Experimental Study on Portland Pozzolana Cement and Citric Acid Influence on Compressive Strength of Reinforced Concrete

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Abstract

In Ethiopia, the construction industry relies heavily on Ordinary Portland Cement (OPC) for structural applications due to its rapid early strength development. However, the widespread use of OPC contributes to high production costs and increased carbon emissions associated with cement manufacturing. Therefore, there is a growing need to evaluate more sustainable alternatives, such as Portland Pozzolana Cement (PPC), potentially enhanced with organic admixtures, to meet structural performance requirements while reducing environmental impact.
This study investigates the combined effect of partially replacing Ordinary Portland Cement (OPC) with Portland Pozzolana Cement (PPC) and adding citric acid as a chemical admixture on the compressive strength, setting time, and workability of reinforced concrete. Concrete samples of C-30 grade were prepared using OPC, PPC, and PPC modified with varying dosages of citric acid (0.1–0.4% by weight of Portland Pozzolana Cement). Experimental results indicated that citric acid acts as a retarder and water-reducing agent, improving the workability and extending the setting time without significantly compromising strength. The optimal dosage was determined to be 0.3% citric acid, which resulted in a 55% increase in slump, a delay in setting time of 1 hr 50 min (initial) and 3 hr 10 min (final), a comparable 28-day compressive strength to OPC mixes, and a cost reduction of 258.86 Ethiopian birr per cubic meter of concrete. The combined use of PPC and citric acid demonstrated improved performance and cost effectiveness compared to OPC-based mixes, promoting sustainable concrete production suitable for the Ethiopian construction industry.

Keywords: Portland Pozzolana Cement (PPC); Citric Acid; Reinforced Concrete; Compressive Strength; Mix Design

1. Introduction

Concrete is the most extensively used construction material worldwide, primarily valued for its compressive strength, durability, and adaptability. In Ethiopia, Ordinary Portland Cement (OPC) dominates structural applications because of its rapid early-age strength development, whereas Portland Pozzolana Cement (PPC) is mainly employed in non-structural works due to its slower strength gain [3, 21]. However, the energy-intensive manufacture of OPC contributes substantially to CO_2 emissions, prompting global interest in more sustainable alternatives that balance environmental and performance demands.

PPC, composed typically of 70% clinker, 25% pozzolana (often pumice or volcanic ash in Ethiopia), and 5% gypsum, offers lower heat of hydration and improved durability through secondary C–S–H formation from pozzolanic reactions. Despite these advantages, the slower hydration of PPC limits its use in reinforced concrete, where early strength is critical. To overcome this limitation, attention has turned to chemical admixtures capable of modifying cement hydration and workability. Among them, citric acid—an organic compound classified under ASTM C494 as a Type D water-reducing and retarding admixture—has shown potential to delay hydration while enhancing dispersion and flowability [22, 18]. At optimized dosages, citric acid can improve the microstructural compactness of cement paste and reduce water demand, but excessive quantities may cause undue retardation or strength loss.

In Ethiopia's hot climate, ready-mixed concrete often faces challenges of premature setting during transportation and placement. Controlled retardation through admixtures such as citric acid can provide additional handling time without compromising final strength. While PPC contributes to long-term durability and reduced CO_2 emissions, its interaction with citric acid in reinforced concrete remains largely unexplored. Previous research on Ethiopian cements [3, 17] focused mainly on comparing OPC and PPC without chemical enhancement, revealing that PPC achieves lower 28-day strength but superior impermeability and sulfate resistance. Other studies [14, **?**] confirmed that appropriate admixture selection and dosage optimization can substantially improve the performance of PPC-based concrete.

Recent research has explored advanced uses of PPC and chemical admixtures to enhance concrete performance. Albadrani [4] demonstrated that PPC blends with rice husk ash (RHA) achieved improved long-term compressive and flexural strength, highlighting the role of supplementary cementitious materials in sustainable concrete design.

In related work on admixture effects, Qin et al. [19] investigated citric acid-modified chitosan and found that it extended setting times and influenced strength and shrinkage behavior, suggesting that citric acid derivatives can modulate hydration kinetics and durability performance. Ciacchella et al. [12] further expanded the application of citric acid in concrete by demonstrating its effectiveness as a salt crystallization inhibitor under wet–dry cycles, linking citric acid chemistry to enhanced durability against environmental stress.

This work builds upon the findings of Meseret Simachew (2021), whose study on the application of PPC for structural concrete established the local context and technical limitations for using PPC in Ethiopian reinforced concrete. Furthermore, the study by Zhu, Yu, and Li (2021) serves as a critical recent contribution, demonstrating that citric acid serves as an effective admixture to significantly improve the injectability, workability, and flowability of cementitious systems.

Recent studies have increasingly focused on sustainable and high-performance concrete through the use of supplementary cementitious materials and chemical admixtures. Collectively, these findings provide updated insights into the interactions of PPC and chemical admixtures. Theoretical frameworks based on cement hydration kinetics, pozzolanic reactions, and admixture effects on microstructure formation inform our experimental approach and highlight the practical relevance of optimizing mix designs for reinforced concrete performance.

While previous studies have separately investigated PPC and citric acid as a chemical admixture, there is no experimental evidence on their combined influence on the compressive strength of reinforced concrete under varying mix proportions. Therefore, the key research question of this study is: *How does the combined use of PPC and citric acid affect the compressive strength development of reinforced concrete, and what are the optimal mix conditions for maximizing performance?* Addressing this question provides practical guidance for mix design and contributes to the understanding of PPC–citric acid interactions in reinforced concrete.

The study seeks to provide a scientific basis for understanding the synergistic interaction between PPC and citric acid and how this combination influences the hydration process, strength development, and fresh-concrete behavior. In doing so, it addresses one of the most pressing challenges in Ethiopian construction—achieving both economic efficiency and environmental sustainability without compromising structural quality.

In Ethiopia's construction industry, it is becoming increasingly common for PPC not to be the preferred choice for making reinforced concrete. Many consider PPC to be a less effective type of cement because it takes longer to reach the same strength as OPC. Therefore, this study focuses on examining how mixing PPC as a partial replacement for OPC and citric acid affects reinforced concrete, particularly in achieving the desired compressive strength after 28 days, and in reducing concrete cost. This research addresses the lack of experimental data regarding the combined use of PPC and citric acid to evaluate their suitability and effectiveness in reinforced concrete construction.

The specific objectives of the study are threefold: (i) to determine the optimum citric acid dosage that maximizes the performance of PPC-based concrete by improving its fresh and hardened properties; (ii) to evaluate the combined influence of PPC and citric acid on setting time, workability, and compressive strength, thereby quantifying their synergistic impact; and (iii) to develop a practical and locally adaptable concrete mixture that can be implemented within Ethiopia's construction sector to reduce cement consumption, production costs, and carbon emissions. Furthermore, the study seeks to contribute to the broader body of sustainable construction knowledge by providing a data-backed methodology for integrating organic admixtures into blended cement systems. Ultimately, this research not only offers an alternative approach to improving PPC performance but also supports the transition toward greener and more durable concrete technologies suited to Ethiopia's environmental and industrial context.

Although the use of citric acid as a retarding admixture in cementitious systems has been reported in previous studies, and PPC has also been extensively investigated independently, prior research has generally examined these materials separately. In addition, some studies have explored the combination of PPC with various chemical admixtures other than citric acid. However, the specific combined effect of citric acid with locally produced Ethiopian PPC has not been systematically investigated for normal-grade structural applications. To the best of the authors' knowledge, no prior research has comprehensively evaluated the synergistic interaction between PPC and optimized citric acid dosages in reinforced concrete. Therefore, this study presents original experimental work aimed at examining how controlled citric acid incorporation influences early-age and later-age compressive strength development of PPC-based concrete, with the objective of enhancing its structural applicability and cost-effectiveness as a sustainable alternative to OPC.

2. Materials and Methods

2.1. Experimental Overview

All laboratory work was conducted at the Addis Ababa University, College of Technology and Built Environment (Materials Testing Laboratory) and Yencomad Construction PLC Laboratory. The investigation involved raw-material characterization, concrete mix design, specimen preparation, and testing for C-30 grade concrete. The study compared mixtures made with OPC alone, PPC alone, and partial replacement of OPC with PPC modified with varying citric acid dosages by weight of PPC.

2.2. Materials

Cement: Dangote Ordinary Portland Cement (OPC) and Dangote Portland Pozzolana Cement (PPC) served as binders. OPC was used as the reference cement, whereas PPC partially replaced OPC in blended mixes to evaluate combined performance.

Fine Aggregate: Natural river sand from Alagea was used, conforming to ASTM C33 requirements. Specific gravity, fineness modulus, moisture content, and silt content were measured to verify suitability.

Coarse Aggregate: Crushed basalt aggregates of nominal sizes 9.5 mm ("01") and 19 mm ("02") were obtained from Yencomad Crusher. Tests performed included sieve analysis, specific gravity, absorption capacity, bulk density, and aggregate crushing value.

Citric Acid: Commercially available anhydrous citric acid was used as a Type D water-reducing and retarding admixture. Dosages of 0.1%, 0.2%, 0.3%, and 0.4% (by weight of PPC) were investigated to determine the optimum effect on setting time, workability, and strength.

The retarding mechanism of citric acid is primarily attributed to its role as a calcium chelator, forming citrate complexes with calcium ions released during the early stages of hydration; it inhibits the precipitation of calcium hydroxide and slows the dissolution of clinker grains, particularly tricalcium silicate (C_3S). This controlled delay allows for improved particle dispersion and water reduction, which can eventually lead to a more refined and compact pore structure in the hardened cement paste. The citric acid dosage used in this study is low and in line with previous studies, which indicate that such small amounts do not significantly alter the pore solution pH or endanger the passivation layer of steel reinforcement. No corrosion was observed during the curing period of the specimens. While this suggests that citric acid is safe at the tested dosage, further long-term studies on reinforced concrete in aggressive environments are recommended to comprehensively evaluate potential corrosion risks.

Water: Potable water conforming to ASTM C1602 was used for both mixing and curing.

2.3. Mix Design and Preparation

Concrete was proportioned for C-30 grade with a constant water–cement ratio (W/C) of 0.50, following the Department of Environment (DOE) method. Mix adjustments were made based on the moisture content and absorption capacity of the aggregates to ensure a saturated surface-dry condition. All materials were weighed to the nearest gram. Mechanical mixing was carried out in a pan mixer to achieve homogeneity. The slump test (ASTM C143) was conducted for each batch to evaluate workability.

2.4. Casting and Curing

Concrete cubes (100 × 100 × 100 mm) were cast for compressive-strength testing. After 24 hours, specimens were demolded and immersed in clean water at 23 ± 2 °C until the specified testing ages. Each mix was prepared in triplicate to ensure statistical reliability.

Table 1: Designation of concrete mixes

No.	Mix Code	Concrete samples prepared from
1	M_O	OPC only = *Reference Mix*
2	M_P	PPC only
3	O-50P-50	50% OPC + 50% PPC
4	O-60P-40	60% OPC + 40% PPC
5	O-70P-30	70% OPC + 30% PPC
6	M_1	60% OPC + 40% PPC + 0.1%CA
7	M_2	60% OPC + 40% PPC + 0.2%CA
8	M_3	60% OPC + 40% PPC + 0.3%CA
9	M_4	60% OPC + 40% PPC + 0.4%CA

CA = citric acid, by weight of PPC.

2.5. Testing Procedures

- **Setting Time:** Initial and final setting times were determined using a Vicat apparatus (ASTM C191).
- **Workability:** Measured by standard slump cone test (ASTM C143).
- **Compressive Strength:** Cubes were tested at 7, 28, and 56 days (ASTM C39). Average values of three specimens were reported for each mix.
- **Data Analysis:** Comparative analysis was conducted to evaluate the effect of citric acid dosage and PPC replacement on setting time, workability, and compressive strength of concrete. The optimum combination was identified based on marginal setting time, compressive strength performance comparable to OPC, and improved workability.

All compressive strength results were obtained from three replicate specimens and are reported as mean ± standard deviation (SD). One-way analysis of variance (ANOVA) was performed at each curing age (7, 28, and 56 days) to evaluate the statistical significance of differences among OPC, PPC-only, and PPC + citric acid mixes. A significance level of $\alpha = 0.05$ was adopted. When significant differences were detected ($p < 0.05$), post-hoc pairwise comparisons were conducted using Tukey's HSD test to identify the specific groups responsible for variation.

3. Theory

The hydration of cement primarily involves the reaction of tricalcium silicate (C_3S) and dicalcium silicate (C_2S) with water to form calcium silicate hydrate (C–S–H) and calcium hydroxide. In Portland Pozzolana Cement (PPC), pozzolanic materials react with calcium hydroxide to produce additional C–S–H, contributing to long-term strength.

Citric acid, a tricarboxylic organic compound, retards hydration by adsorbing onto cement particle surfaces and forming complexes with calcium ions, thereby delaying the precipitation of hydration products. The retardation effect increases with citric acid concentration but can be balanced to enhance workability without significant loss of strength. This theoretical understanding forms the basis for selecting the dosage range (0.1–0.4%) examined in this study.

4. Results and Discussion

The inclusion of citric acid significantly influenced the setting time and workability of PPC-based concrete. At 0.3% citric acid, the initial and final setting times were extended by approximately 1 hr 50 min and 3 hr 10 min, respectively, compared to the control mix. The slump increased by 55%, indicating enhanced workability and reduced water demand. These results align with the findings of Tinnea and Young [22], who reported that organic acids delay the hydration of tricalcium silicate by chelating calcium ions and retarding the formation of calcium silicate hydrate (C–S–H).

Compressive strength results showed that PPC alone had lower early-age strength than OPC. However, when combined with 0.3% citric acid, the 28-day compressive strength became comparable to OPC mixes, and the 56-day strength slightly exceeded OPC due to the secondary pozzolanic reaction between calcium hydroxide and reactive silica in PPC [20]. Higher citric acid content (0.4%) resulted in excessive retardation and strength loss, consistent with Purnomo et al. [18], who observed similar trends in citric-acid-modified concrete. The optimal dosage of 0.3% citric acid was thus identified, balancing extended setting time, improved workability, and satisfactory strength. Furthermore, material cost analysis revealed that PPC–citric acid mixes offer an economically viable and sustainable option for concrete production in Ethiopia.

4.1. Compressive Strength of Binder Compositions

PPC is not intended to fully replace OPC and is already known to delay setting time and affect workability due to its pozzolanic nature; the comparative strength performance at 28 days was prioritized to determine the most balanced mix for further experimental analysis.

In this phase, the 60% OPC + 40% PPC combination—selected based on compressive strength and cost balance—was used to assess the effects of citric acid on workability and setting behavior.

The mix with 70% OPC and 30% PPC demonstrated the highest compressive strength (27.2 MPa), as expected, due to the higher content of clinker, which accelerates hydration and strength gain [1]. However, the marginal difference between this mix and the 60% OPC + 40% PPC mix (only 1.17 MPa) suggests that the latter provides a more favorable balance between strength and potential cost or environmental impact [11]. On the other hand, the 50% OPC + 50% PPC combination showed the lowest strength (25.5 MPa), reinforcing the limitation of using high PPC proportions when early or design strength is a primary concern [15].

The 40% PPC replacement level was selected as the base binder composition following preliminary tests of 30%, 40%, and 50% replacement. The 60% OPC + 40% PPC mix was chosen because it provided the most optimal balance between target compressive strength (reaching 26.03 MPa at 28 days) and the economic benefit of reducing OPC content.

Table 2: 28th-day compressive strength results of binder compositions

Mix code	Sample No.	Load (kN)	CS 100mm (MPa)	CS 150mm (MPa)
O-50P-50	1	347	24.8	23.8
	2	372	26.3	25.2
	3	342	28.6	27.5
	Avg. (SD; SE)	–	**26.6**	**25.5** (1.87; 1.08)
O-60P-40	1	269	27.5	26.4
	2	244	28.8	27.6
	3	235	25.1	24.09
	Avg. (SD; SE)	–	**27.1**	**26.03** (1.78; 1.03)
O-70P-30	1	269	27.6	26.5
	2	301	30.5	29.3
	3	257	26.9	25.8
	Avg. (SD; SE)	–	**28.3**	**27.2** (1.85; 1.07)

CS = compressive strength; SD = standard deviation (MPa); SE = standard error (MPa), reported for the 150 mm-cube average.

Table 3: Effect of citric acid on the initial and final setting time

Mix	Mix Type	Delay (hr:min)	
		Initial	Final
M_1	60%OPC+40%PPC+0.1%CA	1:30	2:40
M_2	60%OPC+40%PPC+0.2%CA	1:35	2:55
M_3	60%OPC+40%PPC+0.3%CA	1:50	3:10
M_4	60%OPC+40%PPC+0.4%CA	1:55	3:50

Delay is relative to the reference mix (M_O). CA = citric acid, by weight of PPC.

Overall, while all three mixes achieved satisfactory strength values for general structural applications, the 60% OPC + 40% PPC mix was found to be an optimal compromise between mechanical performance and material efficiency, justifying its selection for subsequent experimental phases involving admixture modification.

4.2. Setting Time

According to ASTM C494, the delay in initial and final setting time must not be less than 1 hour and not more than 3:30 hours relative to the reference mix, respectively. It can be observed that the 0.1, 0.2, and 0.3% dosages of citric acid cause a delay in initial and final setting time within the ASTM C494 range. However, the result for 0.4% does not conform to ASTM C494 requirements.

The citric acid dosage range of 0.1% to 0.4% was established through trial experiments; it was observed that dosages exceeding 0.4% resulted in setting time delays that failed to comply with ASTM C494 standards and began to adversely affect strength development. We found that 0.4% was the maximum effective dosage, as any higher amount caused setting time delays that exceeded the ASTM C494 limits (not more than 3:30 hours relative to the reference mix) and began to negatively impact strength.

Table 4: Slump test results

Mix code	Mix Type	Slump (mm)
M_O	OPC Mix	55
M_P	PPC Mix	60
M_1	60%OPC+40%PPC+0.1%CA	65
M_2	60%OPC+40%PPC+0.2%CA	70
M_3	60%OPC+40%PPC+0.3%CA	85
M_4	60%OPC+40%PPC+0.4%CA	95

Citric acid retards concrete setting by chelating calcium ions, slowing the hydration of key cement compounds (C_3A and C_3S). This effect is dosage-dependent, with higher concentrations causing longer delays in initial and final setting times. In this study, the maximum dosage was limited to 0.4% of PPC cement, as higher amounts exceeded ASTM C494 limits and could negatively affect workability and compressive strength. The 0.4% dosage was chosen to balance extended workability with acceptable setting and strength performance.

4.3. Workability

Workability, as measured by the slump test, is an essential property that determines how easily concrete can be mixed, placed, and compacted.

The addition of citric acid slightly improved the workability of concrete mixes compared to the control, due to its plasticizing effect and ability to adsorb onto cement particles, reducing interparticle friction and increasing free water for lubrication. Combined with PPC, which enhances flow through its finer particles and pozzolanic content, citric acid further improves fresh concrete properties. This synergistic effect suggests that careful dosing of citric acid can enhance workability without compromising other key properties.

The incorporation of citric acid significantly enhanced the workability of PPC-based concrete. Compared with the control OPC mix (55 mm slump), the mix containing 0.3% citric acid achieved a slump of 85 mm, representing approximately a 55% increase. This improvement is attributed to the chelation of Ca^{2+} ions by citric acid, which delays early hydration and reduces flocculation of cement particles. The adsorption of citrate ions on cement grain surfaces increases electrostatic repulsion and particle dispersion, thereby releasing entrapped water and improving flowability.

In addition, the finer particle size of PPC contributes to improved packing density and lubrication effects in the fresh mix. However, at higher dosage (0.4%), although slump increased to 95 mm, excessive retardation may interfere with early hydration product formation, potentially affecting early-age strength. These findings are consistent with Tinnea and Young [22], who reported that organic acids improve dispersion by suppressing rapid C_3A hydration.

The statistical variability (SD $<$ 5% of mean) confirms that the observed improvement in workability is systematic rather than experimental fluctuation.

Table 5: Compressive strength results (citric acid dosages)

No.	Mix Code	28-day CS (MPa)	SD (MPa)	SE (MPa)
1	M_O	33.9	1.55	0.89
2	M_P	20.9	1.11	0.64
3	M_1	26.5	2.18	1.26
4	M_2	28.2	1.76	1.02
5	M_3	32.4	1.77	1.02
6	M_4	30.1	1.72	0.99

4.4. Compressive Strength

The compressive strength of concrete is one of the most critical factors in determining its suitability for reinforced concrete applications. Compressive strength was measured at 7, 28, and 56 days of curing.

Compressive strength tests were done for the C-30 concrete class. Molds measuring 100 mm cubes were used for the compressive strength tests. Neville [16] suggests a conversion factor of 0.96 to translate 100 mm cube strength to 150 mm cube strength.

The concrete mixed with 40% PPC and 0.3% citric acid (by weight of PPC) has a compressive strength of 32.4 MPa for C-30 at 28 days, which is comparable with OPC-based concrete. Therefore, the preconditions listed in ACI 301 for acceptance of compressive strength of concrete are likewise satisfied by the compressive strength of concrete prepared with 40% PPC and 0.3% citric acid at 28 days.

The mix with 40% PPC and 0.3% citric acid achieved compressive strength slightly lower than the control, mainly due to the dilution effect of PPC and the retarding action of citric acid on cement hydration. While citric acid improves workability, excessive amounts can delay the formation of strength-giving compounds, so a maximum dosage of 0.4% was adopted to balance setting time and compressive strength.

The compressive strength development of PPC–citric acid concrete reflects the combined influence of dilution, retardation, and secondary pozzolanic reactions. At early ages, mixes containing citric acid exhibited slightly reduced strength due to delayed hydration of tricalcium silicate (C_3S), as citrate complexes temporarily inhibit calcium hydroxide precipitation. This prolongs the induction period of hydration and slows the formation of primary C–S–H gel.

However, at 28 days, the mix containing 40% PPC and 0.3% citric acid achieved 32.4 MPa, approaching the control OPC strength (33.9 MPa). The later-age strength recovery is attributed to the pozzolanic reaction between reactive silica in PPC and calcium hydroxide, forming additional secondary C–S–H gel. This reaction refines pore structure and improves matrix densification.

At 56 days, strength slightly exceeded that of PPC-only mixes, confirming that moderate retardation does not permanently hinder hydration but rather redistributes it over time. In contrast, the 0.4% dosage produced marginal strength reduction due to excessive complexation of calcium ions, which can inhibit normal crystal growth of hydration products.

One-way ANOVA analysis ($p < 0.05$) confirms that the differences between control, PPC-only, and PPC + citric acid mixes are statistically significant, indicating that the combined PPC–citric acid interaction has a measurable influence on compressive strength development.

The ANOVA results confirmed statistically significant differences among the mixes at 28 days ($p < 0.05$). The effect size indicates that citric acid dosage significantly influences strength development. Post-hoc analysis showed that the 0.3% citric acid mix did not differ significantly from the control OPC mix ($p > 0.05$), whereas the PPC-only and 0.4% mixes exhibited statistically lower strength ($p < 0.05$). This confirms that 0.3% represents an optimal dosage balancing retardation and strength performance.

4.5. Cost Comparison

The cost comparison is done between the concrete mixes created with OPC, and the concrete mixes prepared with 40% PPC and 0.3% citric acid. The cost of the concrete mix made with 40% PPC and 0.3% citric acid is 258.856 Ethiopian birr less per cubic meter for C-30 than the mix made with OPC. This indicates that cost savings can be obtained without affecting the required compressive strength by employing a concrete mix prepared with PPC and citric acid.

Concrete's widespread use makes cost savings per cubic meter highly impactful, especially in large projects. This study's experimental mix achieved economic efficiency by partially replacing OPC with the less expensive PPC and using citric acid to improve workability, reducing the need for additional costly admixtures while maintaining technical performance.

Although this study does not include advanced microstructural (e.g., SEM, XRD) or durability investigations, its originality lies in the systematic experimental evaluation of the combined effect of PPC and citric acid on the compressive strength of reinforced concrete under varying mix designs. Previous research has implemented detailed microstructural analyses such as XRD and SEM to examine the influence of citric acid on cement hydration mechanisms and phase evolution in cementitious systems, as well as durability-oriented studies on citric-acid modified concrete compositions. Additionally, other researchers have examined microstructural and durability characteristics of blended or admixed cementitious composites with different admixtures and SCMs. However, comprehensive microstructural and durability characterization in the specific context of citric acid combined with locally produced Ethiopian PPC is beyond the scope of the present work and is therefore not addressed here. This study instead provides valuable quantitative data for practitioners and researchers aiming to optimize concrete mixes using PPC and citric acid, thereby filling a practical knowledge gap in concrete mix design.

5. Conclusions and Future Work

The combined utilization of Portland Pozzolana Cement (PPC) and citric acid as a water-reducing and retarding admixture demonstrates a promising approach for producing sustainable, economical, and high-performance reinforced concrete. The experimental findings indicate that incorporating citric acid at an optimal dosage of 0.3% by weight of PPC significantly enhances the workability of fresh concrete while maintaining an acceptable setting time and achieving compressive strength levels comparable to those of mixes prepared with Ordinary Portland Cement (OPC). This balance between workability and strength performance makes the PPC–citric acid blend a viable alternative to conventional OPC systems.

Furthermore, the study underscores the practical relevance of PPC–citric acid concrete for structural applications, particularly in warm climatic regions such as Ethiopia, where extended setting time can improve handling, placement, and finishing operations. The integration of a natural, eco-friendly additive like citric acid also contributes to sustainability by promoting reduced cement consumption and minimizing the reliance on synthetic chemical admixtures.

To build upon these findings, future research should focus on examining the long-term hydration mechanisms of citric-acid-modified PPC concrete. In particular, studies should investigate its compatibility with other chemical and mineral admixtures, as well as its influence on key durability parameters, including drying shrinkage, thermal performance, and reinforcement corrosion resistance under diverse environmental conditions. Such investigations will provide deeper insights into its long-term performance and broaden its potential for use in sustainable structural concrete applications.

This study is limited to the experimental evaluation of compressive strength, setting time, and workability of C-30 grade concrete with a fixed water–cement ratio of 0.50 under controlled laboratory curing conditions. Other important mechanical properties such as tensile and flexural strength were not investigated. In addition, advanced durability assessments (e.g., sulfate resistance, chloride penetration, shrinkage, and creep) and microstructural analyses (e.g., SEM, XRD, or thermal analysis) were beyond the scope of this research due to time constraints and because several of these properties have been extensively examined by other researchers. The dosage range of citric acid was restricted to 0.1–0.4% by weight of PPC, and strength development was monitored up to 56 days only. Furthermore, the findings are based on specific locally sourced materials and laboratory-scale specimens; therefore, full-scale structural behavior and long-term field performance were not evaluated.

All concrete specimens, including control OPC, PPC, and PPC + citric acid mixes, were cast and cured under identical conditions. Samples were kept in a controlled curing room at 23 ± 2 °C and 95% relative humidity until testing. Maintaining consistent environmental conditions was particularly

Table 6: Cost comparison between M_O (OPC only) and $M_{0.3}$ (60% OPC + 40% PPC + 0.3% CA)

Ingredient	Unit	Price (birr/unit)	M_O (OPC only)		$M_{0.3}$ Qty.
			Quantity (Qt.)	Cost (birr)	
Cement (Dangote-PPC)	Qt.	1300	–	–	1.51544
Cement (Dangote-OPC)	Qt.	1650	3.8	6270	2.28
Citric Acid	kg	612	–	–	0.456
Sum				**6270**	

	$M_{0.3}$ Cost (birr)
Cement (Dangote-PPC)	1970.072
Cement (Dangote-OPC)	3762
Citric Acid	279.072
Sum	**6011.144**
Cost Difference	**258.856 birr**

important due to the temperature sensitivity of citric acid, which can influence hydration kinetics and setting time. This approach ensures that any observed differences in compressive strength are attributable to variations in mix composition rather than environmental variability.

Table 7: Mix quantities per m^3 and per 0.1 m^3 trial mix

	Cement (kg)	Water (kg/l)	Sand (kg)	Coarse 10mm (kg)	Coarse 20mm (kg)
Per m^3	380	209	543.3	418.34	849.36
Per 0.1 m^3 trial	38	20.9	54.33	41.834	84.936

Appendices

Table A.1 – Concrete Mix Design (DOE Method)

Stage 1 – Target strength	
Characteristic strength	30 N/mm^2 at 28 days
Standard deviation	8 N/mm^2 (5% defective)
Margin ($k = 1.64$)	$1.64 \times 8 = 13.12$ N/mm^2
Target mean strength	$30 + 13.12 = 43.12$ N/mm^2
Cement type	OPC
Coarse aggregate type	Crushed
Fine aggregate type	Uncrushed & crushed
Free water/cement ratio	0.5
Stage 2 – Water content	
Slump	30–60 mm
Max. aggregate size	19 mm
Free water content	190 kg/m^3
Stage 3 – Cement content	
Cement content	$190 \div 0.5 = 380$ kg/m^3
Stage 4 – Aggregate content	
Relative density (SSD)	2.8
Concrete density	2400 kg/m^3
Total aggregate content	$2400 - 380 - 209 = 1811$ kg/m^3
Stage 5 – Fine/coarse aggregate split	
% passing 600 μm sieve	60%
Proportion of fine aggregate	30%
Fine aggregate content	$1811 \times 0.3 = 543.3$ kg/m^3
Coarse aggregate content	$1811 - 543.3 = 1267.7$ kg/m^3

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