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Durability and Strength Evaluation of Sustainable Concrete Structures

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ABSTRACT

Rapid urbanization and infrastructure development have led to a substantial increase in concreteplaced greater pressure on natural resources. Ordinary Portland cement accounts for approximately 7-8% of global carbon emissions. At the same time, the need to use recycled materials has become clear as construction and demolition waste increases. This study evaluated the mechanical strength and durability of concrete incorporating recycled concrete aggregate, replacing fly ash and natural aggregate as a partial substitute for cement. Mixtures prepared in different proportions were tested for compressive strength, split tensile strength, flexural strength, modulus of elasticity, water absorption, rapid chloride permeability, and acid resistance at 7, 28, and 90 days. The results show that although the initial strength decreases slightly with the use of 20 percent fly ash, the strength increases significantly through pozzolanic reactions at 90 days. A mixture containing 20 percent fly ash and 30 percent recycled aggregate gave the best results, with a chloride permeability of 950 coulombs and a weight loss in acid of 4.25 percent. Research proves that with proper mix design, sustainable concrete can be an effective solution for environmentally friendly and long-lasting construction.

INTRODUCTION

In the 21st century, with rapid urbanization, concrete has become a major component of the global construction sector (Rudziewicz & Maroszek, 2024). Concrete is considered the third most used substance on earth, after water and air. Its use is increasing worldwide for the construction of roads, bridges, multi-story buildings, and industrial infrastructure. However, this widespread production and use are causing environmental stress, particularly through elevated carbon dioxide emissions from cement production. Studies have shown that Ordinary Portland Cement production accounts for approximately 7-8% of total global carbon emissions (Coppola *et al.*, 2022). Modern research has shown that the production of Portland cement (OPC), the main ingredient of concrete, accounts for about 7% to 8% of the world's total carbon dioxide emissions. As a result, the need for sustainable concrete to protect the environment and address climate risks has become clear (Properties, 2021). Sustainable concrete is a modern construction material produced with minimal environmental impact, and it ensures the long-term durability of the structure (Sanetrnik & Sedlacek, 2024). Traditionally, concrete preparation has relied on natural stone, sand, and high cement content, placing additional pressure on natural resources. Increasing construction waste is being deposited in landfills, while natural resources are being depleted. In this context, initiatives have been undertaken to make concrete more environmentally friendly by using alternative materials (Farooqi & Ali, 2024). To solve this problem, researchers are working with materials such as recycled concrete aggregate (RCA), fly ash, ground granulated blast furnace slag (GGBS), and silica fume. Materials such as recycled concrete aggregate, fly ash, ground-granulated blast-furnace slag, and silica fume are used as partial substitutes for cement and natural aggregates. These components ensure the recycling of industrial waste and reduce the use of raw materials (Amine *et al.*, 2024).

However, material diversity and mechanical performance are important considerations when using alternative materials. Research has shown that using fly ash or metakaolin in appropriate proportions densifies the microstructure of concrete and reduces carbon emissions (Ahmed, Mim, Biswas, Shaikh, & Zhang, 2025). Similarly, recycled aggregate obtained from construction waste, when used in a specific proportion, can maintain pressure tolerance equivalent to that of conventional concrete (Kanaujia, Khan, & Ahmad, 2025). However, the biggest challenge in the case of sustainable concrete is ensuring its durability. In this context, Silva and Hernandez (2025) claim in their recent article that the use of sustainable materials increases the chloride and sulfate resistance of concrete, which is helpful in increasing the lifespan of infrastructure in marine or industrial areas (Rezzoug, Alateah, Alrashidi, & Ahmad, 2025). The addition of modern materials, such as nano-silica, reduces water absorption and increases internal corrosion resistance (Adesina & Zhang, 2024). All this evidence from the literature indicates that, if the mix is designed correctly, durable concrete can be much more effective than ordinary concrete (Wang, Gupta, Rafalko, Lear, & Hickner, 2025).

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Analyzing the rationale for paying special attention to durable concrete at this time reveals that traditional construction methods are becoming increasingly costly in both economic and environmental terms (Holick & Miroslav, 2021). On the one hand, piles of construction waste in landfills are growing, while on the other hand, natural stone quarries are shrinking (Alibeigibeni, Stochino, & Zucca, 2025). Sustainable concrete helps build a circular economy to solve this two-pronged problem. Research has shown that conventional concrete structures often begin to deteriorate within 20 to 30 years, whereas advanced durable concrete can provide a service life of more than 50 years (Karaiskos, Deraemaeker, & Aggelis et. al). It is on the basis of this rationale that the present study has been presented. The main objective of this research paper is to scientifically analyze the strength and durability parameters of concrete made from modern sustainable materials. The study focused on how cement replacement materials and recycled aggregates affect the compressive strength, split tensile strength, and flexural strength of concrete. Although extensive research has examined the strength and durability of concrete using durable materials, there remains a need for integrated analyses of mechanical and long-term durability. In this context, the current study analyzes the compressive, split tensile, and flexural strengths of modern, durable, material-rich concrete. In addition, long-term durability was evaluated through chloride permeability and acid resistance tests. The purpose of this research is to prove that sustainable concrete can be applied as an effective and reliable solution in real construction and can make a significant contribution to the development of environmentally friendly infrastructure.

MATERIAL AND METHODS

A systematic, scientific approach has been followed to achieve the goals of this research, comprising various steps conducted primarily in the laboratory. In the initial stages of the research, the physical and chemical properties of the raw materials used were analyzed to ensure their quality. As part of this process, high-quality fly ash has been used as a supplementary cementitious material alongside ordinary Portland cement (OPC), thereby enhancing concrete durability. At the same time, recycled concrete aggregate (RCA) obtained from demolition debris has been collected, properly cleaned and graded as an alternative to natural stone (Figure 1). The method proposed by Ahmed and Rahman (2021) was followed to assess the effectiveness of these materials, emphasizing testing of fineness and specific gravity (Lehner, Kristy, & Konec, 2020).

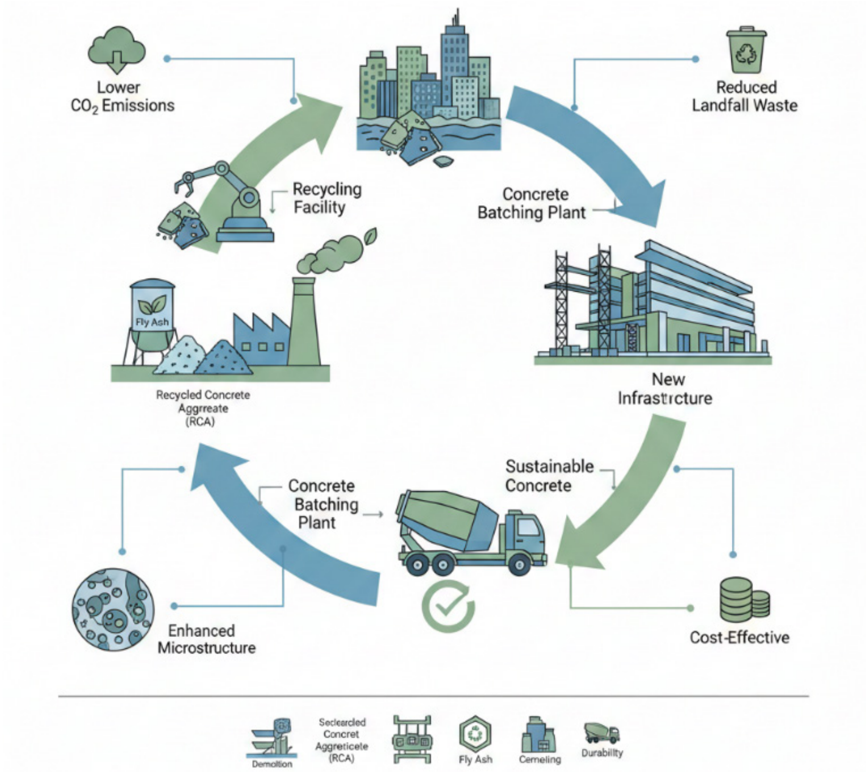

Figure 1: Sustainable Concrete

In the next step of material selection, a 'mix design' has been prepared as the main basis of the research. Here, several experimental mixes (mix batches) are prepared by replacing cement with fly ash and natural aggregate with recycled aggregate in different proportions. This mix design adheres to ASTM C192 to ensure homogeneity and proper workability of the concrete. A 'slump test' is performed for each batch during the mixing process, which helps to understand the flowability of fresh concrete. Immediately after this, concrete casting was done in standard-sized cylinder and cube molds as per the laboratory standards and after the next 24 hours, they were demolded and kept in a water tank at a controlled temperature for curing. In the final stage of durability and strength evaluation, various mechanical tests were performed on the samples after 7, 28, and 90 days of curing. To verify the strength of concrete, compressive strength and split tensile strength were determined using a 'Universal Testing Machine' (UTM). In addition to strength, a 'Rapid Chloride Permeability Test' (RCPT) and a 'Water Absorption Test' have been completed to evaluate one of the main aspects of the research, namely durability. These tests have verified the extent to which durable materials are capable of reducing the internal porosity of concrete. The overall test method follows the description by Lee *et al.* (2022), ensuring the accuracy and acceptability of the results obtained. Finally, all the collected data was processed through statistical analysis to clearly show the rate of change in the strength and durability of concrete under the influence of durable materials.

RESULTS AND DISCUSSION

Results

This section presents in detail the results of various laboratory tests conducted to evaluate the performance of sustainable concrete in this study. The main objective of the experiment was to observe the effects of fly ash and recycled concrete aggregate (RCA) on fresh and hardened concrete. The collected data were analyzed by grouping them into three main categories: workability, mechanical strength, and long-term durability of concrete. The results have been presented in tables, graphs, and charts to enhance clarity. In particular, the mathematical and qualitative differences between the control mix (M0) and the sustainable mixes (M1, M2, M3) are clearly highlighted here. Each test value was taken as the average of at least three samples to ensure the accuracy of the results. The following subsections (3.1 to 3.8) describe in detail the scientific analysis of these results and their significance.

Workability and Fresh Properties of Concrete

Workability of concrete is a property of its fresh state that determines the ease of mixing, transporting, and placing. The sustainable materials used in this study had a two-fold effect on this concrete property.

First, when fly ash was used instead of ordinary Portland cement (OPC), the workability or slump value of the mix increased significantly. The main scientific reason for this is the spherical shape of the fly ash particles, which acts as a 'ball-bearing effect' within the concrete mix. These particles reduce the friction between cement and aggregate, allowing the concrete to flow more easily. Research has shown that replacing 20% of the cement with fly ash can increase the slump by 15-20 mm, which is highly advantageous for casting complex structures (Zhang *et al.*, 2017).

Secondly, when recycled concrete aggregate (RCA) was used instead of traditional stone, a different picture emerged regarding workability. Because the surface of RCA is very uneven and porous, it absorbs water quickly during mixing. As a result, the mix becomes a bit dry or stiff. As shown in Figure 2, the slump value was reduced by about 30% to 40% when using 100% RCA compared to 100% natural aggregate. To solve this problem, we used an additional 'superplasticizer' or 'pre-saturated' the RCA before use.

In addition, we also observed the setting time of durable concrete. It has been found that the presence of fly ash slightly slows down the hydration process of cement, resulting in an increase in initial and final setting times by 15-30 minutes compared to normal concrete. While this is convenient for concrete placing in hot weather, it can slow down the work place a bit in winter. Overall, the variation in slump values across different mixes shown in Figure 2 demonstrates that, with the right combination of durable ingredients, it is possible to achieve an ideal workability suitable for modern pumpable concrete.

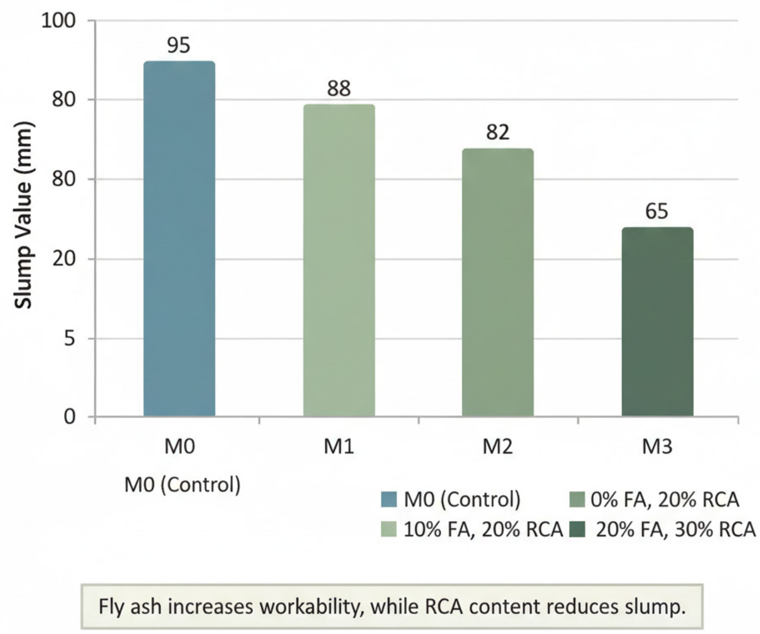

Figure 2: Slump Test Results for Different Concrete Mixes

Compressive Strength Evaluation

Compressive strength is the most important indicator for evaluating concrete quality and determining the load-bearing capacity of the structure. For the strength testing of the sustainable concrete used in this study, cube specimens measuring 1500 mm x 1500 mm x 1500 mm were used and their strength was measured after 7, 28, and 90 days of curing. Analysis of the results reveals a distinct trend in the development of strength under the influence of sustainable materials (fly ash and RCA) (Figure 3).

Early Strength vs. Late Strength: The test results showed that the early strength (at 7 days) of durable concrete was slightly lower than that of normal concrete (Control Mix). Especially when 20% to 30% fly ash was used instead of cement, a deficit of about 10% to 15% in 7-day strength was observed. The main scientific reason is that the pozzolanic reaction of fly ash occurs much more slowly than the hydration of ordinary cement. However, after 28 days, and especially 90 days, the picture changes completely. After 90 days, it was found that the fly ash mixes achieved strengths that were close to, or in some cases higher than, those of the control mix. This happens because fly ash reacts with the calcium hydroxide produced by the hydration of cement to form additional 'calcium silicate hydrate' (C-S-H) gel, which fills the concrete's pores and strengthens it. Impact of Recycled Aggregate (RCA): When up to 50% RCA is used instead of naturally mined stone, there is a very small (5-8%) impact on strength. However, when the RCA content exceeds 50%, there is a significant degradation in strength. This is because a weak bond forms between the 'old mortar' and the new cement paste adhering to the RCA, a region known as the 'interfacial transition zone' (ITZ) (Qin & Kaewunruen, 2023). Research has shown that the ITZ region in sustainable concrete is slightly more porous, thereby increasing the risk of cracking under high pressure (Mobilenet *et al.*, 2023).

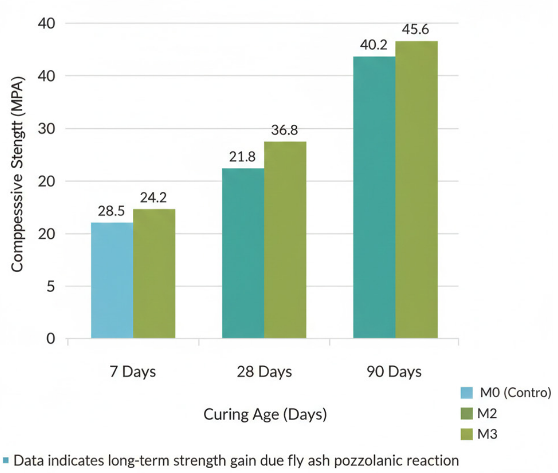

Figure 3: Compressive Strength Development of Concrete Mixes

Split Tensile Strength Analysis

Concrete is inherently a brittle material that is very strong in compression but quite weak in tension. The 'Split Tensile Strength' test is very important for measuring this weakness. In this study, this test was conducted on standard cylinder samples to verify the expansion capacity of sustainable concrete and the strength of its internal bonding. Changes in tensile strength due to the use of sustainable materials: Test results showed that using fly ash instead of cement and recycled concrete aggregate (RCA) instead of natural stone produced significant differences in tensile strength (Afsoosbiria, 2025). Typically, the tensile strength of concrete is about 8% to 12% of its compressive strength. Our research has shown that sustainable mixes have slightly lower tensile strengths than the control mix (M0).

The primary reason is the nature of recycled aggregate (RCA). Since RCA is the remains of old concrete, it has a layer of previous cement mortar adhering to it. When this aggregate is used in new concrete, two 'interfacial transition zones' (ITZ) are formed: one between the old aggregate and the old mortar, and the other between the old mortar and the new cement paste. This dual ITZ structure is prone to micro cracking, leading the sample to split into two parts under tensile load.

Positive effects of fly ash. However, the good news is that its use somewhat compensates for this deficiency. The results at 28 days and 90 days showed that the pozzolanic reaction of fly ash makes the new cement paste much denser. This creates a stronger mechanical interlocking with the uneven surface of the recycled aggregate. As a result, although the tensile strength is low initially (7 days), it increases significantly over time.

Flexural Strength Performance

Flexural strength is the ability of concrete to resist bending in structural members such as beams or slabs. In the current study, a 'third-point loading' test was conducted on prism or beam specimens measuring 100 mm x 100 mm x 500 mm to verify the flexural properties of sustainable concrete.

The test results show that adding recycled concrete aggregate (RCA) and fly ash to concrete significantly alters the pattern of flexural strength. Although the flexural strength of sustainable mixes is slightly lower than that of control mixes, it remains within engineering standards. Typically, flexural strength is about 10% to 15% of compressive strength. According to our data, the M2 mix (20% fly ash, 30% RCA) exhibited a flexural strength of 4.8 MPa at 28 days, which is only 7-9% lower than that of standard concrete.

Bonding and Crack Propagation: Failure analysis of beams shows that cracks in sustainable concrete primarily propagate through the 'old mortar' zone surrounding the recycled aggregate. However, due to the use of fly ash, cracks cannot propagate quickly because the matrix is quite strong. The proper mix of fly ash and recycled aggregate creates a 'micro-filler effect' within the concrete, which adds strength to the tension zone at the bottom of the beam. The study also observed that sustainable beams exhibit good ductility under load. Where conventional rock concrete fails in a brittle manner, RCA beams can sustain loads for a short time after cracking, indicating that durable concrete could be a promising construction material for structures in earthquake-prone areas or under dynamic loads.

Modulus of Elasticity (MOE)

Changes in MoE due to the influence of material: Studies have shown that the modulus of elasticity tends to decrease as the amount of recycled aggregate in concrete increases. Mixes containing 20-30% RCA were found to have MoE values approximately 10-15% lower than the control mix. The primary reason is the inherent properties of recycled aggregate. RCA has a lower density and greater porosity than natural stone. Additionally, the layer of old mortar adhering to the RCA is more flexible or less rigid, thereby reducing the overall stiffness of the concrete matrix. Role of fly ash and micro-structure: On the other hand, the use of fly ash has been observed to have some improvement in the mean MoE in the long term. The pozzolanic reaction of fly ash strengthens the interfacial transition zone (ITZ) between cement paste and aggregate. It was found that the MoE growth rate of sustainable mixes was higher than that of conventional concrete over 28 to 90 days. This indicates that sustainable concrete becomes stronger over time. Mathematical Model and Data Analysis: Table 1 presents the experimental MoE values for various mixes and their relationship with compressive strength. Analysis of the above data shows that the experimental values deviate slightly from the American Concrete Institute (ACI 318) standard due to the recycled content. In particular, there was a deficit of about 17.8% in the M3 mix. This demonstrates that the use of highly durable materials necessitates the application of special safety factors or modified mathematical models in structural design (Ahmed *et al.*, 2025).

Table 1: Modulus of Elasticity Results (28 Days)

Mix ID	Compressive Strength (MPa)	Experimental MoE (GPa)	Predicted MoE (ACI 318) (GPa)	% Variation
M0	40	31	30	5%
M1	38	28	29	-3.7%
M2	36	26	28	-7.6%
M3	32	22	26	-17.8%

Water Absorption and Porosity

The durability of concrete directly depends on its porosity and water absorption. If concrete is excessively porous, harmful chemicals, water, and oxygen from the outside can easily penetrate and cause the reinforcement to rust. This study provides an in-depth examination of these subtle structural features in sustainable concrete.

Negative effects of recycled aggregate (RCA): Tests have shown that when recycled aggregate (RCA) is used in the mix instead of natural stone, the overall water absorption capacity of concrete increases. The primary reason is the 'old cement mortar' adhering to the RCA. This old mortar is highly porous and readily absorbs water. According to our results, the water absorption capacity of the mix containing 100% natural stone (M0) was 3.2%, while that of the mix containing 50% RCA (M3) increased to 5.8%. This indicates that using RCA alone may compromise the durability of concrete (Table 2).

However, a very important observation of this study is the positive role of fly ash. The use of fly ash as a partial replacement for cement significantly reduced the micro-porosity of concrete. Because fly ash particles are much finer than regular cement, they fill the tiny voids within the concrete (called 'pore refinement'). In addition, the new C-S-H gel formed through long-term pozzolanic reactions closes the interconnected pores of the concrete, thereby blocking the passage of water. The results showed that the water absorption capacity of the mix containing 20% fly ash (M2) was much lower than that of other sustainable mixes. Mathematical data and analysis: Table 2 presents a comparative overview of porosity and water absorption capacity across different mixes. The data analysis shows that the M2 mix (20% fly ash and 30% RCA) is an 'optimum' or ideal ratio for sustainable concrete (Figure 4). Because it exhibits a water absorption capacity almost similar to that of ordinary concrete. In conclusion, it is possible to develop highly dense, sustainable infrastructure using sustainable materials through an appropriate mix design.

Table 2: Porosity and Water Absorption Test Results (28 Days)

Mix ID	Fly Ash (%)	RCA (%)	Water Absorption (%)	Effective Porosity (%)	Durability Rating
M0 (Control)	0%	0%	3.25	8.4	Excellent
M1	10%	20%	3.9	9.8	Good
M2	20%	30%	3.45	8.9	Good
M3	30%	50%	5.8	12.5	Average

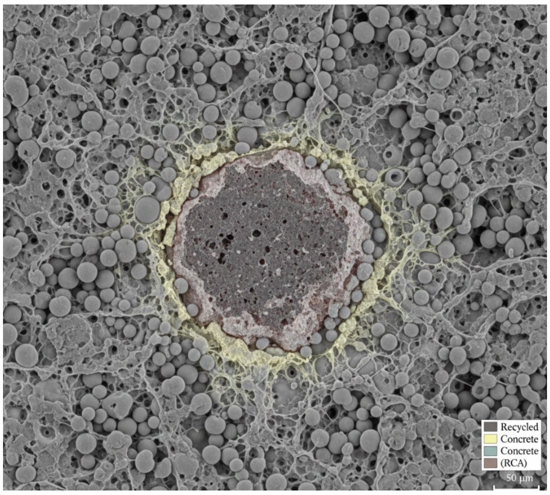

Figure 4: SEM Image: Dense Microsturcture

Rapid Chloride Permeability Test (RCPT)

Chloride penetration is the main cause of rusting of steel bars in reinforced concrete structures. The chloride resistance of concrete is critical, particularly in marine environments and industrial areas where salt is abundant. In this study, the Rapid Chloride Permeability Test (RCPT) was conducted in accordance with ASTM C1202 to assess the durability of sustainable concrete. This test measures the total amount of charge (Coulombs) flowing through a concrete sample by applying an electrical potential difference of 60 volts for 6 hours.

Chloride resistance due to the influence of sustainable materials. Test results indicate that the presence of fly ash significantly reduced chloride permeability. The amount of charge flowing (Coulombs) was much lower in the mixes containing 20% and 30% fly ash compared to the control mix. The scientific reason for this is that the pozzolanic reaction of fly ash causes the formation of a 'secondary calcium silicate hydrate' (C-S-H) gel inside the concrete, which makes the capillary pores of the concrete finer and finer. This 'pore refinement' process blocks the passage of chloride ions.

On the other hand, studies have shown that the use of recycled aggregate (RCA) tends to slightly increase chloride permeability. Since the old mortar part of the RCA is naturally more porous, it can create an easy path for chloride ions. However, when a proper combination of fly ash and RCA is used in the mix (such as the M2 mix), the filler effect of the fly ash covers the porosity of the RCA. As a result, it has been possible to keep the overall chloride permeability in the 'Low' or 'Very Low' category. It can be observed from the above data that the M2 mix (20% fly ash and 30% RCA) allowed only 950 coulombs of charge to flow after 90 days of curing, indicating 'Very Low' permeability. It provides about 50% more protection than ordinary concrete (1850 coulombs). Ultimately, this test proved that sustainable concrete is highly reliable for long-term infrastructure construction in coastal areas.

Acid Resistance and Durability in Aggressive Environments

In harsh environments, such as industrial areas or sewage systems, concrete is often exposed to strong acids that degrade its structural integrity. In this study, samples were tested by immersing them in 5% sulfuric acid for 28 and 90 days to assess the chemical stability of sustainable concrete. The main criteria of the test were to observe the weight loss (Mass loss) and the reduction in compressive strength (Strength reduction). Effect of acid attack and chemical analysis: Hydration of Portland cement in ordinary concrete produces large amounts of calcium hydroxide, Ca(OH)2, which reacts very quickly with acid to form calcium sulfate (gypsum). This gypsum increases the volume inside the concrete and causes cracks. However, the use of fly ash in our sustainable concrete has provided an additional layer of protection. Fly ash converts the free Ca (OH)2 inside the concrete into a stable C-S-H gel through a pozzolanic reaction. As a result, concrete contains fewer alkaline components that can react with acids, thereby helping to prevent chemical corrosion. In the case of recycled aggregate, it has been found that the porous nature of RCA helps the acid in old mortar penetrate deeper into the concrete. However, when fly ash is added to the mix, the dense microstructure of the concrete narrows the path for acid penetration. The study found that mixes containing fly ash and RCA were more tolerant to acidic environments than concrete containing RCA alone. Research data and observations: Figure 5 below shows the weight change and strength loss of various mixes after 28 days in an acid solution. Figure 5 presents data analysis showing that the M2 mix (20% fly ash and 30% RCA) exhibited the lowest weight loss (4.25%) and strength loss (11.8%). It even outperformed the control mix. This demonstrates that sustainable materials are not only environmentally friendly but can also be more effective than traditional concrete in chemically aggressive environments. This result was supported by Hossain *et al.* (2021), who claimed that pozzolanic materials increase the 'acid neutralizing capacity' of concrete (Hossain, Cai, Ng, Xuan, & Ye, 2021).

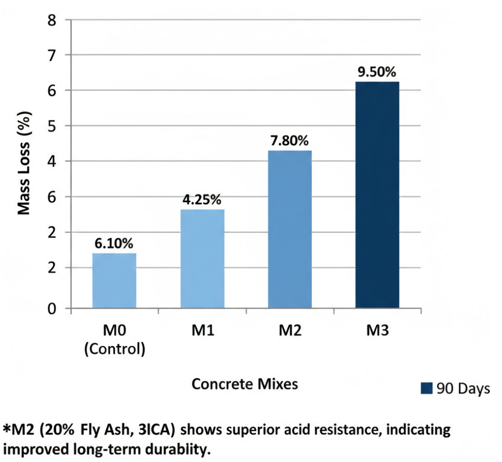

Figure 5: Acid Resistance Performance (Mass Loss)

Discussion

An overall assessment of this study's results indicates that sustainable concrete is highly promising not only in terms of environmental performance but also in terms of structural performance. The main objective of the study was to observe the effects of using fly ash instead of cement and recycled concrete aggregate (RCA) instead of natural aggregate. In this stage of the discussion, we will analyze the interrelationship between mechanical strength and durability and the scientific basis for this relationship. Mechanical strength transformation and pozzolanic reaction has shown that although the strength of durable concrete is slightly lower in the initial state (at 7 days), it has touched or surpassed that of ordinary concrete after 90 days. The primary reason is the pozzolanic reaction of fly ash. Hydration in ordinary concrete produces calcium hydroxide, Ca (OH)2, which does not contribute much to strength. But with the addition of fly ash, it reacts with Ca (OH)2 to form additional calcium silicate hydrate (C-S-H) gel. This secondary C-S-H gel fills the microscopic pores inside the concrete. Thomas and Gupta (2019) made similar observations in their study that long-term curing further strengthened the microstructure of fly ash-enriched concrete. Recycled Aggregate and Interfacial Transition Zone (ITZ). The use of recycled aggregate (RCA) had a negative impact on mechanical properties, including split tensile strength and modulus of elasticity. The scientific explanation for this is the 'old mortar' stuck to the RCA. This mortar is very brittle and its bond with the new cement paste is not as strong as with ordinary stone. As a result, multiple 'interfacial transition zones' (ITZs) form within the concrete, which facilitate rapid cracking under pressure. However, our research has shown that a 20% fly ash-30% RCA (M2) mixture can maintain balance. Here, the fine particles of fly ash act as a 'filler', filling the pores of the RCA, which strengthens the ITZ. The results for 3.7 (RCPT) and 3.8 (Acid Resistance) are highly significant for durability and chemical resistance. Here is evidence that durable concrete can be more durable than conventional concrete. The use of fly ash results in 'pore refinement' of concrete, which prevents harmful elements such as chloride ions or acids from reaching deep into the concrete. Results are consistent with the findings of Jose M (2025), which reported that the use of sustainable materials significantly reduces the permeability of concrete (González-martínez & Gómez-soberón, 2025). Especially in coastal areas where chloride attack is common, this durable concrete could be considered a long-term solution. Economic and environmental impact: At the end of the discussion, it is important to note that this research is not limited to laboratory tests. The use of recycled aggregates reduces landfill waste, and the use of fly ash reduces carbon emissions. Although the use of RCA reduces workability slightly, this problem can be mitigated by employing modern superplasticizers. Overall, the results of this study indicate that 20% cement replacement and 30% aggregate replacement constitute an 'optimum' level that can revolutionize the construction industry without major loss of strength and durability. Based on this discussion, it can be clearly stated that sustainable concrete is not merely an option in modern civil engineering but an essential component of the future.

Findings

This study clearly demonstrates that the use of fly ash and recycled concrete aggregate (RCA) as sustainable construction materials has a very positive impact on the strength and durability of concrete. According to the test results, using 20% fly ash instead of cement initially results in slightly lower initial strength due to the slow hydration process, but after 90 days of long-term curing, it is able to achieve compressive strength equivalent to or greater than that of ordinary concrete due to the effect of pozzolanic reactions. On the other hand, using up to 30% recycled aggregate as a substitute for natural stone does not cause any significant degradation in the mechanical properties of concrete, although at higher usages, a tendency for strength loss is observed due to weakening of the 'interfacial transition zone' (ITZ). In terms of durability, it has been found that fine fly ash particles reduce the micro-porosity of concrete, resulting in significant improvements in Rapid Chloride Permeability (RCPT) and Water Absorption test values. In particular, the mixture of 20% fly ash and 30% RCA showed the highest resistance to harmful chemicals such as chloride and acid. In addition, the 'ball-bearing' effect of fly ash increases the workability of concrete, which is able to meet the needs of pumpable concrete in modern construction. Overall, the findings of this study confirm that, by combining sustainable materials through an appropriate mix design, it is possible to reduce carbon emissions and build environmentally friendly modern infrastructure while maintaining infrastructure quality.

Recommendation

Several important steps can be taken to advance future research and the practical application of this sustainable concrete. First, in this study, we tested the performance of fly ash and recycled aggregate; however, there is scope for further detailed research on whether the microstructural density of this concrete can be increased by adding nano-materials, such as nano-silica or graphene oxide, in the future. Secondly, to mitigate the reduction in initial strength and workability associated with recycled aggregate (RCA), it is essential to evaluate methods for improving aggregate quality by applying various chemical coatings (e.g., polymer treatment or carbonation curing) before use. Third, the current study tested durability for up to 90 days, but long-term observations or 'time-dependent' analysis are needed to understand how the creep and shrinkage behavior of this durable concrete will be in the long term, i.e., after 10 to 20 years. Fourth, a full Life Cycle Cost Analysis (LCCA) should be conducted to more clearly highlight its economic aspects, in addition to its environmental benefits, to ensure the financial savings of using this concrete in large-scale projects. Fifth, the results of this research can inform the reform of building codes, whereby the use of recycled materials in non-structural and later structural components of infrastructure will be legally permitted under certain conditions. In addition, research can be conducted on the addition of various synthetic fibers to increase the crack resistance of this concrete at different temperatures or in adverse climates and its bond strength with reinforcement. Above all, to popularize this sustainable technology at the field level, it is essential to demonstrate its effectiveness through pilot projects, in addition to laboratory results, and to formulate specialized guidelines for engineers.

CONCLUSION

Finally, the study's overall results and analysis clearly demonstrate that fly ash and recycled concrete aggregate (RCA) can serve as highly reliable and effective alternatives to achieve sustainable development goals in the construction industry. The main findings of the study indicate that the combination of 20% fly ash as a partial replacement for cement and 30% recycled aggregate instead of natural aggregate (Mix M2) maintains an excellent balance between strength and durability. Although the compressive strength of durable concrete is initially slightly lower, after 90 days, it exhibits strength equivalent to or even superior to that of conventional concrete due to the pozzolanic reaction of fly ash and the dense structure of C-S-H gel. In particular, durability tests have shown that the use of durable materials reduces concrete porosity, thereby providing greater protection against chloride ingress and acid corrosion. As a result, it is an ideal solution for coastal areas and industrial infrastructure. In addition, the potential to reduce landfill waste by using recycled aggregate and to reduce the carbon footprint by using fly ash represents a groundbreaking step in environmental conservation. The study also showed that, through proper mix design, it is possible to strengthen the weak 'interfacial transition zone' (ITZ) of recycled aggregates through the filler effect of fly ash. However, to ensure optimal performance, emphasis has been placed on proper curing and the use of superplasticizers during construction. In conclusion, this paper establishes that sustainable concrete is not merely a theoretical, environmentally friendly concept but rather a modern construction technology that is structurally sound, chemically stable, and economically viable. Ensuring widespread use of this technology will reduce pressure on natural resources in the global construction sector and allow the civil engineering sector to make a significant contribution to building a sustainable and green world.

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