



Sustainable Concrete Enhancement Using Lemon Juice As A Bio-Admixture: A Comprehensive Study On Workability, Setting Time, And Compressive Strength

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Abstract

Conventional chemical concrete admixtures contribute to environmental pollution, high energy consumption, and high import costs in developing nations. While plant-based alternatives are being explored, the potential of locally available lemon juice remains under-researched. This study experimentally evaluates the impact of lemon juice on concrete workability, setting time, and compressive strength, comparing its performance against a commercial water-reducer and retarder, Sika Plastiment BV40. Concrete samples with a target strength class of 25/30 MPa were created using the ACI mix design procedures and ASTM testing standards. Specified amounts of lemon juice were added at levels of 0.5%, 1%, 1.5%, 2%, 3%, and 5% by weight of cement, while some of the mixing water was replaced with lemon juice. It has been observed that testing the wet and hard states of the mixture is necessary for this study. Slump, Vicat setting time, and compressive strength tests were performed to determine how lemon juice affects the fresh and hardened features of concrete. Experts claim that the test results showed that lemon juice improved the workability of concrete. When the amount of lemon juice was 5%, the slump value increased by approximately 716.7% compared to the control mix. It was observed that 2% lemon juice increased the first setting time by 410 min. This delay was 57.7% more than the delay produced by the market chemical at the same amount. The best strength behavior was achieved when the lemon juice content was 1.5%, where the 28-day compressive strength reached 29.11 MPa. This measurement was approximately 5.2% higher than that of the control concrete and was 0.9 MPa higher than the highest strength achieved by the market chemical. Because there was too much acid and more water, lemon juice amounts higher than 2% caused the strength to drop and the concrete quality to worsen. The study concludes that lemon juice has strong potential as a sustainable and eco-friendly bio-admixture capable of improving the fresh properties of concrete while maintaining or

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enhancing compressive strength at a lower dosage. The optimum dosage range was found to be between 1% and 1.5% by weight of cement. Further studies are recommended to investigate the long-term durability performance, microstructural characteristics, and large-scale practical applications of lemon juice in sustainable concrete technology.

Keywords: Bio-Admixture, Citric Acid, Compressive Strength, Concrete Workability, Lemon Juice, Retarding Admixture, Sustainable Concrete

I. INTRODUCTION

Concrete admixtures play a crucial role in minimizing the production costs of concrete and addressing concrete emergencies. To be widely used, admixtures should be affordable. However, in Ethiopia, particularly in small towns and remote areas, admixtures are not readily available and come at a high cost. This is due to the fact that they are imported from other countries, resulting in significant expenditure of the country's hard currency reserves. Additionally, conventional chemical admixtures are associated with environmental concerns related to energy-intensive manufacturing processes, chemical emissions, and sustainability challenges [1] [2]. Their production process is generally more complex and time-consuming compared to the extraction and preparation of naturally derived bio-origin admixtures [2]. Consequently, there is a growing need to investigate environmentally friendly, locally available, and low-cost alternative materials that can partially or fully replace conventional chemical admixtures in concrete.

Admixtures are materials added to concrete before or during mixing to modify the properties of the fresh and hardened concrete [3]. In modern concrete technology, nearly all concrete mixtures contain one or more admixtures to improve their workability, durability, setting characteristics, and strength performance [4]. These admixtures are commonly classified as chemical admixtures, including water reducers and retarders, and mineral admixtures [5]. In contrast, bio-admixtures are obtained directly from plants or from naturally occurring organic materials [6]. The increasing global interest in the development of sustainable construction materials has accelerated research into the application of bio-admixtures as environmentally compatible alternatives in concrete technology.

In recent years, several researchers have explored the use of plant extracts as concrete admixtures. For instance, a study [7] investigated the use of sugarcane juice (SCJ) as a retarding admixture in



concrete production in Nigeria. Their findings revealed that the setting time of concrete increased proportionally with the SCJ content. However, the compressive strength and workability decreased when the dosage exceeded 10% and 15%, respectively [8] examined the performance of green plant extracts, including cypress, pine, and eucalyptus, as concrete admixtures. The study reported substantial improvements in workability, where the slump values increased from 45 mm for the control concrete to 155, 160, and 165 mm for the cypress, pine, and eucalyptus extracts, respectively. Furthermore, compressive strength improvements of 10%, 17%, and 10% were achieved at the optimum dosages [9] in the influence of water hyacinth extract on the mechanical properties of cement and concrete. The results demonstrated that the setting time increased by 32-44 min with the addition of 10%, 15%, and 20% water hyacinth extract. In addition, the workability and compressive strength of concrete improved progressively with increasing dosage of the admixture. This performance enhancement was attributed to the presence of ketones, aldehydes, alcohols, fatty acids, polysaccharides, and pectins, which improved bonding characteristics, delayed hydration, and enhanced cement particle dispersion.

Although previous studies have demonstrated the potential of plant-based admixtures in improving concrete properties, the majority of the investigated materials mainly focused on general organic compounds without specifically examining the influence of citric acid-rich natural extracts under controlled and comparative conditions. As presented in Fig.1, lemon juice is particularly distinguished from many previously studied bio-admixtures because of its high citric acid concentration and unique chemical composition. Lemon contains various bioactive constituents, including amino acids, polysaccharides, alkaloids, flavonoids, and trace elements, with citric acid being the dominant active organic acid component [10][11]. Lemon juice mainly consists of water, citric acid, and other carboxylic acids [11][12]. In cement chemistry, citric acid is recognized for its ability to retard cement hydration by slowing the early hydration reactions of the tricalcium silicate and tricalcium aluminate phases. This retardation mechanism improves the workability, retention, and setting characteristics of fresh concrete while also influencing the dispersion of cement particles and water-reducing behavior. Furthermore, the acidic and dispersive characteristics of citric acid can contribute to enhanced particle lubrication and improved fresh concrete flowability at lower dosage levels.



Despite the increasing interest in sustainable bio-admixtures, there remains a significant research gap regarding the use of locally sourced lemon juice as a natural water-reducing and retarding admixture for concrete production. To the best of our knowledge, no previous study has comprehensively evaluated the influence of lemon juice on the workability, setting time, and compressive strength of concrete while simultaneously comparing its performance with that of a commercially available water-reducing and retarding admixture under identical experimental conditions. Therefore, the novelty of this study lies in the introduction and evaluation of lemon juice as a locally available, eco-friendly, and sustainable bio-admixture capable of partially replacing conventional chemical admixtures in concrete technology.



Fig. 1. Lemon juice

The primary objective of this study was to experimentally evaluate the influence of lemon juice on the workability, setting time, and compressive strength of concrete and to compare its performance with that of a commercially available water-reducing and retardant admixture. The findings of this study are expected to contribute to the development of sustainable, low-cost, and environmentally friendly construction materials suitable for developing countries and regions with limited access to commercial admixtures.



II. MATERIALS AND METHODS

A. Materials

The research utilized ordinary Portland cement sourced from the Messebo cement factory. The cement had a fineness of 3442.7 cm²/gm and an initial setting time of 115 min at 26% normal consistency. The chemical composition of the cement is listed in Table I. In addition, river sand with a silt content of 3.8% and a specific gravity of 2.56, as well as coarse aggregates with a specific gravity of 2.26 and a unit weight of 1556 kg/m³, were employed. The properties of the fine and coarse aggregates are presented in Table II. The effects of lemon juice were compared with those of Plastiment BV 40, a commercial water-reducing and retarding admixture from Sika Abyssinia Chemical Manufacturing PLC. Lemons were purchased from a local market in Mekelle City. Once an adequate number of lemons were collected, their juices were extracted using a simple preparation method. The lemons were cleaned, washed, and dried before being sliced. A hand tool specifically designed for squeezing was used to extract the juice from the slices. Finally, the extracted juice was stored in plastic bottles.

The chemical compositions of random lemon juice samples were examined at the Mekelle University School of Pharmacy, and the results are shown in Table III. The pH of the juice was determined using a pH meter, and the acidity was measured by titration using 0.5 N NaOH with phenolphthalein as an indicator. The results indicated that lemon juice had a pH of 2.74 and citric acid content of 8.32%. These results clearly demonstrate that lemon juice is characterized by a weakly acidic composition and high water content. [11][12].

TABLE I

CHEMICAL COMPOSITION OF MESSEBO ORDINARY PORTLAND CEMENT

Component	CaO	SiO ₂	Al ₂ O ₃	Fe ₂ O ₃	MgO	others
Amount (%)	64.15	21.23	5.24	3.87	1.72	3.79

TABLE II:

PROPERTIES OF THE FINE AND COARSE AGGREGATES

Aggregate type	Property	Amount
Coarse	Maximum aggregate size(mm)	19



	Unit weight (Kg/M ³)	1556
	Specific gravity G _{SSD}	2.26
	Absorption capacity (%)	0.45
	Moisture content (%)	0.18%
Fine	Fineness modulus	2.68
	Specific gravity G _{SSD}	2.56
	Water absorption (%)	0.17
	Moisture content (%)	2.04

TABLE III
CHEMICAL COMPOSITION OF LEMON JUICE

Component	Citric Acid (C ₆ H ₈ O ₇)	Water	others
Amount mass (%)	8.32	90.8	0.88

B. Preparation of Specimen

Following the preliminary characterization of the constituent materials, a concrete mix with a target compressive strength class of 25/30 MPa was designed according to the procedures specified in ACI 211.4R-08 [13]. The detailed mixing proportions are presented in Table IV. To evaluate the influence of lemon juice on the workability, setting time, and compressive strength of concrete, lemon juice was incorporated into the concrete mixtures at dosages of 0.5%, 1%, 1.5%, 2%, 3%, and 5% by the weight of cement. The admixture dosages were initially calculated based on the mass of cement and subsequently converted into equivalent liquid volumes during batching operations for practical laboratory implementation.

The selected dosage range was established based on prior studies [2] [13], reported that most conventional chemical admixtures and plant-based bio-admixtures are commonly effective at dosages below 5% of cement weight, while optimum performance is generally achieved within the range of 0.3%-1.5%. Accordingly, the present investigation adopted dosages extending up to 5% to evaluate not only the optimum performance range of lemon juice but also the threshold at which



excessive citric acid concentration may adversely affect concrete integrity, hydration behavior, and strength development.

Two admixture incorporation approaches were employed in this study. In the first approach, lemon juice partially replaced mixing water while maintaining the designed water-to-cement ratio. In the second approach, additional lemon juice was introduced without reducing the mixing water content to investigate the influence of excess liquid incorporation on the fresh and hardened properties of the concrete. For comparative analysis, concrete mixtures containing Sika Plastiment BV40 at equivalent dosage levels were prepared and tested under identical laboratory conditions.

C. Compressive strength test

For compressive strength evaluation, cube specimens with dimensions of 150 mm × 150 mm × 150 mm [14] were prepared and tested in accordance with ASTM C192 and ASTM C39. Following casting, the concrete specimens were compacted using standard vibration techniques to minimize the entrapped air and ensure uniform consistency. The specimens were demolded after 24 h and subsequently cured by full immersion in clean potable water maintained at a controlled laboratory temperature of approximately $23 \pm 2^\circ\text{C}$ until the designated testing ages.

Three specimens were prepared and tested for each dosage level and curing age to improve the reliability and reproducibility of the experimental results. For the partial replacement investigation, 42 cube specimens were cast and tested, corresponding to seven concrete mixtures tested at two curing ages, with three replicate specimens per condition. Similarly, for the additional admixture incorporation investigation, 84 cube specimens were prepared for four curing age groups. Consequently, 126 compressive strength specimens were produced and experimentally evaluated throughout the study.

The compressive strength tests were conducted at curing ages of 3, 7, 14, and 28 days, and the reported values represent the average compressive strength obtained from triplicate measurements. The curing conditions were maintained consistently for all the specimen groups to ensure uniform hydration and minimize experimental variability.

D. Statistical Analysis



To enhance the scientific reliability and consistency of the experimental investigation, all laboratory tests were conducted in accordance with the relevant ASTM standards and standardized testing procedures. The reported results for slump, setting time, and compressive strength represent the arithmetic means of three independent measurements for each test condition. In addition, a comparative performance evaluation was conducted among the control concrete, lemon juice-modified concrete, and concrete containing Sika Plastiment BV40 to assess the effectiveness and consistency of the investigated bio-admixture. Where applicable, the experimental variability was evaluated using standard deviation analysis to improve the statistical interpretation and reliability of the obtained results.

TABLE IV
MIX PROPORTION SUMMARY

Code	Cement(Kg)	Water (lit)		W/C		FA (Kg)	CA(Kg)	Admixture (lit)
		EA*	PR**	EA*	PR**			
Controlled (reference) mix								
C0	337	181		0.54		643	990	0
Concrete with a percentage of Lemon juice								
L0.5	337	181	179.32	0.54	0.532	643	990	1.68
L1	337	181	177.63	0.54	0.527	643	990	3.37
L1.5	337	181	175.94	0.54	0.522	643	990	5.06
L2	337	181	174.26	0.54	0.517	643	990	6.74
L3	337	181	170.89	0.54	0.507	643	990	10.11
L5	337	181	164.15	0.54	0.487	643	990	16.85
Concrete with a percentage of Plastiment BV 40								
BV0.5	337	181	179.32	0.54	0.532	643	990	1.68
BV1	337	181	177.63	0.54	0.527	643	990	3.37
BV1.5	337	181	175.94	0.54	0.522	643	990	5.06
BV2	337	181	174.26	0.54	0.517	643	990	6.74
BV3	337	181		0.54				
BV5	337	181	164.15	0.54	0.487	643	990	16.85

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EA*- addition of admixtures without water reduction
PR**- partial replacement admixtures in place of water

E. Test Methods

1)*Setting Time Test*: The cement paste samples were examined for their initial and final setting times using Vicat needles. The samples consisted of varying proportions of lemon juice and Sika Plastiment BV 40, ranging from 0% to 5% of the cement weight. The testing procedures followed the guidelines specified in the ASTM C 191 [15]. To conduct the setting time investigations, water was partially substituted with admixtures, and the normal consistency was determined at 26% of the cement weight for the reference mix.

2)*Slump Test*: The workability of the fresh concrete was assessed using a slump test, which involved varying percentages (0, 0.5, 1, 1.5, 2, 3, and 5%) of lemon juice and Sika Plastiment BV 40 in comparison to the weight of cement. Lemon juice and Sika plastiment BV 40 were used as substitutes for water in these tests. The samples used for the workability assessment were obtained from the concrete mix for cube casting and followed the standard procedure for slump testing of Portland cement concrete, as specified in the ASTM C 143 testing guidelines [16].

3)*Compressive Strength Test*: The concrete mixing procedure adhered to the standard method outlined in ASTM C 192 [14] for casting and curing the test specimens in a laboratory. Initially, the aggregates and cement were dry-mixed for one minute before adding water and lemon juice in accordance with the proportions specified in Table IV. Subsequently, the dry concrete was mixed with water and lemon juice for an additional two minutes to prepare and cast the samples. Concrete samples containing Sika Plastiment BV 40 were prepared and cast for comparison. After 24 h of casting, concrete cubes measuring 150 mm × 150 mm × 150 mm [17] were carefully extracted from the molds. These cubes were then placed in a water tank for curing until the time of testing was reached. Once the curing process was completed, the cubic samples were subjected to compressive strength tests at different time intervals. For samples with additional admixtures, tests were conducted at 3, 7, 14, and 28 days. In contrast, the samples containing 0.5, 1, 1.5, 2, 3, and 5% lemon juice and plastiment BV 40 through partial replacement were evaluated at the ages of 3 and 28 days.



III. RESULTS AND DISCUSSIONS

A. Setting Time Test Results

Fig. 2 shows that substituting lemon juice with water at varying concentrations (0.5, 1, 1.5, 2, and 3%) prolonged the initial setting time. More precisely, the delays experienced were 40, 125, 285, 410, and 365 min. The deceleration in the setting time is linked to the citric acid content in lemon juice, which functions as a retardant. Previous research conducted by various scholars [18], [19], and [20] has demonstrated that citric acid, similar to other retarders, decelerates the initial hydration process of tricalcium aluminate and tricalcium silicate by extending the period of dormancy during hydration. The observed acceleration effect at a 5% dosage can be attributed to the heightened concentration of acid. As the acid concentration increased, the grinding of the cement particles was initiated, resulting in a finer cement composition. Consequently, the hydration of cement proceeds at a faster rate, leading to an accelerated setting time [21]. In addition, the introduction of Sika Plastiment BV40 to the mixture further prolonged the setting time of the specimens. The substitution of lemon juice at the mentioned dosages resulted in delays of 30, 90, 175, 260, 245, and 190 min. Using 2% lemon juice, the maximum delay achieved was 410 min, whereas with 2% Sika Plastiment BV40, the delay reached 260 min. It is worth noting that when compared to Sika Plastiment BV40, lemon juice exhibited an additional delay of 57.7% in the setting time at a 2% dosage.

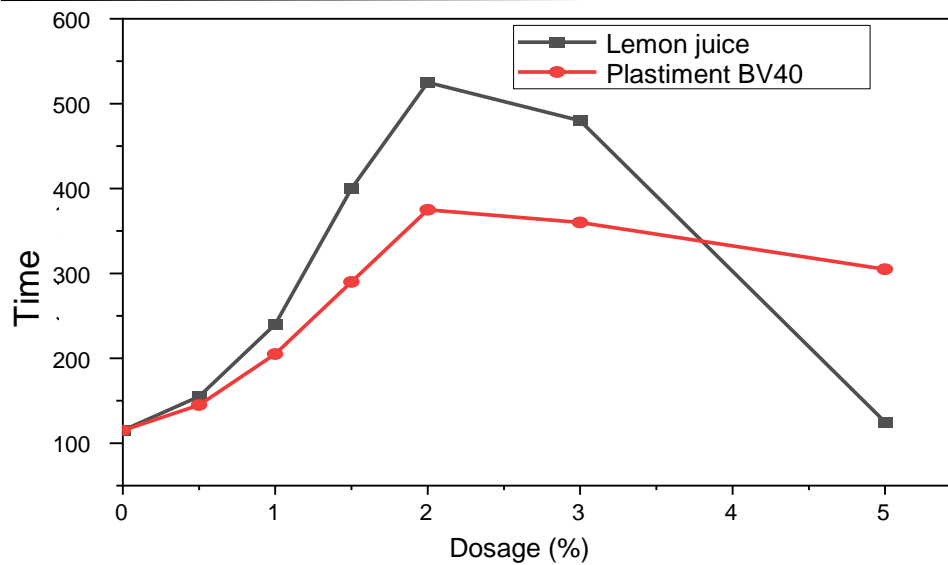


Fig. 2. Setting time of concrete with different dosages of lemon juice and BV40

B. Slump Test Results

The effectiveness of concrete mixed with lemon juice was evaluated by varying the dosage from 0.5% to 5% using a slump-cone test. The outcomes were compared with those of the standard concrete and Sika BV40-infused concrete, as shown in Fig. 3. Similar to the concrete containing Sika Plastiment BV40, the slump value of the lemon juice-infused concrete increased in parallel with the lemon juice concentration of 0.5%, 1%, 1.5%, 2%, 3%, and 5%. Furthermore, for the specified dosages of lemon juice-infused concrete, there were substantial increases of 55.9%, 147.6%, 206.3%, 283.3%, 542.63%, and 716.7% in the slump values compared to the standard concrete. Nevertheless, Plastiment BV40 exhibited superior slump values across all tested dosages. The peak slump value was recorded at the 5% dosage value. At this 5% dosage level, where the maximum slump value was attained, the concrete with Plastiment BV40 displayed an additional 22.1% increase in comparison to the lemon juice mixture.

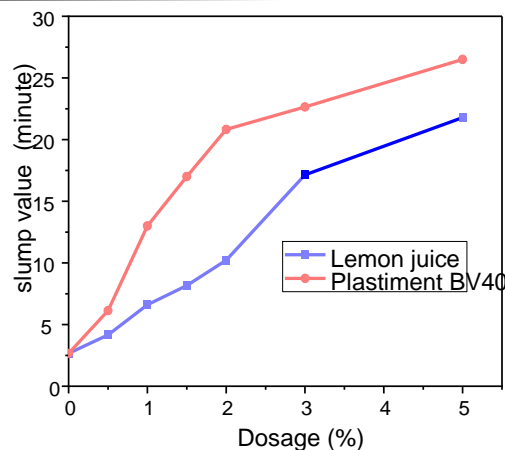


Fig. 3. Effect of lemon juice on workability of concrete

The results of this study indicate that the addition of up to 5% lemon juice enhances the workability of concrete. This improvement can be attributed to the dispersing effect of citric acid on cement grains. Previous studies have also reported that concrete containing citric acid exhibits higher workability than one without citric acid. This can be attributed to the plasticizing properties of citric acid absorbed onto the surface of cement particles, resulting in a negative charge. Consequently, the particles repel each other, leading to the deflocculation and dispersion of the cement particles. This process significantly enhances the fluidity of the system and reduces the amount of water required to achieve the desired workability. Additionally, the slippery nature of the juice itself contributes to the improved flow of concrete mixes.

C. Compressive Strength Test

1) *Partial Replacement of Water by Lemon Juice and Plastiment BV40*: The results of the compressive strength for the substitution of lemon juice and Sika Plastiment BV40 are presented in Fig. 5, showcasing the compressive strengths at 3 and 28 days. The data in Fig. 5 indicate that the compressive strength increased with increasing lemon juice content up to 1.5% for both 3 and 28d of curing. Fig. 6 shows that by replacing 0.5%, 1%, and 1.5% of water with lemon juice, there are additional compressive strengths of 0.45 MPa, 0.88 MPa, and 1.44 MPa, respectively, compared to the control mix at 28 days. However, the concrete containing 2% and 3% lemon juice exhibited a decrease in strength of 0.26 MPa and 5.64 MPa, respectively. After 3 d of curing, the strength increased by 0.6, 1.17, and 0.42 MPa at 0.5%, 1%, and 1.5% lemon juice replacements,



respectively. Conversely, there was a reduction in strength of 1.69 MPa and 3.24 MPa at 2% and 3% lemon juice replacements, respectively.

Furthermore, at both curing ages, the concrete containing 5% lemon juice exhibited fracturing in the curing tank after 3 and 28 days, as illustrated in Fig. 8. In general, the compressive strength of concrete was enhanced when a reduced quantity of lemon juice was substituted for mixing water. This increase in strength can be attributed to the water-reducing properties of citric acid [18] [20][22]. As the water-to-cement ratio decreases, the strength of the concrete increases [23]. Conversely, with an increase in dosage, the acidity concentration also increases, resulting in the deterioration and elimination of concrete constituents, along with a decline in strength [18]. Moreover, when exposed to high levels of acids with a pH below 4.5, the cement paste components are dissolved, leading to the formation of a weak concrete structure.

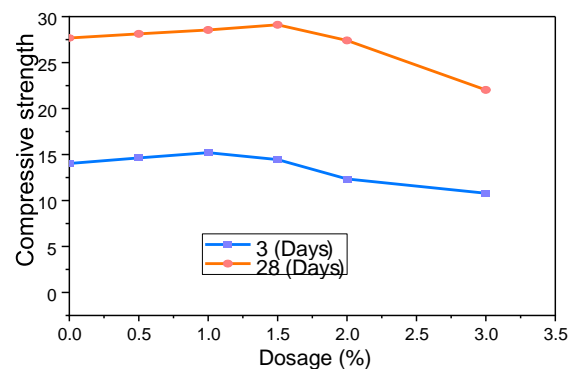


Fig. 4. Effect of partial replacement of lemon juice on compressive strength

Fig. 5 illustrates that the concrete containing 0.5% and 1% of the commercial admixture Plastiment BV40 exhibited strengths of 0.52 MPa and 0.9 MPa, respectively, compared to the reference mix after 3 days. However, when the dosage was increased to 1.5% and 2%, the strength decreased by 0.22 MPa and 3.86 MPa, respectively. After 28 days, the compressive strength of the concrete with 0.5% and 1% of the commercial admixture Plastiment BV40 showed additional strengths of 0.94 MPa and 0.54 MPa, respectively, compared with the reference mix. However, when the dosage was increased to 2% and 3%, there was a loss of strength of 1.01 MPa and 7.49 MPa, respectively. This decline in strength is primarily attributed to the air entrainment in the concrete mix, which weakens its overall strength. The level of air entrainment increased with increasing lignosulfonate concentration. [24]. Similar to lemon juice, the concrete containing 5% Plastiment BV40 fractured



while in the curing tank, as shown in Fig. 8. When dosed at 1.5% and 1%, respectively, the concrete with lemon juice and Plastiment BV40 achieved peak strength at 28 days. At this ideal dosage, lemon juice exhibited a strength of 29.11 MPa, surpassing that of concrete with Plastiment BV40 by an additional 0.9 MPa.

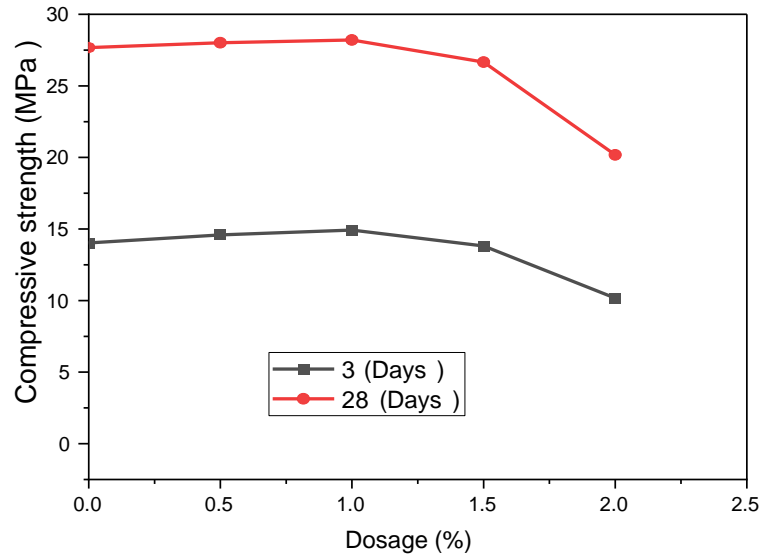


Fig. 5. Effect of partial replacement of Plastiment BV40 on compressive strength

2) *Effect of Incorporating Extra Lemon Juice:* The findings regarding the compressive strength of the supplementary admixtures are shown in Fig. 6 and 7. The compressive strength exhibited a linear decline as the lemon juice content increased up to 3% at 3, 7, 14, and 28 d.

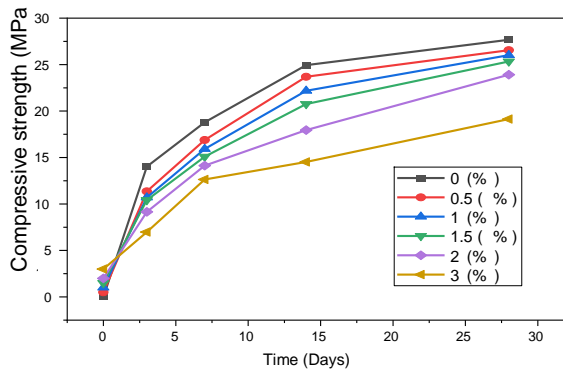


Fig. 6. Effect of the addition of lemon juice on compressive strength

The decline in strength can be attributed to the higher water-to-cement ratio in the concrete due to the dosage, resulting in the failure of the cement pastes to adequately fill the gaps between the larger grains. This, in turn, weakens the overall strength of the concrete. Additionally, the increased



water content creates a larger gap between the aggregates and cement, which negatively impacts the compaction process. As a result, it raises the moisture content while reducing the compressive strength [25][26][27]. Nevertheless, the concrete cube samples experienced breakage and crumbling when a substantial quantity (5% by weight of cement) was included, as illustrated in Fig. 8.

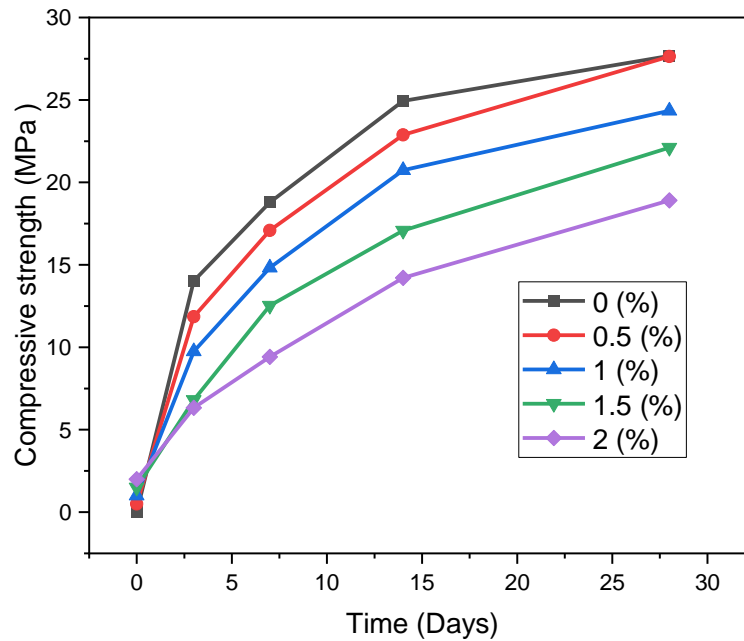


Fig. 7. Effect of extra-addition of Plastiment BV40 on compressive strength

Moreover, the compressive strength of the concrete with lemon juice increased proportionally with the curing age, regardless of the quantity used. This finding supports the notion that lemon juice does not hinder the concrete hydration process at any stage of curing. In a similar manner, the compressive strength of concrete with Plastiment BV40 decreased when the dosage was elevated to 2% during all curing periods. Cube samples exposed to 3% and 5% dosages fractured upon demolding, as illustrated in Fig. 8.



Fig. 8. Effect of substantial dosage of Lemon juice and Plastiment BV40

IV. CONCLUSION

This research examined the influence of lemon juice when used as a concrete admixture and contrasted its effects with those of Sika plastiment BV40, a water-reducing and retarding admixture, on the physical characteristics of both fresh and hardened concrete. The conclusions drawn from the experimental analysis are as follows:

1. The findings of the investigation indicated that the setting time of concrete was delayed when water was partially replaced with lemon juice, in comparison to the reference concrete.
2. Lemon juice enhanced the workability of concrete at all levels of dosage, although it was found to have lower workability than the commercial Sika Plastiment BV40 admixture.
3. The compressive strength of concrete decreased when the percentage of lemon juice exceeded the limit in the concrete mix, similar to the effect observed with the addition of the Sika Plastiment BV40 commercial admixture, at 3, 7, 14, and 28 curing ages.
4. The compressive strength of concrete at 28 days of age was improved by up to 1.5% by partial replacement of water with lemon juice.
5. When compared to concretes with Sika Plastiment BV40 at all dosages, concretes with 5% partial replacement of lemon juice exhibited higher compressive strength.
6. Concrete containing lemon juice at higher dosages (5%) displayed defects similar to those observed in concrete containing the Sika Plastiment BV40 admixture.

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