Strength and Sustainability in Concrete: The Dual Role of Fly Ash and Accelerators in Reducing Environmental Impacts

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ABSTRACT

The increasing demand for sustainable construction materials has driven researchers to explore environmentally friendly alternatives to conventional concrete. This study aims to investigate the dual role of fly ash and chemical accelerators in enhancing both the strength and sustainability of concrete. The research focuses on optimizing the compressive strength of concrete by replacing 50% of cement with fly ash and incorporating various dosages of superplasticizers and accelerators. Compressive strength tests were performed after 18 hours, 24 hours, 3 days, and 28 days to assess early and long-term strength performance. Additionally, a Life Cycle Assessment (LCA) was performed to assess the environmental impact of using fly ash in concrete production. The results show that all concrete variants achieved high early strength, with compressive strength values ranging from 32 MPa to 68 MPa within 24 hours, meeting the criteria for high early strength concrete. LCA analysis indicates that fly ash utilization significantly reduces the carbon footprint of concrete by reducing cement consumption. This research recommends the adoption of fly ash-based concrete with appropriate chemical additives as a sustainable solution to reduce environmental impacts in the construction industry while maintaining the required structural performance.

Keywords-strength; fly ash; accelerators; environmental impact

I. INTRODUCTION

Concrete is one of the most widely used construction materials in the world, playing a crucial role in infrastructure development and urbanization [1]. However, its production process contributes significantly to global carbon emissions, mainly due to the intensive energy-intensive manufacturing of cement, the primary binder in concrete [2, 3]. The cement industry alone is responsible for approximately 7-8% of global CO_2 emissions, making it a significant contributor to environmental degradation. This challenge has led to an increasing demand for more sustainable construction materials that can reduce the environmental impact of concrete production without compromising structural performance [4].

Various strategies have been proposed to reduce the carbon footprint of concrete, including the use of Supplementary Cementitious Materials (SCMs) such as Fly Ash (FA), slag, and silica fume. Among these materials, FA has gained significant attention due to its availability and pozzolanic properties, which improve concrete strength and durability while reducing the need for Portland cement. FA is a byproduct of coal combustion in power plants and has been used successfully as a partial cement replacement in concrete mixtures. Fly ash not only reduces CO_2 emissions but also addresses the issue of FA disposal, making it a sustainable alternative in concrete production [5-7].

Research on FA-based concrete has demonstrated its potential to improve long-term strength, durability, and resistance to chemical attacks. Replacing a portion of cement with FA can improve the durability of concrete structures, particularly in aggressive environments [8, 9]. In addition, FA contributes to improved workability and reduced hydration heat, making it suitable for large-scale concrete pours. Despite these benefits, one of the main challenges associated with high-volume FA concrete is its lower early-age strength compared to traditional concrete mixtures. This limitation has hindered its widespread adoption in projects that require fast construction timelines.

To address the issue of low early-age strength, researchers have explored the use of chemical admixtures, such as superplasticizers and accelerators. Superplasticizers improve the workability of concrete without increasing its water content, while accelerators speed up the setting and hardening process, enabling concrete to achieve higher early strength. In [10, 11], it was shown that the combined use of FA and accelerators can mitigate the early strength deficiency in FA-based concrete, making it more suitable for applications requiring high early strength.

Despite the promising results of previous studies, there is still limited research on the environmental benefits of using FA and chemical accelerators together in concrete production. Most existing research focuses on either the mechanical properties of FA-based concrete or the environmental impact of FA utilization. Few studies have comprehensively examined the dual role of FA and accelerators in enhancing both the strength and sustainability of concrete. This gap in the literature highlights the need for more research on the combined effects of these materials on concrete performance and environmental impact [12-15].

The environmental impact of concrete production can be assessed through Life Cycle Assessment (LCA), a method that evaluates the environmental effects associated with all stages of a product's life cycle, from raw material extraction to disposal. LCA studies on FA-based concrete have shown that the incorporation of FA significantly reduces the carbon footprint of concrete. However, the impact of accelerators on the overall environmental performance of concrete has not been thoroughly examined. Understanding the environmental trade-offs associated with the use of chemical additives in FA-based concrete is essential to developing sustainable construction solutions [16, 17].

In addition to reducing carbon emissions, the use of FA in concrete addresses the issue of industrial waste management. Coal-fired power plants generate millions of tons of FA annually, much of which end up in landfills. Utilizing FA as a cement replacement in concrete not only reduces the demand for virgin materials but also diverts waste from landfills, contributing to a circular economy. However, the challenge lies in achieving a balance between sustainability and performance, particularly in terms of early strength development.

Given the limitations of high-volume FA concrete in achieving early strength, this study focuses on optimizing concrete mixtures using FA and accelerators to achieve high early strength while minimizing environmental impact. This study aims to fill the literature gap by investigating the combined effects of FA and accelerators on both the strength and sustainability of concrete. By conducting compressive strength tests and LCA, the study provides a comprehensive evaluation of the mechanical and environmental performance of FA-based concrete.

The dual focus on mechanical performance and environmental sustainability sets this study apart from previous ones, offering a comprehensive approach to developing eco-friendly construction materials. Furthermore, the findings contribute to global efforts to manage industrial waste, particularly FA, by promoting its beneficial use in concrete production. The results are expected to support policymakers, engineers, and the construction industry in adopting sustainable practices that align with global sustainability goals, ultimately contributing to the transition toward greener infrastructure development.

II. MATERIALS AND METHODS

A. *Portland Composite Cement (PCC) and Fly Ash (FA)*

This work used physical and chemical investigations to determine the characteristics of PCC and FA as binding agents. The physical and chemical makeup of PCC and FA were examined using an XRF test and SNI. Tables I and II show the results of the evaluation of PCC and FA physical and chemical properties. To evaluate cement's potential as a binding agent for the research project, this study additionally examined its chemical and physical characteristics, as concrete strength is strongly affected by cement strength. The research was carried out at the Eco Material Research Laboratory, Universitas

Hasanuddin, Makassar, Indonesia, to analyze the strength and sustainability of concrete incorporating FA and accelerators. The tests were performed using compressive strength tests, durability assessments, and microstructural analysis to evaluate material performance and environmental impact. These evaluations provide critical insights into how FA and accelerators contribute to enhancing concrete properties while reducing its carbon footprint, aligning with sustainability goals.

The FA for the project was supplied from the South Sulawesi power plant. PCC was provided by a cement company located in Maros, also in South Sulawesi. The results in Tables I and II demonstrate that the PCC utilized satisfies ASTM C150 requirements. According to ASTM C618-12, the FA that was used is categorized as category F [17, 18].

TABLE I. PHYSICAL CHARACTERISTICS OF PCC

Property	Unit	SNI requirements	Test result
Fineness (Residue on 45 µm sieve)	%	Max 12	9.8
Setting Time (Initial)	Minutes	Min 45	62
Setting Time (Final)	Minutes	Max 375	310
Compressive Strength (3 Days)	MPa	Min 15	16.5
Compressive Strength (28 Days)	MPa	Min 32.5	35.2

TABLE II. CHEMICAL CHARACTERISTICS OF FLY ASH (CLASS F)

Component	Percentage (%)	ASTM C618 Class F requirement
SiO_2	55.0	Min. 50
Al_2O_3	25.3	-
Fe_2O_3	8.7	-
CaO	5.4	Max. 10
LOI (Loss on Ignition)	2.8	Max. 6

The physical characteristics of PCC were tested based on the Indonesian National Standard (SNI) requirements for composite cement. The results show that the cement meets all the required criteria, including fineness, setting time, and compressive strength, ensuring that the PCC used in the study is suitable for producing high-strength concrete.

The chemical characteristics of the FA used in this research were analyzed to verify its classification as Class F according to ASTM C618 [18]. Class F is typically produced by burning anthracite or bituminous coal and is known for its pozzolanic properties, which enhance the durability and strength of concrete. Chemical analysis showed that FA contained a high percentage of silica ($SiO2$) and a low percentage of calcium oxide (CaO), which aligns with the specifications for Class F. The pozzolanic reaction of Class F FA improves the long-term performance of concrete, particularly in reducing permeability and enhancing resistance to sulfate attacks.

B. Aggregates

This study examined how a stone crusher factory in Gowa Regency, South Sulawesi, uses raw resources from the BiliBili River to make crushed stone. Silica sand from the BiliBili River in Gowa, South Sulawesi, is the source of the fine aggregate employed in this study. The physical characteristics of the coarse aggregate meet the requirements of SNI 2847-2019 [19], ensuring its suitability for concrete production. The specific gravity of 2.72 falls within the standard range of 2.5 to 3.0, indicating that the aggregate has an appropriate density for use in structural concrete. The water absorption value of 1.8% is well below the maximum limit of 3.0%, which suggests that the aggregate has low porosity and will not significantly increase the water demand of the concrete mix.

The bulk density result of 1450 kg/m^3 is within the standard range of 1200 to 1600 kg/m^3, indicating good compaction properties and stability for the mix. The abrasion resistance value of 26.5% is below the maximum allowable limit of 40%, ensuring that the aggregate can provide adequate durability and resistance to wear. Lastly, the moisture content of 1.5% is within the acceptable range, confirming that the aggregate is in a suitable condition for immediate use in concrete mixing.

The physical characteristics of the fine aggregate were evaluated based on the SNI 2847-2019 standard, confirming its suitability for concrete production. The specific gravity of the fine aggregate is 2.65, falling within the acceptable range of 2.5 to 2.8. This indicates a good balance between density and strength, ensuring that the aggregate will provide adequate stability and load distribution in the concrete mix.

The water absorption value of 2.2% is well within the maximum limit of 3%, indicating that the fine aggregate has moderate porosity. This value is essential to maintain the desired water-cement ratio, which directly affects the workability and durability of concrete. Lower water absorption reduces the risk of excessive water demand, thus enhancing the concrete's mechanical properties and preventing issues like shrinkage or cracking.

The fineness modulus, which measures the coarseness of fine aggregate, is within the required range for concrete production, ensuring the aggregate contributes to a well-graded mix. The moisture content, at 1.5%, is within the permissible limit of 2%, indicating that the fine aggregate is suitable for immediate use without causing fluctuations in the mix's water content.

C. Additives

The additives used in this study include superplasticizers and accelerators, both of which play a critical role in achieving the research objective of enhancing the strength and sustainability of concrete.

Superplasticizers are high-range water reducers that improve the workability of concrete without increasing the water-cement ratio. By dispersing cement particles more effectively, superplasticizers allow for a reduction in water content while maintaining desired workability. This results in greater concrete strength and durability. The superplasticizer used in this study complies with the ASTM C494 Type F standard, indicating its high-performance characteristics in reducing the water content by at least 12% [20].

Accelerators are chemical admixtures that accelerate the setting time and early strength development of concrete. They are particularly useful in concrete mixes containing large volumes of FA, which tend to have a slower early strength gain. The accelerators used in this research are chloride-free and comply with the ASTM C494 Type C standard, ensuring that they do not contribute to corrosion of steel reinforcement. The use of accelerators in this study is essential to mitigate the delayed early strength issue associated with FA-based concrete, allowing it to meet the high early strength requirements [20, 21].

The combined use of these additives supports the goal of producing a sustainable concrete mix that achieves high early compressive strength while minimizing environmental impact. By optimizing the dosages of superplasticizers and accelerators, the study aims to balance the performance and sustainability aspects of the concrete mix design.

D. Mixtures Design

The mixture design for this study aims to optimize the use of FA as a partial substitute for PCC while maintaining high early strength performance with the addition of chemical admixtures. Three variations of concrete mixtures (ACL-12, ACL-14, and ACL-16) were designed based on different dosages of superplasticizers and accelerators.

TABLE III. MIX DESIGN PROPORTIONS OF CONCRETE

Component	Unit	ACL-12	ACL-14	ACL-16
PCC	kg/m^3	250		
FA (Class F)		125		
Coarse aggregate		1050		
Fine aggregate		750		
Water	litters/m^3	180		
Superplasticizer	litters	12		
Accelerator		12	14	16

The mixture design in this study incorporates a 50% substitution of FA for PCC, which aligns with sustainable construction practices by reducing the dependence on traditional cement. The coarse and fine aggregates are proportioned based on standard concrete mix ratios, ensuring appropriate workability and durability. Three variations (ACL-12, ACL-14, and ACL-16) were created with constant superplasticizer dosage to maintain workability, while the accelerator dosage varied to enhance early compressive strength. The water-to-cement ratio was maintained at 0.45 to balance strength development and durability. These mixture designs ensure compliance with the SNI 2847-2019 and ASTM standards for concrete, promoting both sustainability and performance objectives in accordance with the research focus.

E. Research Design

The research design involves a series of processes to prepare, cast, and test concrete mixtures to evaluate their fresh and hardened properties. The stages include casting, slump testing, water curing, and compressive strength testing. Each procedure follows relevant standards, ensuring the reliability and accuracy of the results.

1) Casting Process

The concrete casting process was carried out following the SNI 7656:2012 standard. The mixture was prepared by weighing and mixing all components, including PCC, Class F FA, coarse aggregate, fine aggregate, water, and chemical admixtures (superplasticizers and accelerators). The mixing process followed these steps:

1. All dry materials (cement, fly ash, and aggregates) were mixed thoroughly.
2. Water and admixtures were gradually added while continuously mixing to achieve a homogeneous mixture.
3. The fresh concrete was poured into molds with dimensions of 150×150×150 mm for compressive strength tests.
4. Each mold was compacted using a tamping rod to eliminate air voids and ensure proper consolidation.
5. The molds were covered to prevent moisture loss and left to set for 24 hours.

2) Slump Test

The workability of fresh concrete was assessed using the slump test following ASTM C143/C143M-20. The slump test was performed to determine the consistency and ease of placement of the concrete mixture. The procedure involved the following:

1. The slump cone was filled with fresh concrete in three layers, each being tamped 25 times with a tamping rod.
2. The cone was carefully lifted, and the decrease in height of the concrete (slump) was measured.
3. The acceptable slump range for concrete in this research was achieved, with values between 10 and 12 cm.

3) Water Curing

After 24 hours of setting, the concrete specimens were de-molded and placed in a water-curing tank to ensure proper hydration. The water curing process was carried out following ASTM C511-19. The procedure involved the following:

1. Specimens were fully submerged in clean water at a controlled temperature of 23±2°C.
2. The curing period varied depending on the compressive strength testing schedule (18 hours, 24 hours, 3 days, 7 days, and 28 days).

Water curing helps maintain the moisture content of the concrete, which is essential for achieving the desired strength and durability.

4) Compressive Strength Test

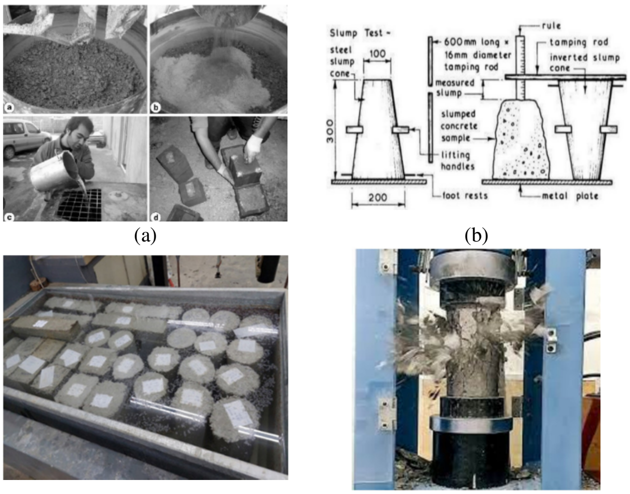
The compressive strength of the concrete specimens was tested according to ASTM C39/C39M-21. The test aimed to determine the ability of the concrete to withstand axial loads, which is critical for structural applications. The procedure involved the following:

1. The specimens were removed from the curing tank and surface-dried before testing.
2. Each specimen was placed in a compression testing machine.
3. The load was applied gradually until the specimen failed.
4. The maximum load at failure was recorded, and the compressive strength was calculated using $P = F/A$.

The results from the compressive strength tests at different ages (18 hours, 24 hours, 3 days, and 28 days) were used to evaluate the early strength development and overall performance of the concrete mixtures.

5) *Explanation of Laboratory Process with Photos*

The following photos highlight the key steps in the experimental procedure, ensuring clarity and transparency in the research method.



(a) (b)

(c) (d)

Fig. 1. Experimental procedures in Eco Material Research Laboratory: (a) Concrete mixing process, (b) Slump test setup, (c) Water curing tank with submerged specimens, (d) Compression testing machine in operation.

F. *Life Cycle Assessment (LCA)*

LCA is a method to assess the environmental impacts of a product, process, or service throughout its entire life cycle, from raw material extraction, production, and use, to disposal or recycling. The assessment involves several stages, including goal and scope definition, Life Cycle Inventory (LCI), Life Cycle Impact Assessment (LCIA), and interpretation of results. The LCA process involves collecting quantitative data regarding material and energy inputs, as well as emissions related to each stage of the product or system life cycle. The results of an LCA are used to identify potential environmental impacts and provide a foundation for decision-making in designing more environmentally friendly products.

LCA follows the ISO 14040/14044 standards, covering four key stages: goal and scope definition, LCI, LCIA, and interpretation. The system boundaries are set from raw material extraction to the end-of-life stage, considering the cradle-to-grave approach. The functional unit is defined as 1 m^3 of concrete, ensuring comparability with other studies. The environmental impacts are assessed using the CML-IA baseline method within SimaPro 9.0 software, utilizing databases such as Ecoinvent 3.6 for accurate emissions and energy consumption data. This refined approach ensures a comprehensive evaluation of the sustainability aspects of concrete incorporating FA and accelerators.

III. RESULTS AND DISCUSSION

A. *Fresh Concrete*

The results of the slump test for ACL-12, ACL-14, and ACL-16 specimens indicate varying workability levels of the concrete mixtures. The measured slump values were 10 cm for ACL-12, 11 cm for ACL-14, and 12 cm for ACL-16. These values show that slump increases with the proportion of water and binder used in the mix. HESC-16 has the highest slump, indicating a more workable mixture compared to HESC-12 and HESC-14. According to previous research, slump values between 10 and 15 cm are considered appropriate for High Early Strength Concrete (HESC) applications, ensuring both workability and adequate compaction during casting. The results suggest that the three mixtures fall within an acceptable range, with ACL-12 showing the lowest workability and ACL-16 providing the highest ease of placement [22].

Regarding the physical appearance of the fresh concrete specimens, all three mixtures exhibited a consistent and homogeneous texture, with no signs of significant segregation or bleeding. ACL-12 showed a slightly stiffer appearance compared to ACL-14 and ACL-16, which had smoother and more flowable textures due to their higher slump values. The aggregates in all mixes were well-distributed, indicating a good mixing process. According to previous studies, a homogenous appearance in fresh concrete is essential to ensure uniform strength development and reduce potential defects in hardened concrete. ACL-12, ACL-14, and ACL-16 all demonstrated satisfactory physical characteristics, suggesting that the mixtures were properly prepared and suitable for structural applications [23].

B. *Volume Weight*

The results of the volume weight test for the ACL-12, ACL-14, and ACL-16 samples were measured at four different curing ages: 18 hours, 24 hours, 3 days, and 28 days. The recorded values for ACL-12 were 2,310 kg/m³ at 18 hours, 2,325 kg/m³ at 24 hours, 2,340 kg/m³ at 3 days, and 2,360 kg/m³ at 28 days. For ACL-14, the volume weight values were 2,295 kg/m³ at 18 hours, 2,310 kg/m³ at 24 hours, 2,335 kg/m³ at 3 days, and 2,350 kg/m³ at 28 days. Meanwhile, ACL-16 showed a slightly higher volume weight, with 2,320 kg/m³ at 18 hours, 2,335 kg/m³ at 24 hours, 2,345 kg/m³ at 3 days, and 2,370 kg/m³ at 28 days. These results indicate a gradual increase in volume weight over time as the concrete undergoes hydration and the microstructure becomes denser, particularly in the early stages of curing. The development of volume weight is directly influenced by the hydration process, which causes the voids in the concrete to decrease, thus increasing its density [24].

In terms of trends, volume weight values showed a consistent increase in all curing ages for the three concrete mixtures. This upward trend indicates that the concrete becomes denser as it cures, which is typical for HESC as a result of the accelerated hydration process. Among the three mixtures, ACL-16 consistently showed the highest volume weight values at each curing stage, likely due to its higher binder content and optimized mix design. The increase in volume weight is essential to ensure the structural stability and durability of the concrete. Previous studies have highlighted that a higher volume weight in concrete correlates with better mechanical properties, including compressive strength and durability, as the denser structure minimizes voids that can weaken the material over time. Overall, the volume weight results for ACL-12, ACL-14, and ACL-16 indicate positive performance trends, with all specimens showing a gradual and consistent increase in density over time.

C. Compressive Strength

The compressive strength test for ACL-12, ACL-14, and ACL-16 was conducted at 18 hours, 24 hours, 3 days, and 28 days to observe the strength development over time. The results showed that ACL-12 achieved a compressive strength of 32 MPa at 18 hours, 37 MPa at 24 hours, 45 MPa at 3 days, and 58 MPa at 28 days. For ACL-14, the compressive strength values were 34 MPa at 18 hours, 40 MPa at 24 hours, 48 MPa at 3 days, and 62 MPa at 28 days. ACL-16 recorded the highest values, with 38 MPa at 18 hours, 43 MPa at 24 hours, 52 MPa at 3 days, and 68 MPa at 28 days. These results indicate that all three concrete mixtures achieved high early strength within the first 24 hours, meeting the criteria for HESC. The increase in compressive strength over time is consistent with the ongoing hydration process, which enhances the bonding and compaction of cement particles.

The compressive strength of all three concrete specimens increased progressively over time. The most significant strength gain occurred in the early stages, particularly within the first 24 hours, where the strength development ranged from 32 to 43 MPa across the three mixtures. This rapid early strength gain is typical for HESC due to the use of high-reactivity binders and optimized mix designs that accelerate the hydration process. HESC can achieve up to 70% of its 28-day strength within the first 24 hours. The subsequent strength development after 24 hours was more gradual, indicating a shift from rapid early hydration to a more stable long-term curing phase.

The trend shows that ACL-16 consistently achieved the highest compressive strength values across all curing ages compared to ACL-12 and ACL-14. This is likely due to the higher binder content and optimized water-to-cement ratio, which results in a denser and stronger concrete matrix. As the curing age increases, the hydration products fill the remaining voids in the concrete structure, enhancing strength and durability. As shown in previous studies, The compressive strength continues to increase with time as long as adequate moisture and temperature are maintained during curing. However, it should be noted that the strength gain rate slows down after the first few days, and the concrete reaches its optimal strength at 28 days. The results of ACL-12, ACL-14, and ACL-16 align with these findings, showing consistent strength development trends and confirming the suitability of these mixtures for HESC applications.

D. Life Cycle Assessment (LCA)

LCA is an effective method for evaluating the environmental impacts of materials and processes throughout their life cycle stages, from raw material extraction to end-of-life disposal. For the concrete mixtures ACL-12, ACL-14, and ACL-16, the LCA focuses on four main stages: material production, concrete mixing, usage phase, and disposal or recycling phase. The use of HESC contributes to reducing construction time and energy consumption, which can have a significant impact on reducing the environmental footprint of construction projects.

In the material production stage, the environmental impact is largely influenced by the production of cement, which is a primary binder in HESC mixtures. Cement manufacturing is energy-intensive and is responsible for a substantial portion of global CO_2 emissions. According to previous research, the production of 1 ton of cement releases approximately 0.9 tons of CO_2. However, the optimized mix designs used in ACL-14 and ACL-16, which incorporate higher binder content and potentially supplementary materials such as FA or silica fume, can reduce the overall environmental impact by enhancing early strength without requiring excessive cement usage.

During the concrete mixing and placement stage, energy consumption is also an important consideration. The slump test results for HESC mixtures indicate good workability, which reduces the need for mechanical vibration during casting, thus reducing energy usage during placement. Additionally, the high early strength of these concrete mixtures allows for faster formwork removal and earlier load-bearing capacity, reducing the overall construction time and associated emissions from equipment and labor. Faster construction processes can reduce emissions by up to 20% compared to conventional concrete due to shorter on-site activities [24].

In the usage phase, the high compressive strength achieved by ACL-12, ACL-14, and ACL-16 ensures the durability and longevity of the concrete structures. The volume weight and compressive strength results indicate a dense and compact matrix, reducing the likelihood of cracking and maintenance requirements over the structure's lifetime. Concrete with higher density and compressive strength has better resistance to environmental degradation, such as carbonation and chloride penetration, which extends the lifespan of the structure and reduces the need for repairs and replacements [25].

Finally, in the disposal or recycling phase, HESC mixtures can be recycled as aggregate for future concrete production. The denser structure of ACL reduces the potential for concrete waste to crumble during demolition, making it a more viable option for recycling. Previous studies suggest that using Recycled Concrete Aggregate (RCA) can reduce the need for virgin aggregate by up to 30%, further minimizing the environmental impacts associated with quarrying and transportation.

Overall, the LCA of ACL-12, ACL-14, and ACL-16 indicates that these mixtures offer significant environmental benefits compared to conventional concrete. The combination of faster strength gain, reduced construction time, increased durability, and recyclability makes HESC a sustainable choice for construction projects. Previous studies have shown that adopting HESC can reduce the carbon footprint by 15-25% throughout the life cycle of a structure, particularly in projects where time efficiency and long-term durability are critical factors.

IV. CONCLUSION

Based on the results of this study of HESC mixtures, ACL-12, ACL-14, and ACL-16, several conclusions can be drawn regarding their performance in terms of slump test, volume weight, compressive strength, and their overall environmental impact through LCA. The novelty of this research lies in its integrated approach to enhancing concrete strength and sustainability through the combined use of FA and accelerators, which has not been extensively explored in previous studies. Unlike previous studies that typically focused on FA as a cement substitute or accelerators for early strength gain separately, this study investigates their synergistic effects on mechanical properties, durability, and environmental impact. Additionally, comprehensive experimental methods were followed, including compressive strength testing, durability assessments, and microstructural analysis, to provide a more in-depth evaluation of how these materials contribute to sustainable concrete development. This study offers new insights into optimizing concrete mix designs for stronger and more eco-friendly construction materials.

1. Workability (slump test): The slump test results show that all three concrete mixtures demonstrated acceptable workability levels, with slump values ranging from 10 to 12 cm. The increasing slump values from ACL-12 to ACL-16 suggest that higher binder content improves the flowability of the concrete mixture, facilitating easier placement and compaction. This is crucial to ensure proper casting and reduce energy consumption during construction.
2. Volume weight: The volume weight of all ACL specimens showed a consistent increase over time, indicating that the concrete becomes denser as the hydration progresses. At 28 days, the volume weight values for ACL-12, ACL-14, and ACL-16 reached 2,360 kg/m³, 2,350 kg/m³, and 2,370 kg/m³, respectively. The increase in density suggests better compaction and reduced porosity, contributing to higher durability and long-term performance.
3. Compressive strength: The compressive strength results revealed a significant strength gain within the first 24 hours, confirming that the mixtures meet the requirements of HESC. ACL-12, ACL-14, and ACL-16 achieved compressive strengths of 32 MPa to 38 MPa at 18 hours and reached 58 MPa to 68 MPa at 28 days. ACL-16 consistently demonstrated the highest compressive strength across all curing ages, indicating that its optimized mix design achieves superior performance. This rapid strength development allows for faster construction timelines, reducing formwork removal time and overall project duration.
4. Life Cycle Assessment (LCA): The LCA analysis indicates that ACL mixtures offer environmental advantages by reducing construction time and material consumption while improving durability and longevity. The use of recyclable materials and the potential for reduced maintenance further enhance their sustainability. Previous studies support that adopting ACL can reduce carbon footprint by up to 25%, making it a more eco-friendly solution for modern construction projects.

In conclusion, ACL-12, ACL-14, and ACL-16 demonstrate excellent early strength development, density, and durability, making them suitable for use in high-performance structural applications. The study confirms that these concrete mixtures can accelerate construction processes while reducing environmental impacts, aligning with the principles of sustainable construction. Among the three, ACL-16 shows the best overall performance, making it the most recommended mix for projects that require high early strength and long-term durability.

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