. 2023, Art. no. 5429, https://doi.org/10.3390/ma16155429.

[83] V. Kavinkumar, A. K. Priya, and R. Praneeth, "Strength of light weight concrete containing fly ash cenosphere," *Materials Today: Proceedings*, Apr. 2023, https://doi.org/10.1016/j.matpr.2023.04.094.

[84] K. R. Arul, "Experimental Study on Lightweight Fly Ash Aggregate Concrete," *International Journal of Innovative Research in Technology*, vol. 6, no. 5, Jan. 2019.