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Experimental Investigation of *Solanum incanum* (Locally Known as Embuay) Juice as a Sustainable and Cost-Effective Bio-Admixture for Concrete: Effects on Workability, Setting Time, and Compressive Strength

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Abstract

Admixtures play a critical role in enhancing concrete performance; however, reliance on imported chemical admixtures in Ethiopia presents economic and environmental challenges. This study evaluates the potential of embuay juice (EJ), derived from *Solanum incanum*, as a sustainable bio-based alternative to conventional water-reducing and retarding admixtures. Experimental investigations were conducted by incorporating EJ at dosages ranging from 0.5% to 5% by cement weight using both partial replacement and additive approaches. Fresh and hardened concrete properties, including workability, setting time, and compressive strength, were assessed and compared with a commercial admixture (Sika Plastiment BV40).

Results indicate that EJ enhances workability, with slump values increasing progressively with dosage, although remaining slightly lower than those achieved with the commercial admixture. A retarding effect was observed at moderate dosages, with a maximum delay of 130 minutes in initial setting time at 1.5% EJ. Compressive strength improved at lower dosages, with optimal performance at 2%, while higher dosages resulted in strength reduction. Cost analysis demonstrated that EJ is a more economical alternative.

Overall, embuay juice shows potential as a locally available bio-admixture; however, further investigation is required to assess its long-term durability and practical applicability.

Keywords: Bioadmixture, Solanum incanum, Embuay juice, sustainable concrete, Workability, Setting time, compressive strength.

1. Introduction

Concrete is the backbone of global infrastructure, yet its production, especially that of ordinary Portland cement (OPC), is linked to significant environmental concerns, contributing approximately 7–8% of global CO₂ emissions (1)(2). To mitigate this impact, the construction sector is increasingly exploring sustainable materials such as bio-based admixtures derived from renewable resources (3)(4).

Admixtures, substances added to concrete before or during mixing, improve properties such as workability, setting time, and mechanical strength (5)(6). While chemical admixtures, such as retarders and water reducers, dominate the market, their production and use entail environmental and economic costs, especially in developing countries such as Ethiopia, which imports most of these products (7)(8).

In contrast, bio-admixtures extracted from plants, agricultural by-products, and organic materials are biodegradable and cost-effective alternatives. Plant-derived polymers like mucilage and saponins can function as natural retarders and water reducers by modifying cement hydration and matrix microstructure(3)(4)(9). Notable examples include cassava starch, sugarcane juice, cactus extract, and water hyacinth all shown to influence setting time and strength profiles of cementitious materials (10)(11)(12).

Solanum incanum, commonly known in Ethiopia as Embuay, is a native plant with a high yield of bioactive juices rich in polysaccharides, glycosides, alkaloids, and saponins(13) (14). Although traditionally used in medicine, its application as a concrete admixture remains unexplored. Given its organic composition and abundance, embuay juice (EJ) is a promising candidate for enhancing the properties of fresh and hardened concrete, while reducing reliance on synthetic chemicals.



Fig. 1. Embuay berry

This study aimed to evaluate the impact of EJ on the workability, setting time, and compressive strength of concrete. It also compares EJ's effectiveness of EJ to that of commercial admixtures and assesses its economic viability. The broader goal is to provide a scientific basis for utilizing indigenous bio-resources in sustainable construction, thereby supporting local economies and environmental stewardship (15) (16).

2. Materials

This study examines Ordinary Portland cement manufactured by the Messebo Cement Factory. The cement's fineness was measured at 3442.7 cm³/g, which meets the factory's established specifications and a normal consistency of 26% by weight of the cement, with initial and final setting times recorded at 115 minutes and 220 minutes, respectively. Additionally, natural sand was obtained from Werkamba, situated near Abi-Adi and approximately 45 km from Mekelle city, whereas the coarse aggregates were sourced from Aregit ketema, located approximately 10 km from Mekelle city. All the necessary tests on the aggregates were performed at the Construction Materials Laboratory of Mekelle University. A comprehensive summary of the properties of both the fine and coarse aggregates is provided in **Table 1**. Throughout the research, potable water was used to wash the fine aggregates as well as for mixing and curing the concrete. The study incorporated Plastiment BV 40, manufactured by Sika Abyssinia Chemical Manufacturing PLC, as a commercial water-reducing and retarding admixture, and a detailed summary of its properties is included in **Table 2**.

Table 1: Properties of the fine and coarse aggregates

S.No.	Property	Fine aggregates	Coarse aggregates
1.	Fineness Modulus	2.6	-
2.	Specific gravity	2.56	2.26
3.	Water absorption (%)	0.17	0.45
4.	Moisture content (%)	2.04	0.18
5.	Silt content (%)	3.8	-
6.	Unit weight ($\frac{Kg}{m^3}$)	-	1556

Table 2: Properties of Sika Plastiment BV40 water reducing and retarding admixture

S. No.	Parameter	Sika Plastiment BV40
1	Appearance	Liquid
2	Color	Brown
3	Density	$1.9 \pm 0.03 \frac{\text{Kg}}{\text{l}}$
4	Recommended dosage	0.5-1.2%

2.1. Plant Material Collection

The plant material (*Solanum incanum* L.), locally known as Embuay, was collected from the Endayesus campus of Mekelle University, located in Mekelle City, Tigray Region, northern Ethiopia. The exact geographical coordinates of the collection site are 13.480736°N latitude and 39.485594°E longitude (13°28'50.6"N, 39°29'08.1"E). The study area represents an urban institutional environment characterized by a semi-arid highland climate and mixed residential–institutional land use. The geographical location was verified using the Google Maps to ensure spatial accuracy.

The plant material was taxonomically identified and authenticated by Mr. Alem Halefom, MSc, Instructor in the Department of Chemistry, Mekelle University, Ethiopia.

Fresh fruits (berries) of *Solanum incanum* were collected from the main campus and thoroughly cleaned and washed to remove impurities. The samples were then air-dried, cut into smaller pieces, and processed to extract the juice using a manual hand-operated squeezer. The extracted juice was subsequently stored in clean plastic containers for further experimental use.

A voucher specimen of *Solanum incanum* was not deposited in a formal herbarium due to logistical constraints and limited access to herbarium facilities during the study period. Nevertheless, plant identification was rigorously confirmed by the aforementioned qualified expert to ensure taxonomic reliability.

2.2. Plant Identification, Collection, and Ethical Compliance

The plant material used in this study, *Solanum incanum* L. (locally known as Embuay), was collected from [insert exact location, e.g., Mekelle, Tigray Region, Ethiopia]. The plant was identified and authenticated by a qualified botanist from [insert institution, e.g., Department of Biology, Mekelle University].

Permission for plant collection was obtained from the relevant local authorities, and the collection was conducted in accordance with institutional and national guidelines for the use of plant resources.

This study did not involve endangered or protected species. All experimental procedures complied with ethical standards for research involving plant materials.



Fig.2.Solanum incanum (Locally Known as Embuay) Juice

The physiochemical properties of embuay juice were assessed by analyzing random samples. The pH of the juice was determined by using a pH meter. To evaluate the fatty acid content, a 10 ml sample of Embuay juice was titrated with 0.5N NaOH, using phenolphthalein as the indicator. The findings regarding

The physiochemical and acidic properties of embuay juice are detailed in **Tables 3** and **4**.

Table 3: Physiochemical analysis of Embuay juice

S.No.	State	Color	pH amount	Specific gravity
1.	liquid	Dark gray	4.2	1.01

Table 4: Acid content

Acid type	Oleic Acid	Lauric Acid	Ricinoleic acid	Palmitic acid
$\frac{\%}{\text{mass}}$	16.92	12.0	17.88	15.36

3. Methodology

3.1. Specimen preparation

Following the completion of the tests on concrete ingredients, a concrete mixture was developed with a strength grade of 25/30 MPa. The mix was designed in accordance with the standards set

forth in ACI 211.4R-08 (17). Specific proportions of the mixtures are listed in **Table 5**. To investigate the effects of setting time, workability, and compressive strength, lemon juice was incorporated into the mixture by substituting 0.5, 1, 1.5, 2, 3, and 5% of the cement weight, with corresponding adjustments made to the water content.

Studies have indicated that admixtures are typically added to cement mixes at levels below 5% of the cement weight. Nonetheless, most admixtures are used at rates below 2%, with a common range of 0.3%–1.5% (18)(19). After noting the beneficial effect of partial replacement, the influence of embuay juice on the compressive strength was evaluated without decreasing the water content. Additionally, concrete samples containing the Sika plastiment BV 40 were produced for comparative analysis with dosages varying from 0.5% to 5%.

Table 5: Concrete mix-design result

S.No.	Material	Quantity (Kg/m ³)
1.	Cement	337
2.	Water	181
3.	Fine aggregate	643
4.	Coarse aggregate	990
5.	w/c	0.54

3.1.1. Setting time test

As seen in **Fig. 2**. Vicat needles were used to assess the initial and final setting times of the cement-paste samples. These samples incorporated different proportions of Embuay juice and Sika Plastiment BV 40, specifically, 0, 0.5, 1, 1.5, 2, 3, and 5%. Testing was performed according to the procedures specified in ASTM C-191(20). It is important to note that during the setting time assessments, a portion of the admixtures was substituted for water.



Fig. 2. Setting time test

3.1.2. Slump test

The slump cone was used to test the workability of fresh concrete containing different percentages (0, 0.5, 1, 1.5, 2, 3, and 5%) of Embuay juice and Sika Plastiment BV40, based on the weight of cement. These tests involved replacing a portion of water with embuay juice and Sika Plastiment BV40. All the workability tests followed the standard test method for the slump of Portland cement concrete, as outlined in the ASTM C-143(21) procedure.

3.1.3. Compressive strength test

The concrete mixing process followed the standard procedure established in ASTM C 192 for the casting and curing of test specimens in the laboratory (22). Initially, the aggregates and cement were combined in a dry mix for one minute, after which water and embuay juice were added according to the proportions detailed in Table 4. The mixture was then blended with the added liquid for an additional two minutes to prepare the samples for casting. Similarly, concrete samples incorporating the Sika plastiment BV 40 were also prepared and cast for comparative analysis. After a 24-hour period of casting, the concrete cubes, each measuring 150 mm × 150 mm × 150 mm, were carefully removed from their molds (23). The cubes were subsequently placed in a water tank for curing until the testing phase. Upon completion of the curing process, the cubic samples were subjected to compressive strength testing at various intervals. For samples with additional admixtures, testing was performed at 3, 7, 14, and 28 d. Conversely, samples containing 0.5, 1, 1.5, 2, 3, and 5% lemon juice and plastiment BV 40 as partial replacements were crushed at ages of 3 and 28 days.

3.2. Cost comparison

Following the completion of the technical investigation, the costs of Embuay juice and Sika Plastiment BV40 were compared. This involved gathering data on material, labor, and juice-squeezing tool costs from the years 2016-2017 E.C. Subsequently, the costs of Embuay juice and Sika Plastiment BV40 were projected for a period of five and ten years, respectively, taking into account the inflation rate. Consequently, cash flow diagrams were created. The inflation rate was calculated by the empirical formula written below.

$$\text{Inflation rate } (f_n) = \frac{f_n - f_{n-1}}{f_{n-1}} \times 100\%, \quad (24) \dots \dots \dots \text{Eq-1}$$

Where, f_n = Cost in succeeding year

f_{n-1} = Cost in the base period

The empirical formula provided below was used to calculate the future value of the cost of Embuay juice and the chemical admixture.

$$F_v = P_v(1 + i)^n[18].....(24). \text{ Eq-2}$$

where: P_v = Present worth

i = annual interest rate

n = number of years

4. Result and Discussions

The characteristics of both fresh and hardened concrete were evaluated by performing tests on setting time, slump, and compressive strength.

4.1. Setting time test results

The setting time results confirm that the Embuay and lemon juices act as retardant. As seen in **Fig. 3.**, the setting time of cement paste prepared with 0.5, 1, 1.5, and 2% replacement of Embuay juice shows additional 30, 80, 130 and 40min delay over the reference concrete respectively. However, at higher dosages (3 and 5%) the cement pastes set faster than the reference mix.

The reason for the delay of the setting time is the fatty-acids found on the juice. Sathya (2014) revealed that Palmitic and oleic acids delaying the setting time by hampering the evaporation of water molecules from the mixed paste (25) and Roar Myrdal (2007) reported carboxylic acids containing greater than two carbon length ($>C_2$) retard the setting time of concrete (26). As seen in **Table 4** Embuay juice contains 15.36% Palmitic acid, 16.92% oleic acid and other fatty-acids with higher carbon length. The reason for shortening of setting times at higher dosages is when the concentration of fatty acids found in Embuay juice increases the fineness increases and as fineness increases the setting time decreases down (21).

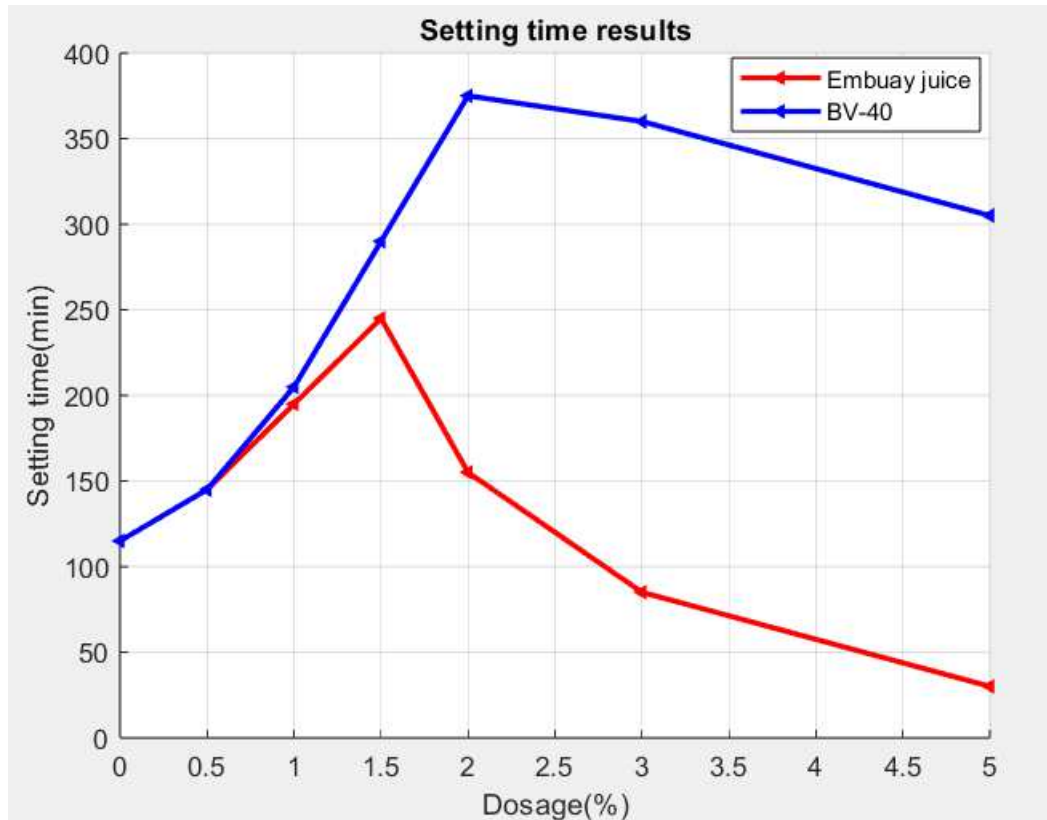


Fig. 3. Effect of Embuay juice and Plastiment BV40 on Setting time

The data presented in **Fig. 3.** indicates that the initial setting time of the mixture is extended by 30, 90, 175, 260, 245, and 190 minutes, respectively, when substituting with 0.5, 1, 1.5, 2, 3, and 5% of commercial Sika Plastiment BV 40 in the cement pastes. In contrast, the reference concrete showed a 113% increase in setting time with a 1.5% replacement of Embuay juice, while a 2% substitution of commercial Sika Plastiment BV40 led to a remarkable 326% increase in initial setting time.

4.2. Slump test results

The performance of concretes incorporating Embuay juice was assessed by incrementally raising the dosages from 0.5% to 5% through the use of a slump cone. The results obtained were subsequently compared with those of the reference concrete and Sika BV40, as depicted in **Fig. 4.** The slump value of concrete, which incorporates Sika Plastiment BV40, a commercial water-reducing and retarding admixture, shows a proportional increase with the addition of Embuay juice. This trend is illustrated in **Fig. 4,** where the slump values rise with dosage percentages of

0.5%, 1%, 1.5%, 2%, 3%, and 5% in comparison to the reference concrete. Furthermore, the same dosages of concrete mixed with Embuay juice resulted in substantial increases in slump values of 87.47%, 231.2%, 516.8%, 632.3%, 724.9%, and 863.6% relative to the reference mix.

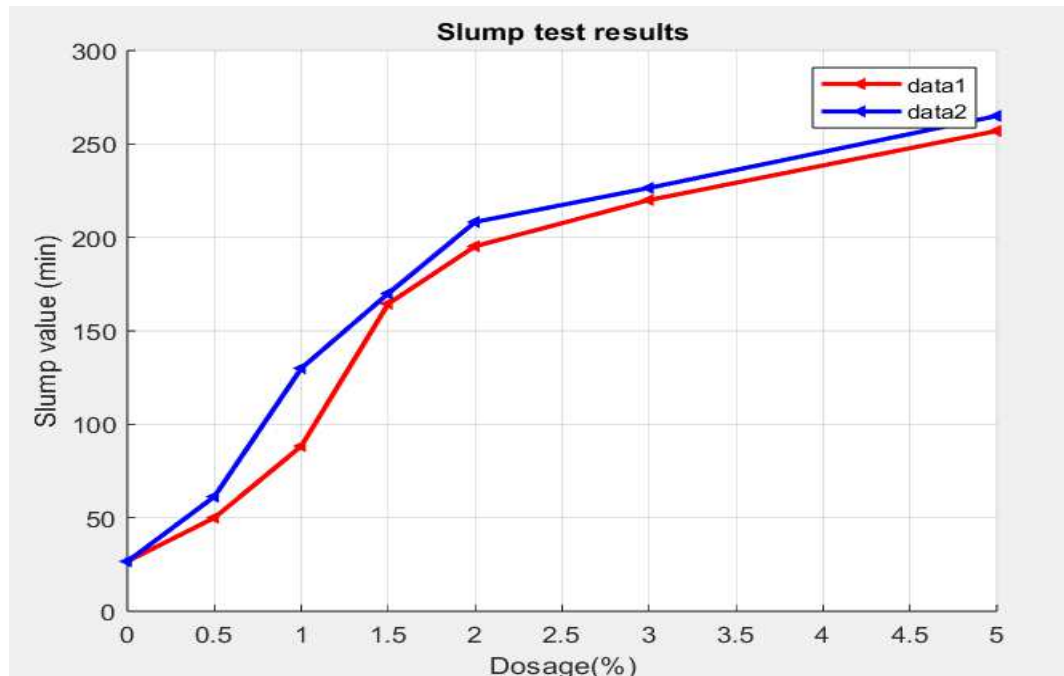


Fig. 4. Effect of Embuay juice and Plastiment BV40 on workability

The results clearly indicate that incorporating up to 5% of Embuay juice as a partial substitute in concrete enhances workability. This enhancement is primarily due to the dispersing effect of fatty-acids on cement grains. Notably, concrete mixtures containing fatty-acids exhibit even greater workability than the reference mix. This can be explained by the plasticizing characteristics of fatty-acids, which adhere to the surfaces of cement particles, imparting a negative charge. Consequently, this leads to the repulsion of particles, facilitating the deflocculation and dispersion of cement grains. As a result, the fluidity of the mixture is improved, reducing the water needed to achieve the desired workability (25). Additionally, the lubricating properties of Embuay juice further enhance the workability of the concrete mixes.

The concrete mixed with Embuay juice shows enhanced workability relative to the reference concrete; however, the concrete incorporating Sika Plastiment BV40 achieves higher slump values across all dosage levels. Notably, when 1.5% of Plastiment BV40 was partially replaced, the concrete began to exhibit flow characteristics. The highest slump values were recorded with a 5% dosage of both Embuay juice and Plastiment BV40. At this dosage, the concrete with Plastiment

BV40 demonstrates an additional 3.10% increase in slump value compared to the mixture containing Embuay juice.

4.3.Compressive strength test results

4.3.1. Partial replacement of water by Embuay juice and Plastiment BV40

The compressive strengths at 3 and 28 days, obtained through the partial substitution of Embuay juice and Sika Plastiment BV40, are presented in **Fig.5.** and **Fig. 6.** below. The results display that the compressive strength of the concrete containing Embuay juice increases up to a dosage of 2% at both 3 and 28 days. When compared to the reference concrete, the compressive strength of the concrete with 0.5, 1, 1.5, and 2% Embuay juice increased by 1.9, 3.92, 6.05, and 7.69% respectively after 3 days. Similarly, there was an increase in compressive strength after 28 days. The concrete with 0.5, 1, 1.5, and 2% Embuay juice replacements showed strength increases of 0.86, 1.5, 2.31, and 3.36% respectively.

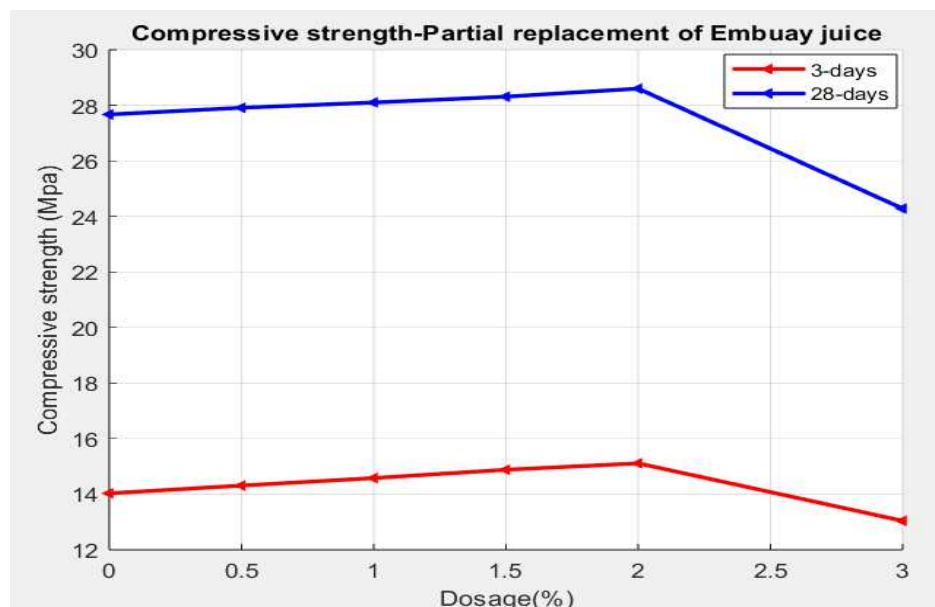


Fig. 5. Effect of partial replacement of Embuay juice on compressive strength

These improvements in strength can be attributed to the reduction in water cement ratio and the reported enhancement of binding capacity of cement grains by fatty acids, as mentioned in reference (25). However, it should be noted that at dosages of 3 and 5%, the concrete cubes exhibited fractures when cured in water tanks. This can be attributed to the higher concentration of fatty acids, which leads to the breakdown of the concrete components (27), and (28). **Fig. 6.** reveals that the concretes containing 0.5% and 1% commercial admixture Plastiment BV40 exhibit an added strength of 0.52 and 0.9 MPa respectively, in comparison to the reference mix after 3

days. However, at dosages of 1.5% and 2%, there is a decrease in strength by 0.22 and 3.86 MPa respectively.

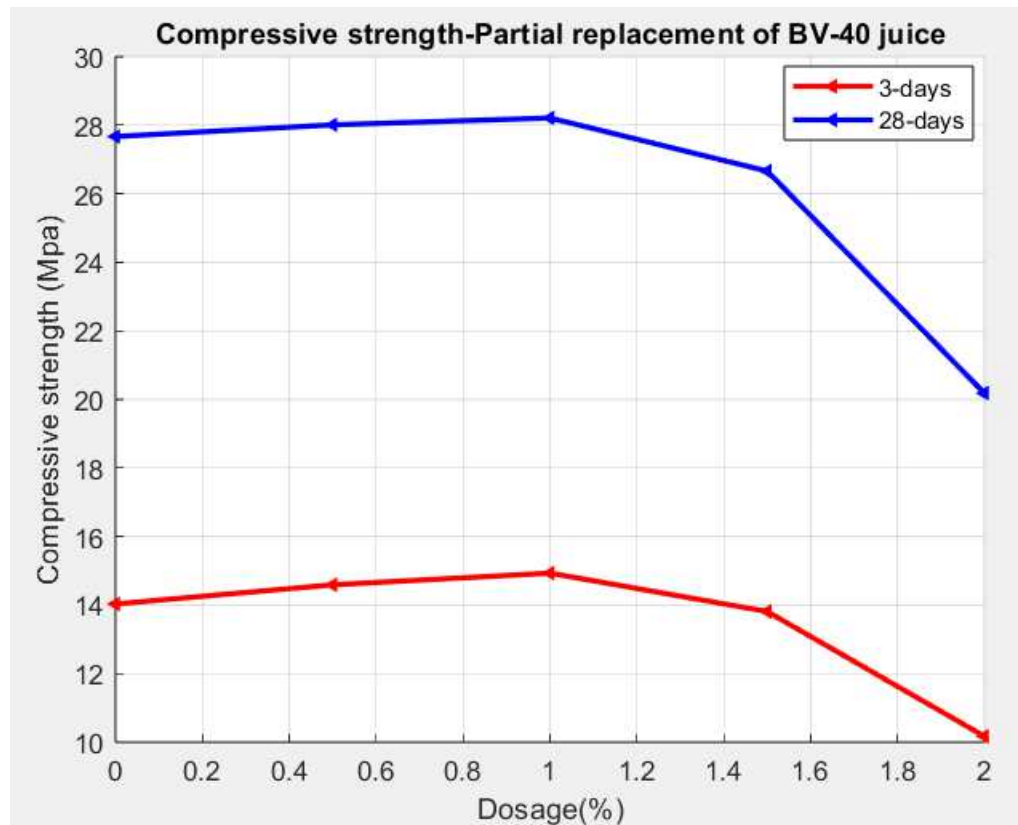


Fig. 6. Effect of partial replacement of Plastiment BV40 on compressive strength

After 28 days, the compressive strength of concrete with 0.5% and 1% commercial admixture Plastiment BV40 demonstrates an additional 0.94 and 0.54 MPa respectively, when compared to the reference mix. Conversely, at dosages of 2% and 3%, there is a loss of strength by 1.01 and 7.49 MPa respectively. This decline in strength can be attributed to the presence of air entrapped within the concrete mix. These air voids significantly weaken the overall strength of the concrete. Furthermore, the amount of air entrainment increases as the content of lignosulphonate rises (29). At the age of 28 days, the highest level of strength was achieved with a dosage of 2% for concrete containing Embuay juice and 1% for concrete containing Plastiment BV 40. At their respective optimal dosages, the Embuay juice resulted in a strength of 28.6 MPa, which is 1.4% higher than the concrete with Plastiment BV 40.

4.3.2. Extra-addition of Embuay juice and Plastiment BV 40

Fig.7. illustrates the impact of the extra addition of Embuay juice in varying percentages on the compressive strength of concrete at different curing ages of 3, 7, 14, and 28 days. Based on the

data presented in **Fig. 7.**, it can be observed that the compressive strength of the concrete increases consistently as the curing ages progress, regardless of the dosages. This clearly indicates that the presence of Embuay juice does not interfere with the hydration process of the concrete over time.

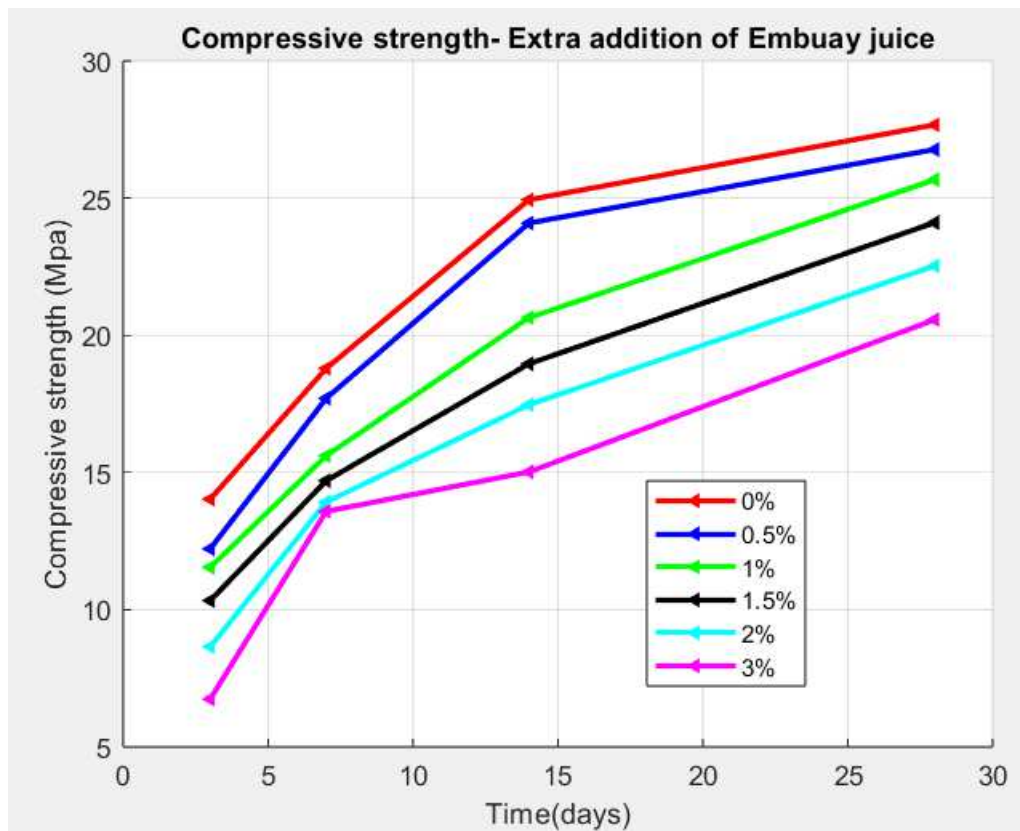


Fig. 7. Effect of extra addition of Embuay juice on compressive strength

The results obtained from testing the compressive strength of concrete mixes with varying dosages of Embuay juice (0.5%, 1%, 1.5%, 2%, 3%, and 5%) at 3, 7, 14, and 28 days reveal a linear decrease in compressive strength as the dosages of Embuay juice increase up to 3%. However, when 5% of Embuay juice is added, it leads to the fracture of the concrete cubes, as depicted in **Fig.9a**. This loss of strength can be attributed to the increased workability of the concrete with higher dosages, causing the cement pastes to fail in filling the voids of the coarser grains and consequently weakening the overall strength of the concrete. Furthermore, the elevated water content results in a greater separation between the aggregates and the cement, adversely affecting the compaction process. Consequently, this leads to an increase in moisture content while diminishing the compressive strength (30) (31).

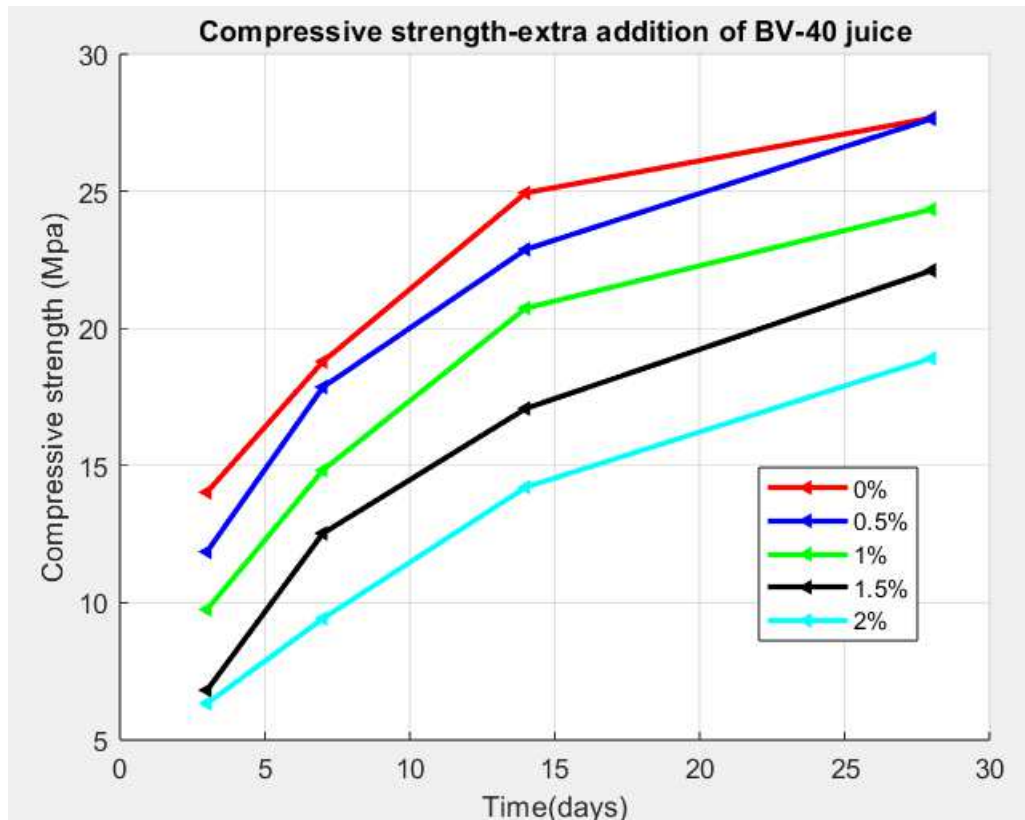


Fig. 8. Effect of extra addition of Plastiment BV40 on compressive strength

For comparison a concrete with 0.5, 1, 1.5% and 2% extra addition of commercial admixture Plastiment BV 40 were casted. The results show in **Fig. 8.** that the Compressive strength decreases with increase in dosage up to 2% at all curing ages. As T. R. Alnejaili (2015) report, the loss of strength was essentially due to the air entraining in the concrete mix, these air voids weaken the strength of concrete. The air entraining increases as the content of lignosulphonate increases (29). Generally, at all dosages of Embuay juice and Plastiment BV 40 the Compressive strength decreased while compared with the reference mix.



Fig. 9a. Effect of high dosage of Embuay juice Fig. 9b. Effect of high dosage of BV40

The concrete cubes experienced fracture and disintegration when a significant amount (5% by weight of cement) of Embuay and plastiment BV 40 were added, as evident in **Fig.9a.** and **Fig.9b.** The increase in Embuay juice and plastiment BV 40 quantity led to the breakdown of concrete components upon contact with a concentrated acid solution (25).

4.4. Cost comparison results

An analysis was performed to compare the costs associated with Embuay juice and Plastiment BV40 by examining the expenses related to juice extraction from the year 2008 onward, as detailed in **Table 6a** and **Table 6b.** In 2011, the prices for Embuay juice and Plastiment BV40 were recorded at 113.6 and 150 ETB per liter, respectively, in Ethiopia. This indicates that the Sika Plastiment BV40 commercial admixture entails an additional expense of 32.04% when compared to Embuay juice. Furthermore, as illustrated in **Table 6c,** the projected costs for lemon juice and Plastiment BV40 were estimated for 5 and 10 years ahead, using 2008 as the reference year and factoring in the average inflation rate for each admixture. The results indicate that, even after 5 and 10 years, Embuay juice continues to be a more economical option than Sika Plastiment BV40 in Ethiopia.

Table 6a: Estimated cost of Embuay juice per one litter from 2008-2011 EC

<i>Year (EC)</i>	<i>2008</i>	<i>2009</i>	<i>2010</i>	<i>2011</i>
Embuay juice cost $\left(\frac{ETB}{lit}\right)$	59.25	78.94	99.5	113.6
Inflation rate (%)	-	33.23	26.04	14.07
Average inflation (%)	24.4			

Table 6b: Cost of Sika plastiment BV 40 per one litter from 2008-2011 EC

<i>Year (EC)</i>	<i>2008</i>	<i>2009</i>	<i>2010</i>	<i>2011</i>
Plastiment BV 40 cost $\left(\frac{ETB}{lit}\right)$	50-70	90-100	120-130	140-160
Average cost $\left(\frac{ETB}{lit}\right)$	60	95	125	150
Inflation rate (%)	-	58.33	31.58	20
Average inflation (%)	36.5			

Table 6c: Cost of Sika Plastiment BV40 per one litter in 2016 and 2021 EC

<i>Year</i>	<i>2016</i>	<i>2021</i>
Estimated cost of Plastiment BV40 $\left(\frac{ETB}{lit}\right)$	995.07	6601.15
Estimated cost of Embuay juice cost $\left(\frac{ETB}{lit}\right)$	472.76	1967.40

4.5. Limitations of the Study

Despite the promising findings, several limitations should be acknowledged:

- The study was conducted under controlled laboratory conditions using a single mix design (C25/30), which may limit the generalizability of the results to other concrete grades and field conditions.
- The chemical composition of Embuay juice was only partially characterized; therefore, the specific mechanisms governing its interaction with cement hydration remain insufficiently understood.
- Variability in the natural composition of plant-based materials may lead to inconsistent performance, depending on factors such as source, season, and extraction method.
- Long-term durability properties, including resistance to chemical attack, shrinkage, and permeability, were not investigated in this study.
- The study did not assess large-scale or field applications, which are necessary to evaluate practical feasibility and performance under real construction conditions.

Future research should address these limitations to better establish the reliability and applicability of Embuay juice as a sustainable concrete admixture.

5. Conclusions

This study evaluated the potential use of Embuay juice (*Solanum incanum*) as a bio-admixture in concrete and compared its performance with a commercial admixture (Sika Plastiment BV40). Based on the experimental findings, the following conclusions can be drawn:

- The incorporation of Embuay juice resulted in an increase in workability, with slump values increasing as dosage increased. However, the performance remained slightly lower than that of the commercial admixture.
- Embuay juice exhibited retarding effects at lower dosages, increasing the setting time of cement paste, which may be attributed to the presence of fatty acids.
- An improvement in compressive strength was observed at lower dosages (up to 2% replacement), although higher dosages ($\geq 3\%$) resulted in strength reduction and, in some cases, specimen deterioration.
- The results suggest that the performance of Embuay juice is highly dependent on dosage and method of incorporation.
- Although the cost analysis indicates potential economic advantages, the variability in mechanical performance suggests that further validation is required before practical application.

Overall, Embuay juice shows potential as a locally available bio-admixture; however, its application should be approached with caution due to performance limitations at higher dosages.

6. Availability of Data

Thank you for this valuable comment. The manuscript has been revised to include a dedicated “Data Availability” section in accordance with the journal guidelines. The statement clarifies that the datasets generated and analysed during the study are available from the corresponding author upon reasonable request. Additional details regarding the nature and origin of the data have also been provided to improve transparency.

7. Acknowledgement

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9. Declaration of computing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper

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