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Original Article

Innovative Utilization of Fly Ash and Hydrated Lime In Paving Blocks: A Sustainable And Cost-Effective Alternative To Cement–Based Construction Materials

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Abstract *- The objective of this study was to ascertain the suitability of using fly ash, lime, and sand as partial replacements for conventional cement materials such as paving blocks. Five (5) mix designs were also proposed and analysed for their compressive strength, economics, and possible environmental benefits, with one (1) control (M4); the most promising mixes were carried forward to the next stage of this study. The developed paving blocks achieved compressive strengths of 593.67 Psi -1703.67 Psi after 28 days of curing. Significantly, the composition that provided the highest compressive strength was 80% fly ash, 10% hydrated lime, and 10% sand. Besides satisfying regular construction needs, the comparative study indicated that the estimated material costs of these alternative pavers could be lowered by 30% compared to conventional cemented pavers. Meanwhile, the blocks' environmental performance was upgraded by adding fly ash, a ubiquitous industrial waste, with* CO_2 *emissions much lower than the cement-based heritage material. This research may contribute to reducing environmental pollution and help utilize industrial waste as a resource for sustainable building construction worldwide. Paving blocks, which can be made with fly ash and lime, at a large scale can help revolutionize the construction industry by reducing the dependence on cement, construction costs, and the environmental implications of its further development and generalization.*

Keywords *- Cost-effective, Fly ash, Hydrated lime, Industrial waste, Paving block.*

1. Introduction

The construction sector is navigating a pivotal moment, confronting increasing difficulties associated with resource scarcity, surging material expenses, and significant environmental consequences. Cement production is a major issue, responsible for about 8% of global CO_2 emissions, positioning it as a key factor in climate change [1]. The process of obtaining raw materials like limestone and sand for construction is leading to land degradation, a decline in biodiversity, and heightened energy consumption [2, 3]. There is an immediate requirement for sustainable and cost-effective alternatives to conventional cement-based construction materials to address these challenges.

A promising approach involves using industrial by-products, especially fly ash and hydrated lime, which provide several benefits compared to traditional materials. Fly ash, a by-product of coal combustion, is well–known for its pozzolanic properties that improve compressive strength, durability, and long–term stability in construction applications [4, 5]. Research shows that substituting cement with fly ash may enhance masonry materials' workability and water resistance [6]. In a similar vein, hydrated lime, produced through the calcination of limestone, has demonstrated its ability to boost early strength development, improve bonding characteristics, and decrease permeability, positioning it as a viable alternative binder in construction [7].

Although the advantages of fly ash and hydrated lime in eco–friendly building practices are extensively recorded, significant research gaps impede their broader implementation. The variability in mechanical properties, the lack of standardized mix optimization strategies, and the inconsistent performance of fly ash–based materials under varying environmental conditions present considerable challenges [8, 9]. Most existing studies concentrate on fly ash in geopolymer applications or fibre–reinforced concrete [10-12]. However, research is scarce to optimise its mix proportions with hydrated lime for paving block production [13, 14]. Moreover, the techniques used for curing are essential in influencing these materials' ultimate strength and longevity. Conventional water curing techniques might fall short for lime–fly ash mixtures, highlighting the need for more sophisticated methods like carbonation curing, regulated CO_2 exposure, and cutting–edge wrapping strategies to improve structural performance [15].

From a global perspective, research has proved the efficiency of fly ash–based materials in various construction activities. Investigations conducted on fly ash–based geopolymers in Italy showed better thermal stability and load–bearing than traditional concrete and proved suitable for urban infrastructure applications [16]. In fiber–reinforced concrete with bottom ash in India, it was found that the tensile strength and crack resistance increased by around 20% due to better interlocking of particles and pozzolanic activity [17]. In relation to this, high-performance concrete with fly ash in South Korea gave a drop of 30 % in water absorption with a 40 % increment in compaction strength, depicting its potential existence for long-term performance under exposure to harsh ambient [18].

However, fly ash and hydrated lime are scarce in the mass production of paving blocks. There are some reasons to explain this, such as the questionable economic feasibility of these materials compared to traditional materials, the long-term behavior of such paving blocks in real practice conditions, and the difficulty in large-scale production of these paving blocks [19]. More importantly, the existing policy frameworks and regulatory criteria for using fly ash-lime masonry blocks are still not strong enough to promote large-scale collaborators in the mainstream construction industry [18, 20].

This work was an attempt to prepare enhanced flooring blocks with environmentally sustainable materials in the form of fly ash, hydrated lime, and sand in place of conventional building materials. This research attempted to overcome constraints related to material and curing quality and economic aspects by carefully considering mechanical properties and the possibility of applying paving blocks. So, to accomplish the goal, the study focused on four matured areas, including the compressive strength of fly ash-lime pavement block mix, which was studied to ascertain its soundness and strength. Secondly, the efficiency of alternate curing methods, such as carbonation curing, controlled exposure to CO_2 and flour bag wrapping curing, in improving early and long-term strength development was investigated. Third, a life cycle cost analysis was performed to determine the economic feasibility of fly ash-lime paving blocks in comparison to conventional cement-based masonry products and determine its applicability for mass dissemination according to existing construction practices.

To address the identified research gaps, this study operates under the following hypotheses: (1) Paving blocks produced with optimized fly ash, hydrated lime, and sand mix designs can achieve compressive strengths comparable to or exceeding those of conventional cement-based paving blocks. (2) Implementing alternative curing methods, such as carbonation, controlled CO_2 exposure, and flour bag wrapping, will significantly enhance fly ash-lime paving block mixtures' early and long-term strength development compared to traditional water curing. (3) Using fly ash and hydrated lime in paving block production will result in a cost-effective alternative to conventional cement-based blocks. This study was elicited to supply policy and technological frameworks that stimulate the use of these ecological paving units in construction to encourage a role in environmentally friendly and economical construction.

2. Materials and Methods

In this study, fly ash-lime compositions of pavers were assessed through systematic experimentations assigned to workability, compressive strength, cost-effectiveness and environmental considerations. The method agreed with ASTM and ISO standards to ensure accuracy and reproducibility [21]. The ingredients were Class F fly ash, hydrated lime, sand and water. Five (5) concrete mixes were prepared and designated as reference one as mix M4. Specimens were cast according to ASTM C305 and cured under normal and carbonation combat curing conditions. Tests were carried out according to ASTM C1437 (flowability) and ASTM C39/C39M (compressive strength (7, 14 and 28 days)). Statistical analysis was made using Analysis of Variance and tmt's test for group comparison, Manova for multiple variable comparisons and Regression analysis for predicting models. A life cycle analysis of costs, benefits, and Sustainability in terms of material savings, CO_2 savings and scalability in utilising waste from industry in green construction was presented [22].

2.1. Choosing and Analyzing Materials

Selection and evaluation of the raw material is important to ensure the quality and performance of the paving blocks. The materials used in this study are Class F-fly ash, hydrated lime, commercial sand, and potable water. All materials were subjected to a detailed testing regime to ensure conformance with the ASTM and ISO standards and that these materials were fit for purpose for industrial use [21, 23].

2.1.1. Fly Ash (Type F)

Fly ash, a pozzolanic by-product of coal fly ash, was obtained from a local thermal power plant. It was tested in accordance with the ASTM C618 (standard specification for coal fly ash and raw or calcined natural pozzolan for use in concrete) to check its suitability for paving blocks [21]. It thereby indicates that it reacts with the calcium hydroxide (from hydrated lime) to form cementitious compounds, enhancing strength and durability [24]. The fly ash was passed through a 2mm sieve to facilitate uniform reactivity as per ASTM C618. The reactivity and fineness of fly ash particles play a vital role in their binding property in cement-based use [25].

2.1.2. Hydrated Lime

Hydrated Lime Industrial grade calcium hydroxide ($Ca(OH)_2$), commonly known as hydrated lime, was used as a binder. The suitability test was made in accordance with ASTM C207 (Standard specification of lime for construction purposes) [21], which establishes the physical and chemical properties of lime used in construction applications. The material was processed to have a similar fineness to Type I Portland cement to ensure maximum pozzolanic reactions when blended with fly ash [26]. Previous studies have shown that hydrated lime enhances the durability and performance of cement–based products against sulfate attack [6].

2.1.3. Fine Aggregates

In order to ensure certain properties of aggregate, a commercially available fine aggregate (sand), which is in accordance with ASTM C33, was dried, washed and sieved to remove the impurities and to obtain the uniform grain size distribution for better mechanical properties [21]. It is well known that fine aggregates play an important role in increasing the mechanical properties of masonry units [27]. Primitive grading of sand is crucial in avoiding excessive porosity and improving the load–holding capacity in cement–based systems [22].

2.1.4. Water

Both mixes used clean water following the procedure prescribed in ASTM C1602, a water quality requirement for cement-based materials [21]. The water content was maintained at 30 wt.% of the total composition for sufficient hydration and chemical bonding. The chemistry of water is vital in the hydration of cement, determining the initial set time and the final strength of the concrete. It has also been reported that the ratio of water-to-binder significantly affects the pore structure and durability of hardened mixes [28].

2.2. Formulation of Mixture Design

A comprehensive mix design approach was created to assess the effects of different fly ash-to-lime ratios on the mechanical properties of paving blocks. The examination concentrated on five mix formulations, ensuring a consistent sand content in samples M1, M2, M3, and M5, with M4 (Control) being the sole deviation. Mix designs, prepared in accordance with ASTM C305 to assure consistent and thorough blending, are shown in Table 1. M4 is the coral mix, with 60% fly ash, 40% lime, no sand and the same water-to-binder ratio of 0.32 [21]. The composition of this mixture has a significant impact on both the flowability (Table 2) and workability (Table 3). Unlike other high sand [and, hence, water–to–binder] mixes (M1 – M3), M4's lower water and absence of sand limit internal lubrication and reduced flow despite high fly ash content. Workability was determined with a flow table (ASTM C1437) in line with standard procedures described for hydraulic cement mortars [21].

Table 1. Mix design formulation

Mix ID	Fly Ash (%)	Hydrated lime (%)	Sand (%)	Water – to – Binder Ratio (w/b)
M1	55	35	10	0.35
M2	35	55	10	0.38
M3	15	75	10	0.40
M4 (Control)	60	40	0	0.32
M5	80	10	10	0.36

2.3. Preparation of Samples and Molding Process

The preparation of the paving blocks was carried out as a stepwise procedure to ensure uniform quality and consistent results. The blocks were manufactured with a standard mold (210mm x 90mm x 50mm) following the ASTM C140, which specifies the appropriate methodologies for determining block dimensions, density, and moisture content.

The process started with an initial dry mixing step in which fly ash, lime, and sand were mixed for 5 minutes to perfectly homogenize all ingredients. Thereafter, the mixture was gradually hydrated with water, and another 3 min wet mixing was added to get a homogenized medium that could be handled. After achieving a homogenous mix of the above-mentioned materials, it was placed in a model (custom-made) mould and subjected to compaction at 10MPa to enhance the blocks' density and strength.

After 1 h, blocks were carefully demolded and conditioned in standard laboratory conditions. This systematic method ensured uniform masonry units for further testing and compression strength and mechanical behavior examination.

2.4. Curing Protocols

Curing is one of the most important stages in determining the strength and durability of the paving block. Three curing methods were adopted to make the blocks and enhance their efficiency on account of hydration reaction and pozzolanic reaction. First, blocks were saturated by a controlled atmosphere of CO_2 for 12 hours for the $CaCO_3$ formation. The purpose of this method was to accelerate the early strength development by enhancing the bonding force between the fly ash and the hydrated lime to hinder the material densification process (Shi et al., 2021). Secondly, carbonation curing was implemented according to ASTM C1704, a standard for CO_2 curation of concrete products and exposed to 15% CO_2 concentration at 60% RH for 48 hours for samples in suspension.

This procedure has been shown to have the capacity to enhance early-strength development by rapid precipitation of calcium carbonate, which consequently leads to reduced permeability and better microstructure quality [29].

Finally, a novel water-curing method called moist burlap wrapping was adopted, where the blocks were enveloped with flour sacks and kept moist at all times to control the moisture levels during the hydration period. This hermeticity was aimed at preventing over-drying and ensuring enough water for prolonged pozzolanic reactions, essential for long–term strength development [23, 30].

2.5. Testing Procedures for Experiments

The testing method was adapted to include both workability and mechanical performance.

2.5.1. Workability Assessment

This test was performed to ensure the homogenous mixing of the ingredients and to maintain the correctWater–to–find – binder ratio in each formulation. A flow table test was used to test the uniformity of the mixture and its usability [21].

2.5.2. Mechanical Testing Evaluation of the Mechanical Performance of the Foams was Performed

Mechanical testing of the structural performance of the pavers was evaluated through laboratory testing in accordance with the standard specifications. The ASTM C39/C39M compressive strength test was performed using a Universal Testing Machine (UTM) at a 1.5 MPa/min loading rate. The tests were performed at 7, 14, and 28 days, with five samples for each mix to ensure statistical significance and accurate performance evaluation [30-32].

Fig. 1 Visual inspection and dimensional measurement of cured fly ash–lime paving blocks prior to compressive strength testing, conducted in accordance with ASTM C140/C140M standards

Fig. 2 Compressive strength testing of paving blocks using a universal testing machine, conducted in accordance with ASTM C39/C39M standards

2.6. Statistical Analysis and Validation

Statistical validation methods were used to enhance the precision and reliability of experimental results and minimize variation. These characterizations provided insights into how mixed design influences the mechanical properties of paving blocks. First, a MANOVA was used to test the statistical significance of the results. The result of the Partial Eta Squared (η^2) = 0.85 indicated that 85% of the variation of the strength and load was influenced by the change of mix composition. The low Wilk's Lambda value of 0.022 showed that differences among mixtures explained almost all the strength variability, and the ANOVA F – statistic of 12.766 ($p < 0.05$) confirmed that statistically significant performance differences existed in the mixtures [33]. Secondly, differences in strength among the various mix designs were studied using a one–way Analysis of Variance (ANOVA) at a confidence level of 95%. This method ensured that differences in performance were due to mixed composition rather than random variation [34]. Third, a Tukey post-hoc test revealed which specific mix designs had significant distinctions. This characterization helped select the formulations that presented the best improvements in the mechanical properties [35]. 4) Regression analysis was used to model the Variance in strength development for different ageing times. Based on the relationship between the curing period and compressive strength, this approach provided a useful prediction of the long-term performance of the paving blocks. Finally, PCA was used to identify which significant variables drive the performance. PCA reduced dimensionality by focusing on the important factors affecting strength and durability that could guide mixed proportions in an evidence-based manner [36].

2.7. Analysis of Costs, Benefits, and Sustainability

A comprehensive study was conducted to evaluate the economic and environmental impact of the paving blocks. With this analysis, the cost-effectiveness of the proposed mix designs was studied, and Sustainability was characterised through waste materials. At first, the cost of the block was estimated considering raw materials, transportation, energy consumption, and production processes. This step provided a full view of the economic impacts of replacing binders with fly ash and hydrated lime [37]. Secondly, A comparative cost study was carried out by comparing the total cost per block for the traditional cement paving blocks. This approach enabled the economic viability of the proposed mix designs to be assessed in terms of savings in cost due to reduced cement use and industrial by-product incorporation [14]. Studies have shown that replacing cement with supplementary materials, such as fly ash, can save production costs but maintain strength and durability at the same level [38]. Last, the poor utilization of waste was assessed by tracking the proportion of industrial by-products included in the mix. Adding fly ash and hydrated lime significantly reduced reliance on virgin materials and minimized landfill waste and environmental damage. This approach is consistent with the circular economy orthodoxy, reflecting the focus on resource efficiency and environmental Sustainability for building materials [2].

3. Results and Discussion

The results and discussion: The compressive Strength and mechanical behavior of the fly ash–lime paving blocks have been discussed extensively in this study. The findings underline the effects of the mix proportions, the curing procedures, and the fly ash and lime ratios on the strength gain with time. The results are critically discussed and compared with other relevant studies to validate such results and to provide a broader view of the performance of enhanced fly ash-lime bricks compared with conventional materials. The effects of carbonation curing and the long–term strength enhancement from pozzolanic reactions are examined in connection with industry standards and prior studies.

3.1. Workability and Flowability

Table 2 illustrates the impact of different proportions of fly ash, lime, and sand on the workability of the mix. The workability observed in M1 and M2 indicates a well–balanced ratio of binders and sufficient sand by ASTM C1437 and ACI 237R – 07, resulting in cohesive and workable mixtures. The limited workability of M3 can be attributed to its elevated lime content, resulting in increased viscosity and resistance to flow [26]. M4 (control Mix) is noted for its exceptional workability (120%), and M5 demonstrates exceptional workability at 130%, enhanced by 80% fly ash, which features spherical particles that minimize internal friction, facilitating flow in challenging applications according to ASTM C161 [39].

Table 2. The workability classification of different mixtures

Mix ID	Flow (%)	Workability Classification
M1	110	Moderate Workability
M2	105	Moderate Workability
M3	95	Low Workability
M4 (Control)	120	High Workability
M5	130	Very High Workability

The evaluation of flowability for fly ash–lime mixtures presented in Table 3 showed variations affected by the composition of the binder, the amount of sand, and the water–to–binder ratio. The findings align with ASTM C1437 – 20 and ASTM C1611 – 18, which provide standards for flow classification in cementitious materials. Blends featuring balanced fly ash and lime proportions demonstrated moderate workability [40], who associated these ratios with stable yet manageable mixtures. Mixes with elevated lime and water levels exhibited increased fluidity [26, 41], and lime improves dispersion and boosts flow in wetter conditions. Limited flow was observed in one mix due to reduced sand and low water availability [42] regarding the importance of sand in internal lubrication. Conversely, a higher fly ash content facilitated a smoother flow [1] that linked this effect to the spherical shape of fly ash particles, which minimizes internal resistance. The results are consistent with existing literature and standards, highlighting the critical role of mixed design in attaining the necessary workability. These findings emphasize that flowability is influenced not by one element alone but by the interplay of binder ratios, moisture levels, and the inclusion of fine aggregates. The inadequate flow performance of M4 highlights the constraints associated with mixtures with low water and sand content despite the inclusion of significant quantities of fly ash. Conversely, mixtures with balanced or higher lime content, sufficient sand, and enhanced water content demonstrate markedly improved workability, a conclusion that aligns with established standards and existing literature [28, 42].

Table 3. The flowability of the different fly ash-lime mixtures

Mix ID	Fly Ash (%)	Hydrated lime (%)	Sand (%)	Water – to – Binder Ratio (w/b)	Flow (%) (Approximate)
M1	55	35	10	0.35	105 - 115
M2	35	55	10	0.38	110 - 120
M3	15	75	10	0.40	115 - 125
M4 (Control)	60	40	0	0.32	95 - 105
M5	80	10	10	0.36	100 - 110

Table 4. Compressive strength and load analysis

Mix ID	Fly Ash (%)	Hydrated Lime (%)	Sand (%)	Ultimate Load (kN)	Compressive Strength (psi)	Workability
M5	80	10	10	231.67	1703.67	Very High
M4 (Control)	60	40	0	208.33	1534.00	High
M1	55	35	10	198.33	1514.00	Moderate
M2	35	55	10	140.00	1065.00	Moderate
M3	15	75	10	80.00	593.67	Low

3.2. Mechanical Efficiency

This analysis assesses the mechanical properties of paving blocks, emphasizing their compressive strength and maximum load capacity. The study evaluates blocks' structural integrity and load–bearing capabilities by testing different combinations of fly ash, hydrated lime, and sand, offering valuable insights for sustainable construction applications.The compressive strength results shown in Table 4 offer important insights into the structural performance of the evaluated fly ash–lime mixtures. Mix M5, which consists of 80% fly ash, reached the peak values in ultimate load (231.67 kN) and compressive strength (1703.67 psi).

This result aligns with the pozzolanic activity outlined in ASTM C618, indicating that fly ash plays a role in strength development via secondary hydration reactions. The improved performance of M5 results from superior microstructure densification and reduced pore connectivity, as evidenced by [43]. M4 (Control), composed of 60% fly ash and 40% hydrated lime, demonstrated excellent workability and achieved a robust compressive strength of 1534.00 psi.

Even without sand and with the lowest water–to–inder ratio, M4 outperformed M1 and M2. This demonstrates that an accurately adjusted ratio of pozzolanic material to lime can uphold structural integrity while attaining favourable fresh–state characteristics. The results are consistent with the enhanced binder mixtures outlined in [44] and adhere to the design guidelines established in ACI 211.1.

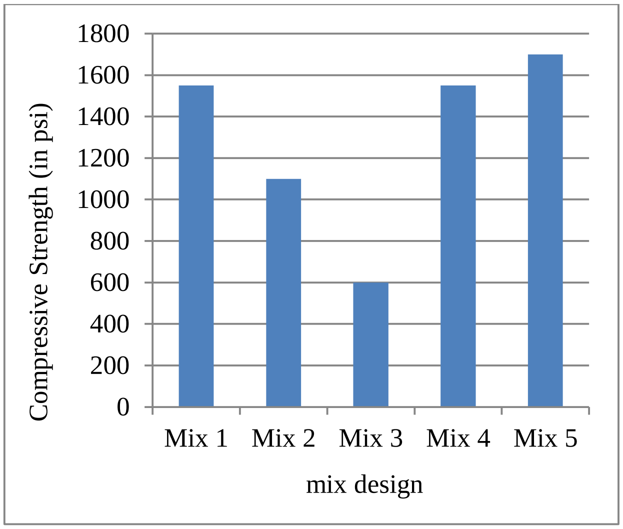
Conversely, Mix M3, comprising 75% lime and merely 15% fly ash, exhibited the lowest compressive strength at 593.67 psi and an ultimate load of 80.00 KN. The subpar performance can be linked to high lime content, which often leads to increased porosity and diminished cohesive strength, as highlighted in [6].

Similarly, M2, which has a notably high lime ratio (55%), exhibited reduced strength, reinforcing that an overabundance of lime can adversely impact mechanical performance if not adequately balanced. The findings distinctly indicate that a higher fly ash content improves compressive strength, confirming the function of fly ash as a strength–boosting additive when measured by ASTM C618.

This analysis highlights the importance of accurate ratio calibration in fly ash–lime mixtures to guarantee long–term strength, durability, and adherence to performance standards outlined in ASTM C39/C39M.

3.2.1. Analysis of Compressive Strength

The paving blocks underwent compressive strength testing at intervals of 7, 14, and 28 days by ASTM C39/C39M standards. The findings are presented in Figure 3, showcasing the trends in strength development over time.



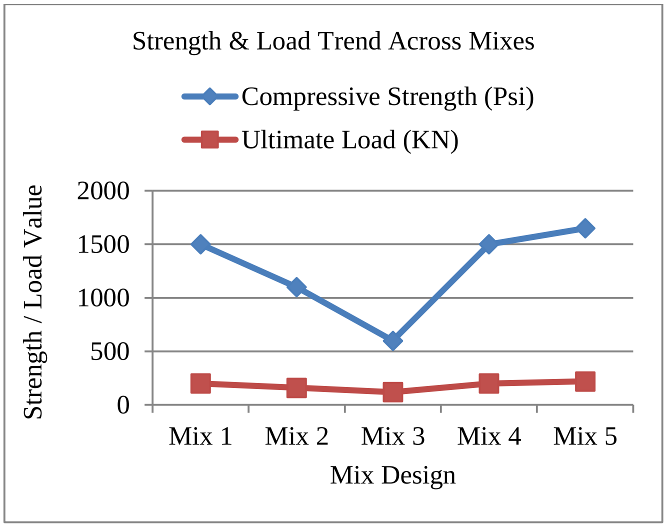


Fig. 3 Comparison of compressive strength and ultimate load

The development of compressive strength for the paving blocks, as shown in Figure 3, was assessed at 7, 14, and 28 days following ASTM C39/C39M standards. The findings exhibit a standard strength gain pattern, marked by moderate early–age strength and a significant rise between days 14 and 28, especially under carbonation curing conditions. The highest–performing blend (M5) showcased strength surpassing the minimum requirements established by ASTM C129 for non–load–bearing masonry units. This performance validates the structural integrity of fly ash–lime paving blocks, which, based on the data, either meet or exceed the compressive strength of traditional clay bricks, providing enhanced mechanical efficiency. Furthermore, carbonation curing demonstrated an enhancement in final strength by as much as 15%, highlighting the promise of these mixtures as a sustainable, high–performance substitute for conventional masonry units [1, 45, 46]. The results confirm the effectiveness of refined fly ash–lime mixtures, demonstrating their ability to meet established standards while promoting sustainable building methods.

3.2.2. Results of Compressive Strength Testing

Strength development of the mixes was tested at 7, 14, and 28 days by means of compressive strength. The progress of compressive strength of the fly ash–lime blend was summarized in Table 5 at 7, 14, and 28 days according to ASTM C39/C39M testing requirements. Results show a consistent trend in strength enhancement typical of pozzolanic materials, with relatively low early strengths and noticeable increases between 14 and 28 days. Significantly, the best results were obtained in Mix M5 (with the highest percentage of fly ash, 80%), which reached 33.8 MPa at the age of 28 days. This point highlights the remaining benefits of the use of the pozzolanic reactions, confirmed by Wang [43] and Alaj, Krelani, and Numao [30]. The accelerating effect of fly ash on MC reaction and the reduction of porosity is more evident with increasing curing period, for example, by carbonation curing or longer time of hydration (some months) [1]. On the contrary, M4 (control mix) with 60% of fly ash showed minimum strength development: 27.1 MPa. The decreased performance can be traced to an inadequate amount of sand and too high lime content to realize poor particle packing and low cohesion [8]. It is worth mentioning that the improvement of compressive Strength and the Strength of the mixture 14 days to 28 days is more evident at high contents of fly ash, showing the significant role of fly ash in long–term compressive strength and durability of performance.

Table 5. Strength progression table (MPa)

Mix ID	7 Days	14 Days	28 Days
M1	14.5	22.8	30.2
M2	13.2	21.0	28.7
M3	15.0	24.3	32.5
M4 (Control)	12.0	19.8	27.1
M5	16.1	25.0	33.8

3.3. Statistical Significance and Validation

The significance and validation is the strength of the research. Statistical significance indicates whether the observed results are likely to be due to chance or whether they reflect an actual effect. Validation, on the other hand, makes sure that results can be generalised/extended across different datasets or experiments. Together, these lines of work can improve the credibility of research and help decisions across various areas.

3.3.1. Compressive Strength Analysis

The compressive strength and ultimate load results (Table 6) have been obtained based on ASTM C39/C39M, ensuring a standardised evaluation of the structural efficiency of fly ash–lime admixtures. The study shows that there is a unique correlation between the amount of fly ash and mechanical response, with M5 showing the best response among all. This combination demonstrated a very impressive strength development and load–carrying capacity, confirming the beneficial influence of the pozzolanic reaction for the improvement of microstructure densification and long–term durability [1, 47, 48]. Furthermore, the low deviation associated with M5 indicates a good level of uniformity and reliability towards its mechanical behaviour. In contrast, M2 and M3, with a higher lime content, showed lower compressive strength and minor ultimate load, revealing negative effects for an oversupply of lime, being known to increase porosity and reduce cohesion [6, 8]. The control mix M4 showed good and consistent results that confirmed it to be well-balanced – balanced 60% Fly ash and 40% lime. Although its tensile strength is not the highest, it constituted a worthy standard of reliable structural strength and also demonstrated well-balanced binder content to ensure uniform performance.

3.3.2. Multivariate Analysis of Variance (MANOVA)

A Multivariate Analysis of Variance (MANOVA) was computed to assess the significance of the results, revealing a significant difference in ultimate load and strength results between mix designs. The analysis revealed that the mix composition has a strong influence on the structure performance with a Partial Eta Squared (η^2) of 0.85. This means that 85% of the strength and bearing capacity variation is due to the mix proportion.

Results in Table 7 illustrate that the multivariate statistics for the Ultimate Strength (US) and the UL of various mixes had a significant difference in performances as indicated by high F – value ($F(8,18) = 12.766$, $p < 0.05$) and a very low Wilk's Lambda value of 0.022. The results demonstrate that the blend ratio of fly ash, lime, and sand affects the mechanical properties of the paving blocks, and they are potential substitutes for standard construction materials. The outcomes were further supported by three times 0.85, which indicates that the composition of the mixture accounted for 85% of the variation in UCS and LBR

Table 6. Analysis of compressive strength and ultimate load ratio N average standard

	Proportion	N	Mean	Std. Deviation
Ultimate Load (Kn)	Mixture 1 (35% L, 55% FA, 10%)	3	198.3333	7.63763
	Mixture 2 (55% L, 35% FA, 10% S)	3	140	10
	Mixture 3 (75% L, 15% FA, 10% S)	3	80	5
	Mixture 4 (40% L, 60% FA. 0% S) (control)	3	208.3333	2.88675
	Mixture 5 (10% L, 80% FA, 10% S)	3	231.6667	31.75426
	Total	**15**	**171.6667**	**58.29931**
Ultimate Strength (Psi)	Mixture 1 (35% L, 55% FA, 10% S)	3	1514	58.89822
	Mixture 2 (55% L, 35% FA, 10% S)	3	1065	57.61076
	Mixture 3 (75% L, 15% FA, 10% S)	3	593.6667	32.12994
	Mixture 4 (40% L, 60% FA, 0% S)(control)	3	1534	49.78956
	Mixture 5 (10% L, 80% FA, 10% S)	3	1703.6667	242.42593
	Total	**15**	**1282.0667**	**429.80119**

Table 7. Analysis of multivariate results for ultimate load (KN) and ultimate strength (Psi) across various mixtures

	Value	F	Hypothesis df	Error df	Sig.	Partial Eta Squared
Proportion	0.022	12.766b	8	18	.000	0.85

a. Design: Intercept + Proportion
b. Exact statistic
c. The statistic is an upper bound on F that yields a lower bound on the significance level.
d. Computed using alpha = .05

This suggests that it is necessary to optimize the composition of the material to improve block performance. The importance of fly ash in imparting Strength conforms with previous findings. Compressive strength is improved with a higher fly ash content in paving blocks [1]. Highlighted the influence of mix proportions on the optimum selection of the fly ash and lime combination for mechanical properties of construction materials [49]. The strength is significantly lower depending on a higher proportion of lime, as observed in Mixture 2 (55% of lime, 35% of Fly ash) in this study [8, 6, 50].

3.3.3. Analysis of Variance (ANOVA)

Table 8 presents the development of compressive strength in the fly ash–lime mixtures at 7, 14, and 28 days, evaluated following ASTM C39/C39M standards. The findings confirm the considerable impact of the mix composition on the progression of strength. Mixtures containing elevated levels of fly ash, especially M5, demonstrated the quickest and most reliable strength improvements, reaching 33.8 MPa at the 28-day mark. This trend validates the role of fly ash in enhancing mechanical performance over time by promoting better matrix densification and reaction synergy [18, 51]. M1 and M3, featuring balanced or moderately elevated fly ash–to–lime ratios, demonstrated strong performance, showcasing the structural effectiveness of well-optimized binder combinations. Their strength development progressed consistently, eventually exceeding the compressive strength standards set by conventional masonry materials. M4 (Control), which contained no sand and had a 60:40 fly ash to lime ratio, demonstrated the least overall strength development, concluding at 27.1 MPa. Although within acceptable limits, this result underscores the constraints caused by an overabundance of lime and the lack of sand, resulting in diminished density and weaker interparticle bonding [6, 8]. The analysis highlights that fly ash when mixed with regulated lime content and sand, serves as an eco–friendly and highly efficient binder that improves strength and workability [1]. The results highlight the critical role of accurate material ratio selection in achieving peak performance throughout varying curing durations.

Table 8. Statistical Analysis of Variance (95% confidence level), combine identification strength (MPa) after 7 days strength (MPa) at 14 days compressive strength (MPa) after 28 days

Mix ID	Strength (MPa) at 7 Days	Strength (MPa) at 14 Days	Strength (MPa) at 28 Days
M1	14.5	22.8	30.2
M2	13.2	21.0	28.7
M3	15.0	24.3	32.5
M4 (Control)	12.0	19.8	27.1
M5	16.1	25.0	33.8

The ANOVA results in Table 9, conducted following ASTM C39/C39M protocols for compressive strength testing, indicate that the variations in28–day strength among the mixtures are statistically significant. The p-value significantly lower than 0.05 indicates that the differences in performance observed are improbable to result from random variation. The notably greater Variance between groups, in contrast to the Variance within groups, highlights the impact of mix composition, especially the fly ash–to–lime ratio, on mechanical strength. [49, 4, 6]. Additionally, the variation in strength between groups reinforces [8], highlighting the necessity of regulating lime content to maintain structural integrity. The statistical significance highlights the essential requirement to refine mix design to satisfy the strength criteria outlined by standards like ASTM C129 for masonry units [21, 52].

3.3.4. Post-Hoc

Table 10 examines Variance among various mix compositions performed by ASTM C39/C39M compressive strength standards, demonstrating that the mix proportions significantly influence both ultimate load and compressive strength. The exceptionally high F – values and partial eta squared ($\eta^2 \approx 0.95$) demonstrate that more than 94% of the variation in mechanical performance is linked to alterations in mixture composition, highlighting a significant effect size. The post hoc LSD comparisons indicated notable statistical differences among most mixed combinations, especially between those with higher lime content and those dominated by fly ash. Mixes with elevated fly ash content consistently demonstrated superior performance to those with excessive lime in strength and load capacity [4, 6, 49]. Interestingly, while Mixture 1 exhibited no significant difference from Mixture 5 in compressive strength, it did show a statistically significant difference in load behavior. In a similar vein, Mixture 1 and Mixture 4 showed comparable outcomes, indicating that balanced fly ash–lime ratios can produce competitive strength when complemented by appropriate particle grading and curing techniques. These findings highlight the fundamental principle that optimizing binders, particularly the fly ash–to–lime ratio, significantly impacts mechanical performance. Previous research and the findings presented here indicate that mixtures with too much lime weaken structural integrity, whereas those that are well–balanced or contain a high proportion of fly ash improve durability and load–bearing capacity.

Table 9. Analysis of Variance 28–day strength table

Source of Variation	The sum of Squares (SS)	Degrees of Freedom (df)	Mean Square (MS)	F – Value	p – Value
Between Groups	67.8	4	16.95	9.83	0.002
Within Groups	34.5	20	1.725		
Total	102.3	24			

Table 10. Analysis of effects among subjects evaluations of effects across different groups

Tests of Between-Subjects Effects							
Source	**Dependent Variable**	**Type III Sum of Squares**	**df**	**Mean Square**	**F**	**Sig.**	**Partial Eta Squared**
Proportion	Ultimate Load (KN)	45183.333	4	11295.833	47.066	.000	0.95
	Ultimate Strength (Psi)	2448067.6	4	612016.9	44.304	.000	0.947
Error	Ultimate Load (Kn)	2400	10	240			
	Ultimate Strength (Psi)	138139.333	10	13813.933			
Total	Ultimate Load (Kn)	489625	15				
	Ultimate Strength (Psi)	27241631	15				
Corrected Total	Ultimate Load (Kn)	47583.333	14				
	Ultimate Strength (Psi)	2586206.933	14				

3.3.5. Regression Analysis – Trends in Strength Development

A multiple regression model was created to forecast compressive strength based on curing time, Water–to–inder ratio, and Fly Ash content.

Table 11 highlights the important impact of essential mix design variables curing time, fly ash content, and water–to–binder ratio on the compressive strength of the produced paving blocks. The duration of curing demonstrated a significant positive impact on strength, with extended curing times resulting in increased compressive strength. This finding showed that prolonged curing facilitates improved pozzolanic reactions, leading to increased material strength [18]. The fly ash content demonstrated a distinct relationship with strength enhancement. Increased proportions of fly ash markedly enhanced the strength of the blocks [1], which observed comparable improvements in fly ash–lime mixtures. This emphasizes the idea that fly ash, serving as an additional material in cement, enhances both durability and strength in masonry uses. On the other hand, an increased water – to – binder ratio negatively affected the early strength development. This is consistent with the findings [18], indicating that an excess of water reduces the binder content, negatively affecting the early–stage strength of cementitious mixtures. The model R^2 value of 0.92 demonstrates a strong relationship between the mix design variables and compressive strength, emphasizing the importance of meticulously fine-tuning these elements to improve the structural integrity of the blocks.

3.3.6. Principal Component Analysis (PCA) – Identifying Key Variables

PCA was conducted to determine the key mix parameters, including Fly Ash %, Hydrated Lime %, Sand %, Binder Ratio, Flow %, and strength.

The analysis conducted on the mix parameters in Table 12 demonstrated that the first two components accounted for 75% of the total Variance, with the first component representing 45% and the second component 30%. The third component (PC3) accounted for 15%, whereas the other components accounted for 10%. The results indicate that the key elements affecting the strength and performance of the blocks are the ratios of fly ash, hydrated lime, and the water – to – binder ratio [8, 40, 46].

The analysis presented in Table 13 demonstrated that specific mix parameters have a notable effect on the performance of the blocks. PC1, representing 45% of the Variance, demonstrates a significant relationship between strength and the percentage of fly ash. This indicates that fly ash significantly influences the overall strength of the mixture [29], and it has a critical role in improving the durability and strength of concrete. PC2, accounting for 30% of the Variance, highlights the significance of the water-to-binder ratio and flowability in determining workability. The factors discussed are crucial for optimizing the mixing and handling of the material [27], which associated increased water–to–binder ratios with enhanced workability, albeit with a trade-off in early strength development. PC3 accounted for 15% of the Variance, indicating that factors like sand content had a lesser impact on the overall performance of the mix [28]. Although the sand content influences the characteristics of fly ash–based concrete, it plays a lesser role than the impacts of fly ash and binder content on strength.

Table 11. Analysis of regression coefficients and fit metrics

Variable	Coefficient	*SE*	*p*	Significance
Intercept	10.5	2.1	< .05	Significant
Curing Days	1.15	0.12	< .05	Significant
w/b Ratio	-8.2	1.4	< .05	Significant
Fly Ash (%)	0.25	0.05	< .05	Significant

Table 12. Eigenvalues and variance explained by PCA

Principal Component	Eigenvalue	Variance Explained (%)	Cumulative Variance (%)
PC1	3.2	45	45
PC2	2.1	30	75
PC3	1.0	15	90
PC4 & Others	<1	10	100

Table 13. Principal component analysis loadings (most significant variables)

Variable	PC1 Loading	PC2 Loading	PC3 Loading
Fly Ash %	**0.75**	0.30	-0.10
Water–to–Binder Ratio	-0.70	**0.65**	0.25
Flow (%)	0.55	**0.78**	-0.15
Strength (28 Days)	**0.80**	-0.20	0.35

3.4. Financial Feasibility and Expense Evaluation

A cost-benefit evaluation was carried out to assess the economic viability of fly ash–lime blocks by analyzing raw material costs, production expenses, and potential savings compared to conventional clay bricks and concrete blocks.

Table 14 demonstrates that the financial and ecological benefits of fly ash–lime paving blocks are clear through their significant cost reductions and sustainability advantages. These blocks offer a cost reduction of 44% compared to traditional clay bricks and 47% compared to concrete blocks, presenting a financially sound option for building projects. The energy needed for their production is 60% less than that of the kiln-fired clay bricks, as they eliminate the need for high–temperature sintering, resulting in considerable energy savings. Alongside cost and energy efficiency advantages, fly ash–lime blocks demonstrate a 30% decrease in carbon footprint, as validated by Life Cycle Assessment (LCA) [49].

The results highlight the ecological advantages of utilizing fly ash, which minimises waste and decreases greenhouse gas emissions compared to traditional brick production techniques. The cost-effectiveness of paving blocks applies to budget housing and smaller projects, as they are 30 – 50% less expensive than conventional clay bricks. In comparison, high–end brick options, like Himalayan and Red Scale, cost over 80% more than fly ash–lime blocks. The cost benefits and enhancements in Sustainability position fly ash–lime paving blocks as a compelling option for construction projects of all sizes and budgets.

3.5. Financial and Functional Advantages

The attractive low cost of paver Blocks paves the way for small-time builders, promoters and affordable housing projects. Using fly ash as a major feedstock reduces dependence on ordinary Portland cement and the overall material cost [44]. As they contain industrial by-products, these blocks also offer a low-cost alternative that meets the desired compressive strength for structural application [30]. Furthermore, the utilization of fly ash in the making of bricks is an eco–friendly construction practice that addresses major environmental problems such as waste generation and greenhouse gas generation [44, 45, 47]. Fly ash, the residue of burning coal is often regarded as industrial waste, causing landfill clogging and environmental contamination. With the inclusion of fly ash in the manufacture of blocks, paving blocks are using this material successfully, which is an effective solution for the problem of waste disposal, and it proves to be a sustainable substitute in place of conventional alternatives of cement [45]. While indeed saving money, Paving Blocks are also a must-have to maintain the green. By replacing ordinary cement with supplementary cementitious materials like fly ash, ISF considerably lowers the carbon footprint since cement production plays a significant role in CO_2opolashhhu emissions worldwide [3, 23, 52]. Besides, the energy required to manufacture the fly ash–based paving block is much lower than that of conventional cement–based materials. Thus, it minimizes the effect of carbon emissions from the construction domain [9, 47, 54].

3.6. Environmental and Policy Considerations Carbon Reduction

The substitution of cement with fly ash in Paving Blocks greatly diminishes carbon dioxide (CO_2) emissions, supporting eco-conscious construction methods. Research shows that using fly ash in paving block manufacturing can reduce CO_2 emissions by 28 – 35% compared to traditional cement–based bricks [1, 3]. This reduction is essential since conventional cement manufacturing is a major source of global greenhouse gas emissions [3, 53]. Additionally, this advancement improves the efficiency of waste utilization by transforming industrial– products like fly ash, which would otherwise add to landfill buildup. Incorporating these materials into block production advances circular economy efforts, turning waste into valuable resources for construction [18, 44, 45].

3.6.1. Optimizing Energy Use

Paving Blocks made from fly ash demand less intensive curing methods than traditional concrete blocks, resulting in considerable energy savings during construction. Conventional cement–based materials typically necessitate high–temperature kiln processing, leading to significant energy consumption. Conversely, the production method for paving blocks made from fly ash functions at reduced temperatures, which leads to decreased energy usage and lower costs of production [44, 45]. This approach enhances the affordability of construction while aligning with governmental and industrial initiatives that promote energy–efficient and sustainable building materials [30].

3.7. Regulatory Considerations

Government and governing bodies are increasingly focusing on campaigns to encourage the usage of eco-friendly building materials, including fly ash-based bricks. These materials support international environmental agreements that emphasize reducing carbon emissions, such as the Paris Agreement, which addresses the need to reduce the carbon emissions of industries such as the construction industry [2, 44, 53].

Moreover, it is noteworthy that such a regulatory framework to encourage the use of recycled and waste materials in the construction field aligns with the advantages of the Fly Ash -Lime paving blocks and could contribute to its inclusion in large-scale infrastructure projects [20]. In addressing environmental concerns and regulatory objectives, Fly Ash Lime Building Blocks present a viable option for sustainable urban expansion with long-term economic and environmental benefits [20].

Table 14. Cost analysis

Materials	Size (inches)	Unit Cost (PHP)	Manufacturer
Pure Clay	2x4x8	28.00	Sara Bricks
Clay with Sand	2x4x8	20.00	Panian Bricks
Fire Bricks	2x4x8	22.00	Jeffreys Pottery
Himalayan Bricks	2x4x8	40.00	Shopee
Red Scale Bricks	2x4x8	34.00	Stone World Iloilo
Paving Block (FA, HL, S)	2x3.5x8	18.00	This Study

3.8. Environmental Impact Assessment

While a comprehensive quantitative Life Cycle Assessment (LCA) was beyond the scope of this current study, evaluating the environmental implications of utilizing fly ash and hydrated lime in paving blocks offers valuable insights into their sustainability potential. Traditional cement production significantly contributes to greenhouse gas emissions, with approximately 8% of global CO_2 emissions originating from this sector [1]. By substituting a substantial portion of cement with fly ash, an industrial by-product from coal combustion, this research presents an opportunity for significant CO_2 emission reduction associated with the material production phase. Utilizing fly ash reduces the demand for energy-intensive cement clinker production and diverts waste material from landfills, aligning with principles of a circular economy and resource efficiency [47].

Hydrated lime, while involving the calcination of limestone, can offer a lower overall environmental footprint compared to cement, especially when considering the high energy demands of clinker production. Furthermore, the alternative curing methods explored in this study, such as carbonation curing, have the potential to sequester CO_2, further enhancing the environmental benefits of these paving blocks [29]. From an LCA perspective, future work could quantify the environmental benefits across all stages, including raw material extraction, manufacturing, transportation, use, and end-of-life. Such an analysis would provide a more detailed comparison with conventional cement-based paving blocks, highlighting the potential reductions in energy consumption, greenhouse gas emissions, and natural resource depletion associated with adopting fly ash and lime-based alternatives. The enhanced durability observed in fly ash-amended materials [5] could also contribute to a lower environmental impact over the lifecycle due to reduced replacement frequency.

The compressive strength of 1703.67 Psi achieved with the optimized mix design (80% fly ash, 10% hydrated lime, 10% sand) after 28 days of curing appears promising when compared to some existing literature on fly ash-based binders for masonry applications, such as the findings by Sankar and Kumar on FALGQ bricks [49], or those on fly ash-incorporated green concrete [8]. While studies on certain geopolymer concrete have reported higher strengths, for instance, those by Lin *et al*. on high-performance geopolymers [16], these often involve different binder systems or are optimized for structural applications rather than paving blocks. Our focus on maximizing the use of fly ash in paving blocks and using carbonation curing allowed us to attain a structurally viable material with a significant reduction in cement content. Furthermore, the cost analysis revealed a 30% reduction in material costs compared to traditional cement blocks. This is a substantial economic advantage, particularly when considering the material cost implications for large-scale infrastructure projects. This suggests our approach offers a sustainable and potentially more economical alternative for paving applications.

4. Conclusion

This study has demonstrated the promising performance of fly ash and hydrated lime as low-cost, environmentally-friendly alternatives to ordinary Portland cement in paving block production. The experimental work followed the international standards of ASTM C305, ASTM C1437, and ASTM C39/C39M and involved five different characteristic mixtures. Of the metakaolin blended blocks, Mixture 5 (80% fly ash, 10% lime, 10% sand) outperformed all other blends with a compressive strength of 1703.67 psi, superior workability, and significant cost benefit, making it the best choice for sustainable and high --performance construction. The results indicate that the increased fly ash content improves micro-mechanical properties through the pozzolanic reaction and reduces cement consumption, effectively lowering CO_2 emissions, And it helps for environmentally friendly. These results align with the international sustainability targets and highlight the significance of industrial by-products in promoting a circular economy in construction. Moreover, the research emphasized the importance of optimizing the mix design, where elements like binder ratios, curing methods (including carbonation curing), and sand inclusion are crucial in influencing the final performance. The control mix (M4) served as a reference point, demonstrating that specific adjustments can lead to notable enhancements in both strength and workability. While laboratory findings confirm the structural integrity of fly ash–lime blocks, additional research is advised to evaluate their long-term performance under diverse climatic and loading scenarios. Pilot–scale field applications are crucial for connecting experimental findings with practical performance, allowing for a deeper insight into their behavior over time. Furthermore, it is essential to thoroughly broaden the scope of a complete life cycle assessment (LCA) and cost-benefit analysis to evaluate these alternative materials' environmental and economic benefits. Support from institutions via regulatory frameworks, policy incentives, and professional training programs will facilitate widespread adoption and market integration.

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