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Performance of potato starch admixture on fresh and hardened behaviours of concrete at varied mix design ratios

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HIGHLIGHTS

- Potato starch was adopted as a natural admixture in concrete.
- Mix design ratios were varied with different percentage fractions of potato starch dosage.
- The effect of potato starch admixture on the fresh and hardened concrete properties was investigated.
- The optimum percentage of potato starch content for all mixes was stipulated.

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ABSTRACT

The urgency to attenuate techno-economic and ecological threats constituted by chemical admixtures has necessitated the adoption of feasible natural admixtures. The chemical interaction of admixtures with concrete ingredients affects concrete's plastic and hardened structure. The impact of concrete properties on construction works is of great concern to engineers as it plays a vital role towards viable infrastructural development. This study focused on developing an eco-friendly, sustainable structural concrete using potato starch (PS) as an admixture. PS has been included to in concrete in discrete percentages (0%, 0.4%, 0.8%, 1.2%, 1.6%, 2.0%) of cement weight employing mix ratios of 1: 1.5: 2, 1:2:4, 1:3:6 and water-cement ratio of 0.6. This study evaluates the effect of PS-admixture on concrete properties in the plastic state (setting time and workability) and at the hardened state (compressive strength) at 7, 21, 28, 56, and 90 days of curing. Potato starch (PS) admixture showed higher compressive strengths in concrete mixes with lower ratios (1:2:4 and 1:3:6). The strength test results for the 1:1.5:2, 1:2:4 and 1:3:6 mix ratios show a maximum strength of 32.77 N/mm^2, 35.12 N/mm^2 and 38.97 N/mm^2 respectively for 28 curing days, at 1.2% PS addition, after which there was a strength-reduction. Rise A rise in the percentage inclusion of PS boosts the setting- time of cement paste and compressive strength. An optimal- percentage of 1.2% PS by cement- weight is advised for reliable concrete strength performance. Utilization of PS in concrete is recommended and should be embraced, considering its low- cost, availability, environmental amicability, and ability to enhance structural durability.

1. Introduction

Concrete strength assessment is crucial to eco-friendly infrastructural buildout, and compressive strength is the principal index as it determines the quality of construction works [1-5]. This study is imperative to circumvent the tragedies of structural failure emanating from poor concrete properties. The current study has formulated an experimental program to investigate the novelty of adopting a natural biopolymer (potato starch) as an admixture and evaluating its effects on the workability, setting time, and compressive strength of concrete at varied curing periods.

Admixtures are additional substances incorporated into the concrete mix during or immediately before mixing to modify the quality of concrete. They are commonly embraced to advance refined concrete works that can perform satisfactorily under different loading conditions in the advent of challenging environmental factors. As they interact chemically with the constituents of concrete, they impel the characteristics of concrete. Their impact varies with the cement type, mix ratio, and quantity. Their applications in engineering works are on the increase due to their edge such as ameliorated workability, better frost and sulfate-retardant, fireproof, cracking-control, acceleration or retardation in setting-time, high concrete strength, increased flow for the equal water-cement ratio, coloring and improved quality [6-8]. Admixtures are categorized as either mineral or chemical. Aqueous materials added to cement to transform concrete traits are regarded as chemical admixtures. These include accelerating, water-reducing, retarding admixtures and those combining two or more features [9-11]. Mineral admixtures are pozzolanic inorganic auxiliary-cementitious elements that can boost essential attributes of concrete, such as

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durability, strength, and permeability. They include rice husk ash, sawdust ash, ground-granulated-blast furnace slag, silica fume, and cassava peel ash [12-15].

The exigency of minimizing dependence on chemical admixtures and the issue of their availability and cost in developing areas has led researchers to investigate and deploy naturally occurring admixtures that are abundantly accessible, cost-effective, eco-friendly, and can be produced locally. Such alternatives include cassava starch, maize starch, corn starch, black liquor, Gum Arabic Karroo, and broiler hen egg [16-19]. More studies are required on these local alternatives, which validates the need for this study as potato starch can also be adopted.

Potatoes (Solanum tuberosum) are annual underground tubers that grow on the roots of the potato plant. They are grown in torrid nations due to their roots, which contain high starch content. The starch extracted from potatoes is regarded as potato starch (PS). This extraction involves crushing the potatoes and the starch grains produced from the destroyed cells. Potato starch is a thickener in many recipes because of its water-absorption tendency. PS could serve as a good fried food coating and a suitable gluten-free flour alternative in baking recipes. This study examines the effect of PS as a substitute for chemical admixtures in concrete production.

Several studies have been done on the use of chemical admixtures as well as their supplementary materials. Adetayo and Jubril [20] ascertained the essence of Ripe Plantain peel ash (RPPA) and Unripe Plantain peel ash (UPPA) on concrete. At 0%, 1.5%, and 2.5% by weight, RPPA and UPPA were added as admixture and blended with other constituents. Grade M15 was addressed with a 1:2:4 mix and water-cement ratio of 0.7. Their study showed that the workability of concrete rises with the addition of RPPA and UPPA. The compressive-strength values of RPPA at 28 and 90 days are higher than that of UPPA at 1.5% and 2.5% proportions. Andrew et al. [6] examined the impact of Na_2CO_3-admixture on the properties of concrete at assorted mix ratios. Na_2CO_3 was added at a 0.5% interval from 0 to 2.0% by weight of OPC. The strength tests were done after 7, 28, 56, and 90 days of curing. Their results proved that Na_2CO_3 has an accelerating influence on setting time and enhanced its early strength gain but had opposite long-term effects on strength with increasing dosage. The authors recommended an optimal percentage of 1% Na_2CO_3 for accelerating effects in concrete. Oni et al. [9] evaluated the relevance of cassava starch (CS)-admixture in concrete. The authors carried out their study by adding CS by weight of cement at 0.4% to 2.0%. CS improved concrete properties at an optimum of 0.8% CS. They confirmed CS as a retarding-admixture in hot-weather-concreting because CS increased the initial and final setting time of concrete at each rise in percentage addition.

Sybis and Konował [7] analyzed the impact of the inclusion of restructured starches on rheology and the preferred physicochemical characteristics of cement pastes and mortars. The authors ascertained the feasibility of adopting customized starches as plasticizers. Their study showed a reasonable deduction in the yield points and plastic viscosities of the cement slurries and a rise in the flow diameters of the cement mortars and concretes due to all the tested starch hydrolysates. PS that were not starch hydrolysates revealed the thickening of the cement mix and increased yield point. Adam et al. [21] showed that concrete mixes containing cassava flour were stronger than the control mix, with a 3% cassava flour blend generating the best results. The authors examined the compressive, split-tensile, and flexural strengths of concrete made with cassava flour up to 5% by weight of cement, using the water-cement ratio of 0.35 and a carboxylate-based superplasticizing admixture. Akindahunsi and Uzoegbo [22] adopted cassava and maize starch as admixtures in concrete. They considered the effect of these starches on the sorptivity, oxygen-permeability, and strength of concrete using 0.5% to 2.0% of the starches. Incorporating admixtures reduced the cement paste's setting time but improved the concrete's strength and durability.

The distinction of this study lies in the material adopted as admixture, water-cement ratio, percentage admixture addition, mix ratios, and concrete properties addressed. This study focused on adopting a fully green natural plasticizer that participates in ecosystem protection and sustainability. Considering its thickness-refinement and deceleration ability, investigating PS as an admixture is worth addressing. This study intends to evaluate the effect of PS-admixture on the characteristics of concrete at discrete mix ratios.

2. Materials and methodology

2.1 Materials

The materials employed in this study include Grade 42.5N, BUA brand of Ordinary Portland Cement (OPC) which conformed to the specifications of BS EN 17075_ [23], fine aggregate (river sand), coarse aggregate with a maximum size of 14 mm, clean and drinkable water free from impurities by BS EN 197-1_ [24], and potato starch (PS) with dosage ranging from 0.4% to 2.0% by cement weight. The potatoes were procured from a local market at Ndioru, Ikwuano, Abia State of Nigeria. PS was dried directly under the sun before use. The starch constituents were activated with hot water at a temperature of 80 ^{o}c for 30 minutes to ensure a complete breakdown of the intermolecular bonds of the starch molecules. The required percentage proportion of PS by weight of cement was separately prepared and allowed to cool to room temperature before mixing with the concrete. The chemical composition of the starch is presented in Table 1.

Table 2 captured the physical attributes of cement, aggregates, and admixture. Tables 3 and 4 show the particle distribution of the aggregates. The specific surface area of the cement (4150 cm^2/g) was less than that of potato starch (4932 cm^2/g), which indicates that the admixture is finer than that of cement. There will be a retardation tendency during the induction phase of the hydration of cement as the granules of PS are adsorbed onto the cement. The reactivity of tricalcium aluminate is inhibited in this process, while the formation of ettringite in concrete is reduced. This reduction enhances the production of concrete with high resistance to sulphate attack. The mean size of PS grains is higher than that of Oni et al. [25] (15.27μm) and Akindahunsi and Uzoegbo [22] (14.29 μm).

Table 3 shows that the grading of the fine aggregate lies between the acceptable limits as stated in BS 882_ [26]. Table 4 shows that the distribution of the coarse aggregate is between the upper and lower limits, respectively, as stipulated in BS 882_ [26]. Sand and granite have coefficients of uniformity and curvature values of 2.67 and 1.83, 0.96 and 1.05, respectively, obtained from Tables 3 and 4. This implies that the aggregates are well-graded and suitable for workable concrete. The nature of their gradation minimizes the tendency for concrete to bleed, segregate, and experience plastic shrinkage cracking.

Table 1: Chemical properties of potato starch

Symbol	Element	Concentration (ppm)
Si	Silicon	50.3
Al	Aluminum	16.2
Mg	Magnesium	80.6
P	Phosphor	42.5
Na	Sodium	550.7

Table 2: Physical properties of concrete constituents

Material	Property	Value	Specification ASTM C 33_ [27]
	Moisture Content	3.54%	0 - 4%
Fine Aggregate	Water Absorption	2.65%	< 4%
	Bulk density	1533.7	1200 – 1800 kg/m^3
	Specific Gravity (SSD)	2.54	2.4 -2.9
	Moisture Content	3.49%	0 - 4%
Course Aggregate	Water Absorption	3.01%	< 4%
	Bulk density	1421.2	1200 – 1800 kg/m3
	Specific Gravity (SSD)	2.54	2.4 -2.9
	Initial Setting time	132	> 60 minutes
	Final Setting time	243	< 375 minutes
Cement	Specific gravity	3.12	3.10 – 3.15
	Fineness	8.4%	-
	Specific surface area	4150 cm^2/g	-
	Mean Size	15.32 µm	-
Potato Starch (PS)	Median Size	14.21 µm	-
	Specific surface area	4932^2/g	-

Table 3: Grain size distribution of sand

Sieve size (mm)	Mass of sand passing (g)	Mass of sand Retained (g)	% passing
4.75	760	0	100
2.36	645.32	114.68	84.91
1.18	467.56	177.76	61.52
0.850	324.18	143.38	42.65
0.6	204.46	119.72	26.90
0.425	97.18	107.28	12.78
0.3	60.51	36.67	7.96
0.212	34.65	25.86	4.56
0.15	12.45	22.20	1.64
0.075	5.64	6.81	0.74
Pan	0	5.64	0
Total		760	

Table 4: Grain size distribution of gravel

Sieve size (mm)	Mass of granite passin (g)	Mass of granite retained (g)	% passing
31.5	3560	0	100
22.4	3212.37	347.63	90.24
19	2856.34	356.03	80.24
16	1468.23	1388.11	41.25
12.5	820.72	647.51	23.06
9.5	469.56	351.16	13.20
6.3	78.41	391.15	2.21
4.75	22.35	56.06	0.63
Pan	0	0	0
Total		3560	

2.2 Methodology

2.2.1 Experimental program

The experimental program includes tests on the aggregates, cement, plastic, and hardened concrete with and without the admixture**.** The workability of the fresh concrete was measured using a slump test in accordance with BS EN 12350-2_ [28]. Cured concrete cube specimens were subjected to compressive strength tests at 7, 21, 28, 56, and 90 days curing ages in accordance with BS EN 12390-3_ [29].

2.2.2 Design mix

Concrete mixes were produced using (150×150×150) mm standard molds in ratios 1:1.5:2, 1:2:4, and 1:3:6 with the water-binder ratio at 0.6 as the pre-established constant optimum water-binder ratio. In the absence of the admixture, control specimens were first prepared. Subsequently, test specimens were made by adding PS to different mixes of 0.4% to 2%, employing a 0.4% increase in dosage by cement weight. The admixture was first dissolved in water when the aqueous solution was heated to 180 ^{0}C. Then, the dissolved liquids were included in the concrete mix. Concrete cube specimens were prepared from the various mixes and cured in water for 7, 21, 28, 56, and 90 days. These curing durations were selected to examine the rate of strength development, resistance to freezing and thawing, volume stability, and durability of the concrete in construction works. The mix proportions for the experimental study were captured in Table 5.

Table 5: Mix proportion of batching materials

Mix ratio	Mixture	Admixture(%)	Cement (Kg/m^3)	Sand (Kg/m^3)	Granite (Kg/m^3)	Water-cement ratio
	X_0	0	654.60	982.00	1309.30	
	X_1	0.4	654.72	982.08	1309.45	
1:1.5:2	X_2	0.8	655.53	983.30	1311.06	0.6
	X_3	1.2	656.49	984.74	1312.98	
	X_4	1.6	657.51	986.40	1315.03	
	X_5	2.0	657.56	986.34	1315.12	
	Y_0	0	494.28	988.56	1977.12	
	Y_1	0.4	495.75	991.50	1983.00	
1:2:4	Y_2	0.8	496.23	992.46	1984.92	0.6
	Y_3	1.2	496.84	993.68	1987.36	
	Y_4	1.6	497.26	994.52	1989.04	
	Y_5	2.0	498.21	996.42	1992.84	
	Z0	0	308.42	925.26	1850.52	
	Z1	0.4	321.02	963.06	1926.12	
1:3:6	Z2	0.8	317.15	951.45	1902.90	0.6
	Z3	1.2	328.42	985.26	1970.52	
	Z4	1.6	330.02	990.06	1980.12	
	Z5	2.0	324.19	972.56	1945.14	

3. Results and discussion

3.1 Results of setting time test

The need to effectively handle concrete during construction validates the necessity of ascertaining the initial and final setting times when cement starts losing its plasticity and when all of its plasticity is gone. In Figure 1, the setting time tests show a progressive increase in the setting time with the addition of potato starch (PS) admixture. Initial and final setting times for the control mix were 132 and 243 mins and gradually increased to 229 and 415 mins, respectively, with the addition of PS up to 2.0% by weight of cement. The reports of [9, 22] showed similar trend. The rise in the initial and final setting times for each percentage inclusion of CS over the control are 36 minutes, 53 minutes, 60 minutes, 86 minutes, 97 minutes and 53 minutes, 73 minutes, 90 minutes, 130 minutes, 172 minutes, respectively. The presence of tricalcium aluminates (C_3A) in the cement paste and the adsorption of starch polymers to them contributed to the retardation. The delayed hydration process is also traceable to the influence of the hydroxyl group of starch, which promotes the special complexation of calcium ions. Hydration delay is a great advantage for concrete works done in hot weather conditions. It also gives site workers more time to place and finish the concrete. However, too much retardation can cause the concrete to be too weak and soft. The fineness nature of the cement and potato starch increased the surface area. It quickened the hydration process, contributing to the concrete's increased setting time and early strength development.

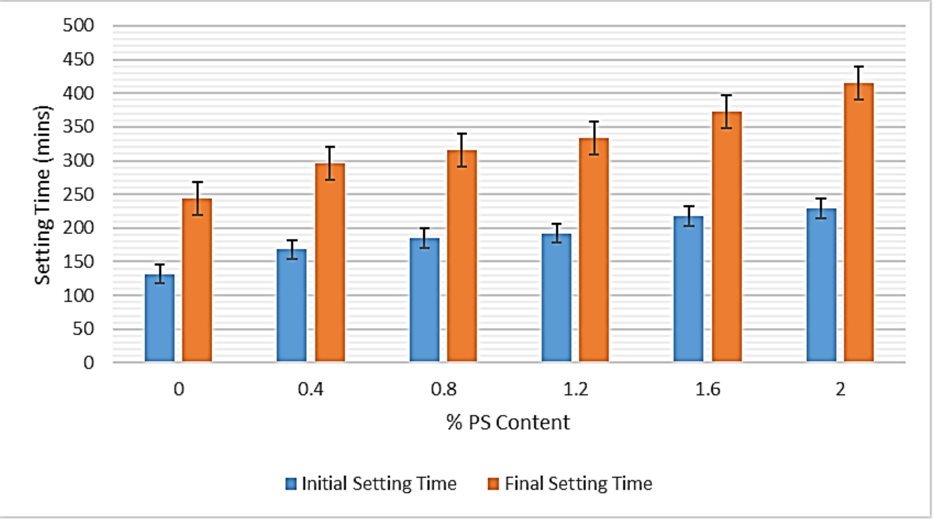

Figure 1: Variation of Setting Time with % PS Content

3.2 Results of workability test

The workability outcome of different PS-concrete mixes measured using slump are shown in Figure. 2. There was a reduction in slump values from 93 mm to 19 mm, 97 mm to 16 mm, and 98 mm to 20 mm for mix ratios 1:1.5:2, 1:2:4, and 1:3:6, respectively. The thickening quality of PS contributed to the decrease in slump values. The mix flowability decreased due to the rise in the internal friction of the cement paste within the concrete. The results had correspondence and disparity with the findings of [22] and [6] respectively. PS 0.0, PS 0.4 and 0.8, PS 1.2 and 1.6, and PS 2.0 have high, medium, low, and very low workability, respectively, and can be adopted for piling works, normal reinforced concrete works, mass concrete footings, and rigid pavements, respectively. Concrete at 1.6% and 2.0% inclusion of PS depicted low and very low slumps, implying that supplemental effort is needed to consummate excellent compaction when juxtaposed with the other mixes. A porous concrete is often a product of low workability. The interrelation of pore spaces within a concrete mix can be reduced with PS of 1.6% and 2.0% and the permeability of concrete. Mix ratios of 1:2:4 and 1:3:6 are most suitable when used in the construction industry as concrete block-binder, pavement works, and fire-resistant wallboard, while mix ratios of 1:1.5:2 can be employed for paint filler, clay, and limestone binder.

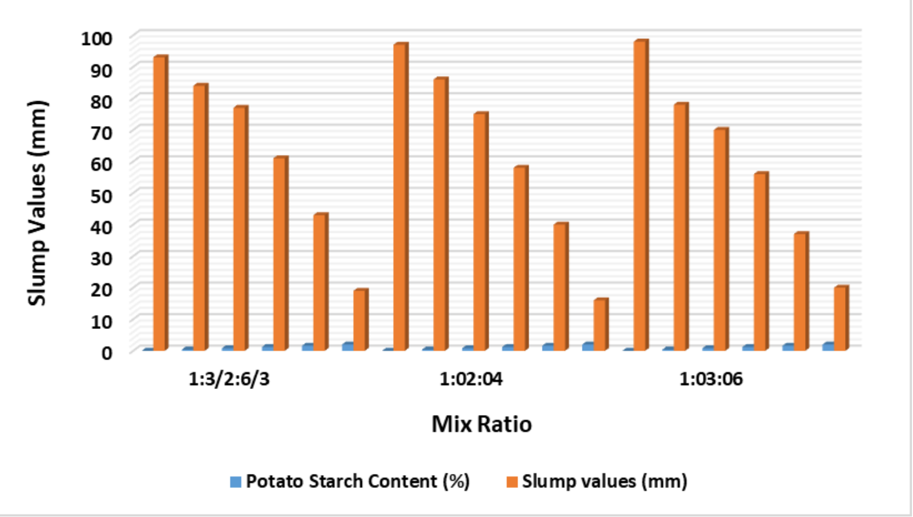

Figure 2: Variation of slump values with mixed ratios

3.3 Results of compressive strength test

Figures 3 to 5 showed that the compressive strength expanded above the control at all percentage additions of PS during the entire curing days. This enlargement is traceable to the viscosity-remodeling ability of PS, which includes minimized tendency of bleeding and segregation in concrete, revamped degree of hydration, internal curing, and the ability to prevent the formation of unwanted hydration products such as ettringite in concrete. The presence of tricalcium silicates (C_3S) determines the early strength, while dicalcium silicates (C_2S) account for the long-term strength phenomenon.

The PS admixture had higher compressive strengths for lower mix proportions (1:2:4 and 1:3:6), as shown in Figures 3-5. For all the mixes, the maximum compressive strength was found at 1.2% addition of PS at all curing days. At 28 days of curing, the recorded strengths were at their peak at 32.77 N/mm^2, 35.12 N/mm^2, and 38.97 N/mm^2 at 1.2% PS inclusion for

1:1.5:2, 1:2:4, and 1:3:6 mix ratios respectively. Concretes produced with a mix ratio of 1:3:6 had the highest compressive strength. Concrete made with a mix ratio of 1:1.5:2 had the least strength. Beyond 1.2%, there was a reduction in strength due to a decrease in the viscosity-enhancing property of the starch. Considering the biodegradable nature of the admixture, its long-term effect on concrete might have an adverse effect beyond a 1.2% addition. This outcome shows non-uniformity and coincidence with the results of [6] and [9, 22, 30, 31] because of the chemical and natural composition of the admixture used. Concrete containing chemical admixtures behaved differently from those of natural biopolymers.

As the curing ages increase, the strength values are added in all cases. The prolonged retardation of PS furnishes the lower strength of the concrete at early periods of curing. Improved compaction, the dispersion of cement particles, the production of denser gel due to delayed setting, and enhanced workability aided the elevated strength on later curing days.

From Figure 3, it was observed that the concretes had 51.5%, 33.9%, 35.9%, 19.5%, and 18.4% increments in the compressive strengths for a concrete mix of 1:1.5:2 at 1.2% PS addition by cement weight in comparison with the control mixes at 0% for 7, 21, 28, 56, and 90 days curing periods respectively. There were 13.6%, and 22.2%, 7.9% and 15.0%, 7.9% and 13.2%, 6.4% and 12.3%, 8.2% and 14.5% reductions in strength for 1.6% and 2.0% PS inclusion when juxtaposed with 1.2% PS inclusion by cement weight at curing durations of 7, 21, 28, 56 and 90 days respectively for concrete mix 1:1.5:2.

There were 49.1%, 41.54%, 40.0%, 28.9%, and 32.4% increments in strengths for a concrete mix of 1:2:4 at 1.2% PS addition by cement weight in comparison with the control mixes at 0% for 7, 21, 28, 56, and 90 days curing periods respectively, as captured in figure 4. It was also observed that concrete made with mix 1:2:4, had 7.26% and 19.2%, 6.0% and 9.9%, 6.7% and 12.7%, 5.4% and 12.0%, 7.0% and 9.1% reductions in strength for 1.6% and 2.0% PS inclusion when collated with 1.2% PS inclusion by cement weight at curing durations of 7, 21, 28, 56 and 90 days respectively.

In Figure 5, the concretes made with mix 1:3:6 had increments of 52.2%, 51.0%, 37.0%, 24.7%, and 24.2% in their compressive strength at 1.2% PS addition by cement weight when analogized with the control mixes at 0% for 7, 21, 28, 56, and 90 days curing periods respectively. It was also observed that concrete made with mix 1:3:6 had 4.0% and 7.5%, 6.5% and 9.7%, 10.0% and 11.2%, 7.0% and 11.8%, 7.2% and 10.8% reductions in strength for 1.6% and 2.0% PS inclusion when contrasted with 1.2% PS inclusion by cement weight at curing durations of 7, 21, 28, 56 and 90 days respectively.

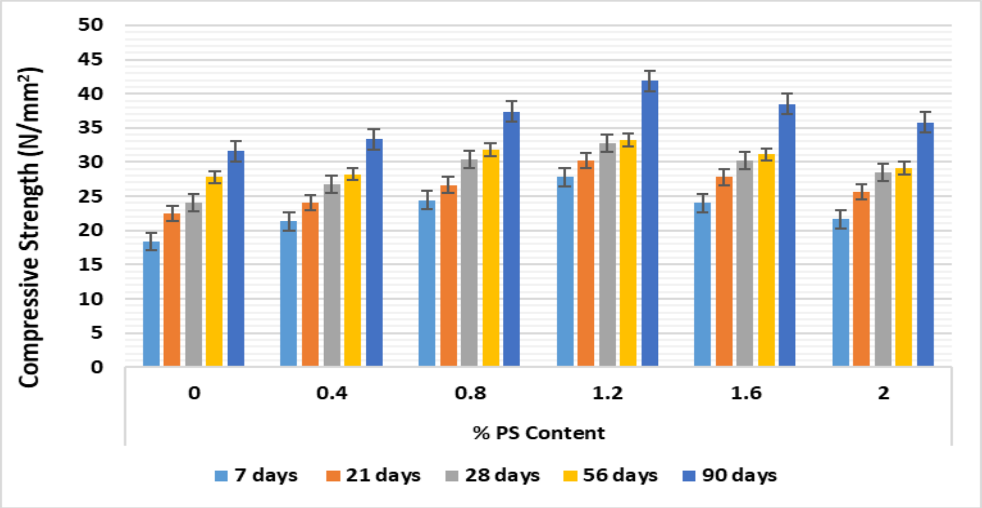

Figure 3: Compressive strength of PS Concrete at a mix ratio of 1:1.5:2 at varying curing days

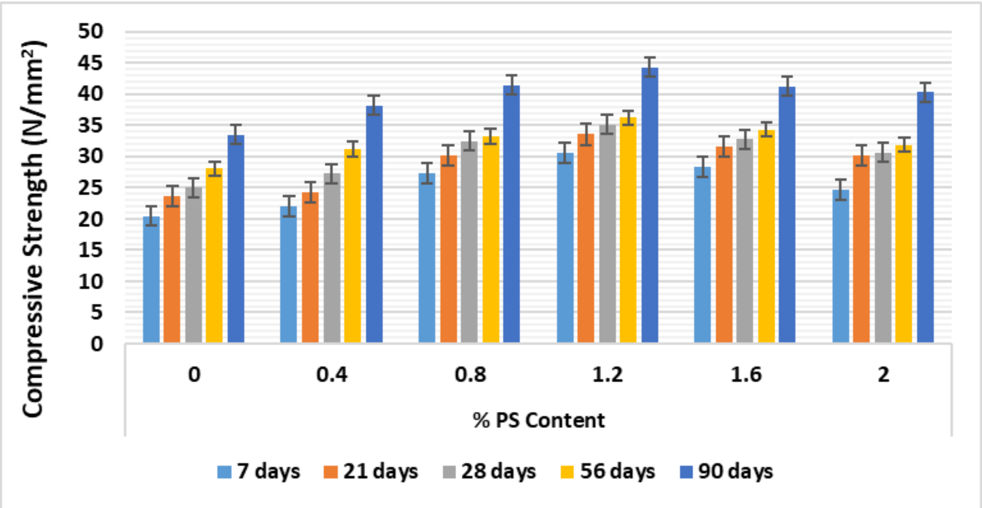

Figure 4: Compressive strength of PS Concrete at a mix ratio of 1:2:4 at varying curing days

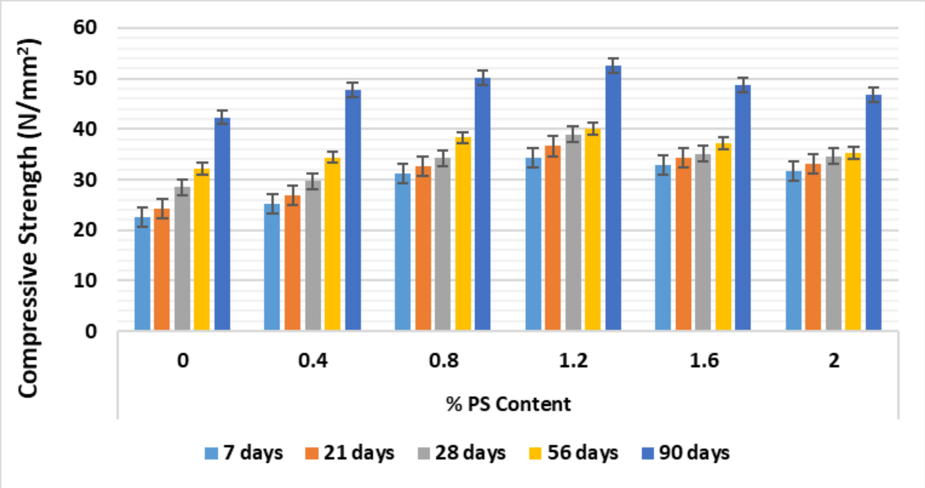

Figure 5: Compressive strength of PS Concrete at a mix ratio of 1:3:6 at varying curing days

4. Conclusion

From the upshot of this experimental study, potato starch (PS) can be regarded as a viscosity-permutating admixture in concrete, along with its retarding characteristics. This property is a great advantage to concrete production under hot weather scenarios. The rise in PS percentage addition minimized the workability of concrete but increased the setting time of cement paste and the compressive strength. This trade-off enhances the production of self-compacting concrete. The observed increase in strength with the addition of PS is significant in construction works where early strength is needed, such as concrete repairs and pavement construction. Adding not more than 1.2% PS by cement weight is recommended to achieve optimum results in better strength performance. With respect to the retarding property of PS, potential adjustments could be made during construction depending on the peculiarity of the project. Potato starch-based concrete could benefit flooring, walkways, soundproofing, and water-resistant backings. However, it should be applied cautiously when employed for foundations and tunnels. In summary, adopting PS as an admixture will fix the issues of cost, sustainability, and availability associated with dependence on chemical admixtures in concreting. The interest in the production of green concrete is also revamped through the outcome of the current study.

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Data availability statement

The data that support the findings of this study are available on request from the corresponding author.

Conflicts of interest

The authors declare that there is no conflict of interest.

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