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Effects of Varying Water-Cement Ratio and Polycarboxylate Ether Admixtures on the Characteristic of High Performance Concrete.

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Abstract

Globally, there has been strong interest in the quality, and performance of conventional concrete on the life cycle of infrastructures. Initiating a wider concern on concrete performance, to provide required capability as structural component, which sustains various degrees of forces, such as upthrust and downthrust forces, seismic effects and aircraft, rail, or explosive vibration. This has been necessitated by the account of incessant collapse recorded globally and particularly in developing economies, like Nigeria. A closer observation reveals that little attention is paid to the production of concrete at the job site, most importantly in the developing economy. This underscores the importance of high-performance concrete adoption using Polycarboxylate Ether (PCE) in construction of infrastructure. High-performance concrete (HPC), offers advantages such as improving initial strength, reducing cement, water quantities, and the amount of concrete needed for optimal strength. Despite its efficacy, questions have been raised about the economic, environmental, and ecological impacts of the effect of various water/cement ratio and PCE in HPC production, and sustainability. The present experimental research evaluates the incorporation of local materials, with a view to fostering the economic growth of the native developing countries by harnessing their local materials and reducing dependence on foreign concrete materials. Relatively, experimental study was conducted to compare the performance outcome of optimized mineral materials HPC with PCE admixture with conventional HPC concrete using varying w/c ratio, and data were evaluated. The workability and strength of fresh and hardened properties produced from local River Sand and Crushed Stone materials at varying w/c ratios. Observation of workability and strength development for different dosages of PCE and water in concrete indicates a steady increase in workability over the control, with high flow, and gives a good compacting factor. The experimental tests for hardened concrete were conducted at various water curing times of 3, 7, and 28 days, which yielded relatively higher compressive, split, and flexural strength of the specimen with the conventional HPC concrete. Therefore, HPC-PCE is highly recommended for structural engineering construction. The findings of this study are expected to support engineers and material designers in making evidence-based decisions when incorporating local sustainable materials into high-performance concrete applications.

Keywords: High-Performance Concrete (HPC), Polycarboxylate-Ether (PCE) admixtures, Water-cement ratio, Workability, infrastructure, Sustainable Materials.

Introduction

Concrete is a universally accepted load-bearing construction material contain cement being develop by Joseph Aspdin, as one of its fundamental ingredient (Ibrahim, 2019).It has since been incorporated with other mineral compounds to significantly improve its performance. The quest for modern smart cities with a high taste for quality pushes for the demand for light-weight load-bearing long-span bridges, heavy hydraulic structures, and high-rise buildings with slender column sizes (Ikponmwosa *et al.*, 2023) has been increasing on the project site. However, adequate quality and high-performance concrete are losing their integrity on most job sites, which breeds incessant structural collapse and calls for active research and development. Strong empirical evidence shows that about 30 billion tons of concrete are used annually, making it the second most widely consumed material after water worldwide (Nithurshan & Elakneswaran, 2023). Though concrete has some drawbacks, which include but are not limited to shrinkage, creeping, brittleness, and low tensile strength(He *et al*., 2022). Over the years, these disadvantages have been relatively compensated for by the ductility of reinforcement bars (rebar) or fibers.

It is now well established from a variety of studies that new material discoveries have led to the development and improvement of performance of modern concrete, with high strength, longevity, flowability, toughness, and durability attracting interest from both industry and academia (Rao *et al*., 2024). There is consensus among scientists on the unique properties of polycarboxylate ether superplasticizers in concrete, including, but not limited to, PCE potentials in compensating for cement's initial lack of strength, reducing the amount of cement and water needed in production, requiring less concrete to achieve load-bearing capacity, increasing service life, and providing environmental benefits. The negative effect of PCE points to the level of pollution at the production and application stages (Ibrahim, 2019). Recently, disagreement has arisen among scholars regarding the economic and ecological benefits of green building, resource conservation, and sustainable development goals. Policy must be enforced because PCE is a synthetic product that relies heavily on petrochemical materials.

Universally, large publications are establishing the fact that the construction of infrastructures, housing projects, and associated activities release approximately18% carbon gas emissions (Adesina, 2020), which makes construction materials production detrimental to the sustainable environment. This is factual about the petrochemical products used in the production of high-performance concretes, which include polycarboxylate superplasticizer (Xun *et al*., 2020)such as Methacrylate ester-based PCE (MPEG PCE), Vinyl ester-based PCE (VPEG PCE), diethylene glycol vinyl ether and ethylene oxide (GPEG PCE), among others. Though some of these materials are less effective due to their susceptibility to concrete segregation and bleeding, the modern PCE superplasticizers, like IPEG or HPEG, and MPEG PCEs have been improved in properties to surpass the former (Rao *et al*., 2024).

Kou *et al*. (2025)postulate that PCEs have been developed with a variety of functions to meet different site conditions, which include slump retention, early strength, and muck resistance, which are common practices at most job sites. Scholars posit that high-performance concretes (HPC) are specialized types produced by careful handling of quality ingredients, optimizing the mix-design, addition of chemical admixtures, or supplementary cementitious materials (Ikponmwosa *et al.,* 2023). At present, HPC PCE superplasticizer concretes are increasingly published; however, PCE manufacture is grossly reliant on synthesized raw materials from petrochemicals, which are predominantly a source of green house gases. But in recent years, the focus of many scholars has been attracted by the principle of low carbon (Rao *et al*., 2024), environmental conservation, and the application and advancement of green construction/buildings (Abellan-garcia *et al*., 2023; Zhu *et al*., 2022; Nduka *et al.,* 2022).

Some cross-sectional academic studies hypothesize the cost relationship an association between the civil engineering and housing project`s, and PCEs, with respect to the net cost of the imported materials, especially the influence of PCEs superplasticizer in HPC used for the modern building project across the continents. Recently, these researchers posit that housing cost has a direct correlation with the cost of materials, evolving from the cost of importation, duty, and transportation. Hence, an alternative construction material, such as locally developed supplements, to mitigate this economic effect and the associated influence, is grossly required for curbing housing deficits. This local materials exploration possesses a potential for maximizing gross national product (GNP) and gross domestic product (GDP) for national development. Besides, existing literature on natural pozzolanic materials in the construction field is extensive and focuses particularly on the mineral composition of pozzolanic weathered fine aggregate from mineral parent rock, which enhances the structural integrity and performance of concrete structures. Up to the present time, most of the publications skewed towards an additional synthesis chemical to improve the strength of HPC.

A large and growing body of literature argues and opines that the suitability of HPC-PCEs concretes for the environment does support the principle of environmental conservation, low carbon, green construction application, and advancement, and green materials, which drives local eco-friendly materials harnessing(Kou *et al*., 2025; Nduka *et al*., 2022).A growing body of literature, like *Ikponmwosa et al.* (2023), posits on the potential of local aggregates optimization for achieving HPC, with an output compressive strength of 52.22N/mm^2, giving about 126% increment over the traditional concrete mix. In their study noted some other researchers' work incorporating available local material such as glass powder, silica fume, industrial by-product (ductal), dolomite, and steel fibers, etc. HPC concrete developed doubled, and in the case of ductal incorporation, a triple-strength was achieved. However, a limited publication of this exists, especially across different climate zones (hot temperate regions).

Therefore, there is a need for a systematic experimental investigation to quantify the influence of water–cement ratio and polycarboxylate ether admixture on the performance characteristics of high-performance concrete produced using eco-friendly local materials such as River Sand and Crush Stones. Addressing this research gap will contribute to evidence-based mix design guidelines that support both structural performance requirements and sustainability objectives. Hence, the experimental research data will add to the knowledge base on HPC concrete production for construction sites and serve as a basis for decision-making among policymakers.

Materials and Methods

This section focuses on the ingredients and experimental procedure in the development of a high performance concrete.

In the experimental study involving the preparation of 72 specimens, including the control, being the HPC concrete produced from varying percentages of PCE (0%, 1%, 1.5% and 2%), and w/c ratio (0.3, 0.35) blended with eroded parent rock sand, and 10mm plus 20mm diameter crushed stones. The workability test for fresh and strength-hardened concrete was conducted at different curing days (3, 7, 28 days) in water, which is suitable for the temperate climate of the study scope.

Materials

The fine aggregates for the specimen were from eroded rock deposited abundantly in a nearby stream and crushed stone from the parent rock quarry. The superplasticizer was Polycarboxylate ether (PCE), and water was obtained from a potable tap of the Civil Engineering laboratory of the University of Ibadan, Nigeria. The binder was from the local market, satisfying Type I CEM II Ordinary Portland Cement, 42.5N OPC. The standard conforms to Nigerian cement standards, NIS 444-1: 2003 and EN 197-1:2011 specifications. It is among the most commonly used cements in the construction industry, delivered in 50kg bags. Table 1 reveals the uniformity and consistency of the aggregates graphically represented on the particle size distribution curve in Figure 1.

Table 1: Sieve Analysis (Fine Aggregate)

Sieve Size (mm)	**Mass Retained(g)**	**Cumulative Mass Retained (g)**	**Cumulative% Retained**	**Cumulative % Passing**
4.75	5.11	5.11	1.02	98.98
2.00	21.71	26.82	5.36	94.64
0.85	67.31	94.13	18.826	81.17
0.425	53.91	148.06	29.61	70.39
0.212	106.01	254.07	50.81	49.19
0.15	105.19	359.26	71.85	28.15
0.075	84.41	443.67	88.73	11.27
0	56.33	500	100.00	0.00
Fineness Modulus	=Sum % Cumulative Retained in 0.6mm/100=			2.66

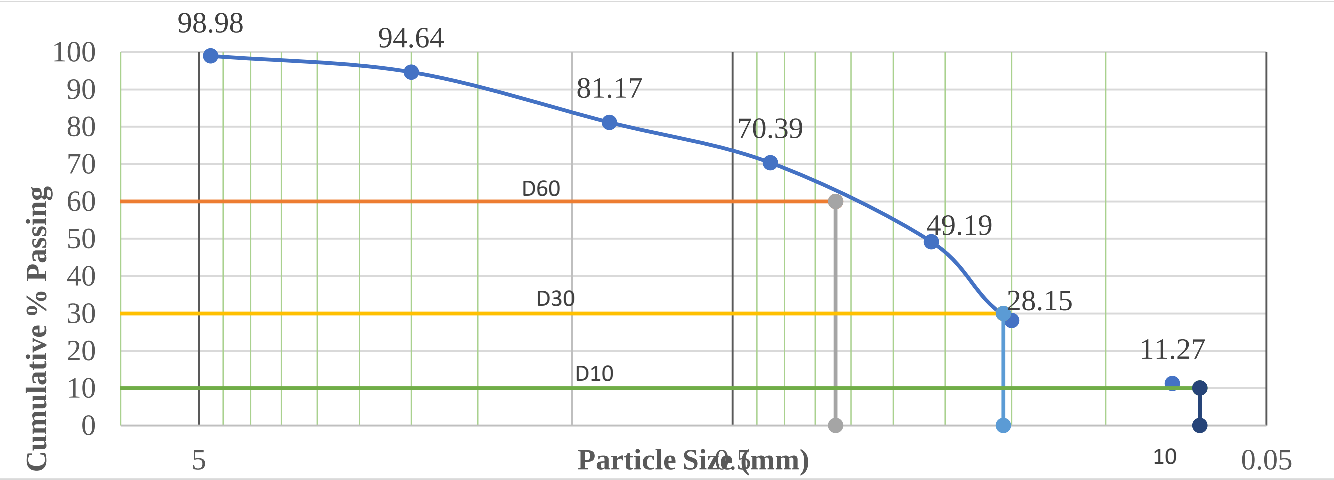

Figure 1: Particle Distribution Curve/graph

%Passing Sieve No. 30 (0.6mm) = 25.1707
Results on Sieve Analysis (Fine Aggregate)
D60 (mm) 0.3206
D30 (mm) 0.1555
D10 (mm) 0.0666

Cc = Coefficient of Curvature
=D30*D30/(D10*D60) = 1.1322

Cu = Coefficient of Uniformity=
= D60/D10 = 4.8164

Methods
Department of Environmental, British Method (DOE), was adopted for a target strength of 50MPa to achieve 30 to 60mm slump at 0.32 w/c. The density of the cement was 750.0kg/m³and 642.860kg/m³, the fine aggregate was 511.10 kg/m³ and 600.86kg/m³, and 833.900kg/m³ and 901.290kg/m³ for varying 0.3 and 0.35 w/c, respectively, as shown in Table 3.

Mixing

Batching for the concrete proportioning for all ingredients was by weight (Figure 3) in kilograms as shown in Table 3,and mixing of concrete was mechanically achieved using a 0.045m³ metal drum concrete-mixer machine for 5 minutes in accordance with BS ISO 18650-1,2:2021 and BS 1881-125. The control specimen was prepared with the conventional ingredients, while the samples of the HPC-PCE were prepared at different percentages of dosage, and at two types of w/c ratios. The local eco-friendly mineral of fine and coarse aggregate were the main constituents in all the specimens as presented in Table 4.

Table 3: Design Mix and Proportioning of ingredients and PCE

Number of Cubes	Water/Cement Ratio	Superplasticizer (% by cement weight)	Mix Design Water Content (kg/m³)	Cement Content (kg/m³)	Fine Aggregate (kg/m³)	Coarse Aggregate (kg/m³)	PCE Dosage (kg/m³)	Expected Strength (Mpa)
12	0.3	1	225.00	750.00	511.10	833.90	7.50	≥ 50
12	0.3	1.5	225.00	750.00	511.10	833.90	11.25	≥ 50
12	0.3	2	225.00	750.00	511.10	833.90	15.00	≥ 50
12	0.35	1	225.00	642.86	600.86	901.29	6.43	≥ 50
12	0.35	1.5	225.00	642.86	600.86	901.29	9.64	≥ 50
12	0.35	2	225.00	642.86	600.86	901.29	12.86	≥ 50
72			**16200.00**	**50142.86**	**40030.46**	**62466.69**	**752.14**	

Table 4: Mix Proportion by Weight for 12 Cubes

	Water Content (L)	Cement (Kg)	Fine Aggregate (Kg)	Coarse Aggregate (10mm) (Kg)	Coarse Aggregate (20mm) (Kg)	Total Aggregate (Kg)	Superplasticizer (Ml)
MIX 1	9.11	30.38	20.70	11.26	22.52	33.77	0.00
MIX 2	9.11	30.38	20.70	11.26	22.52	33.77	277.40
MIX 3	9.11	30.38	20.70	11.26	22.52	33.77	416.10
MIX 4	9.11	30.38	20.70	11.26	22.52	33.77	554.79
MIX 5	9.11	26.04	24.33	12.17	24.33	36.50	0.00
MIX 6	9.11	26.04	24.33	12.17	24.33	36.50	237.77
MIX 7	9.11	26.04	24.33	12.17	24.33	36.50	356.65
MIX 8	9.11	26.04	24.33	12.17	24.33	36.50	475.54
TOTAL	72.90	225.64	180.14	93.70	187.40	281.10	2318.25

Experimental Test on Fresh and Hardened Concrete

An experimental test was conducted for workability on fresh concrete using the slump cone apparatus in accordance with ASTM C143-05 (Figure 4), compaction factor in accordance with BS EN 12350-4:2000 and BS1199 (Figure 5), and Flow Table consistency test in accordance with BS EN 12350-5:2000. Hardened concrete tests were conducted to conform to the British Standard, BS EN 12390-3:2019. Compressive cube test in figure 9 (BS EN 12390-1:2000), conducted after curing the concrete cube (Figure 6) made in a mould dimensioned 150 x 150 x 150 mm as shown in figure 7. To ensure safety, performance, and durability of concrete, care is taken to determine the stiffness against deformation and resistance against drift during seismic effects; attention is given to evaluating the elastic modulus. This was done following ACI 318, ACI 363R, BS EN 1992, and ASTM C 469.

The water immersion curing method was adopted for 3 days, 7 days, and 28 days, before crushing. The cubes were dry after being removed from water, and weighed to obtain the density before being subjected to the crushing machine for compression, which is a destructive method.



Figure 2: Mechanical sieving **Figure 3:** Batching by weight **Figure 4:** Measuring Slump **Figure 5:** Compaction Test Apparatus




Figure 6: Curing, water immersion **Figure 7:** Concrete in Metal Mould **Figure 8:** Weighing Concrete **Figure 9:** Compressive test.

Experimental Result and Discussion

Result

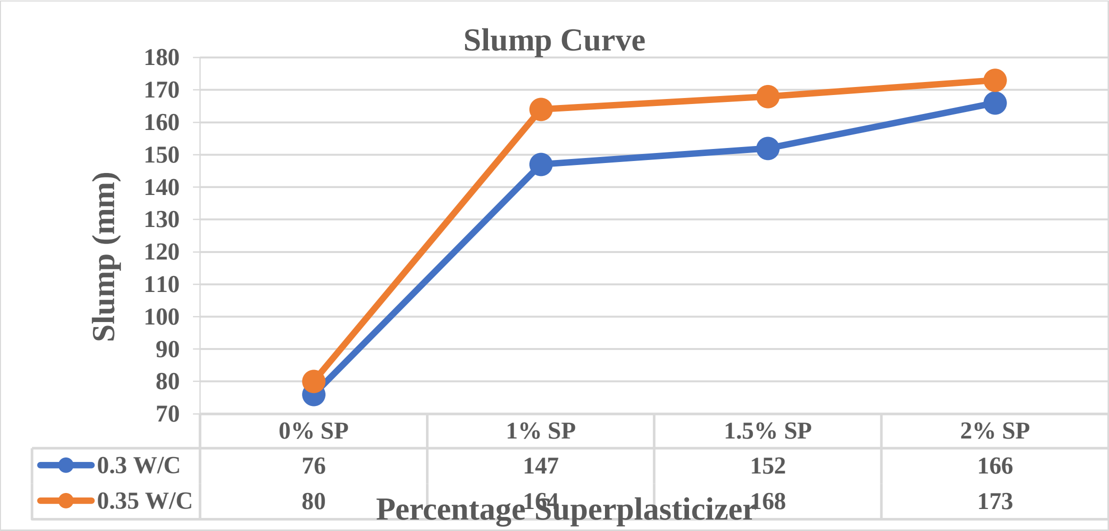

Figure 10a: Concrete Slump Test for HPC-PCE Curve

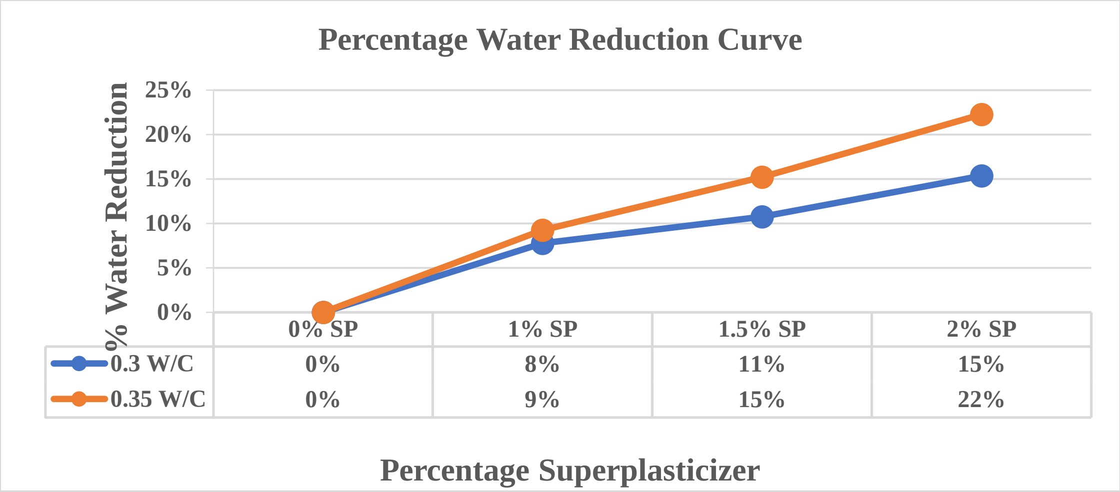

Figure10b: Percentage Water Reduction on HPC-PCE Curve

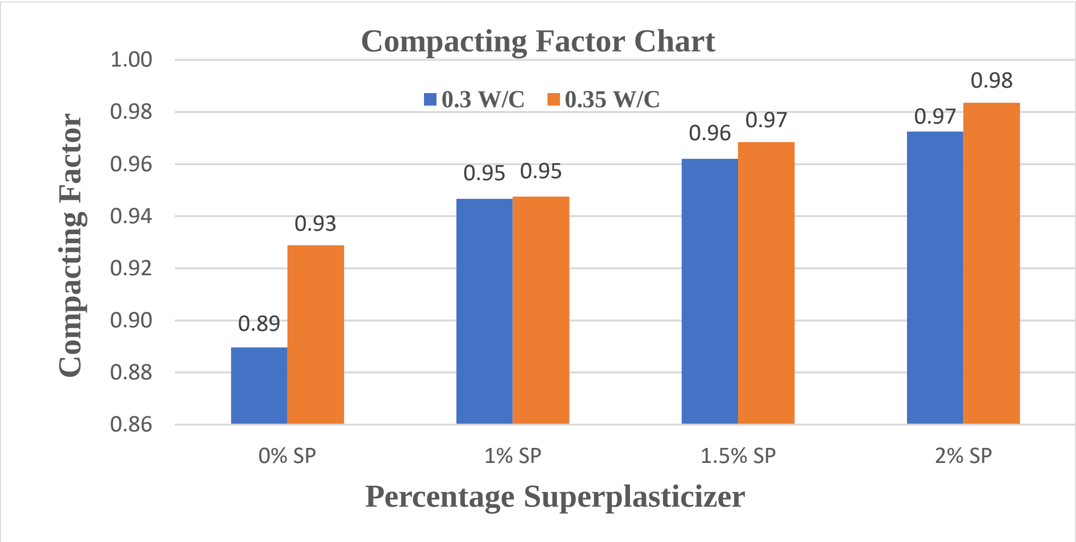

Figure10c: Compacting Factor for HPC

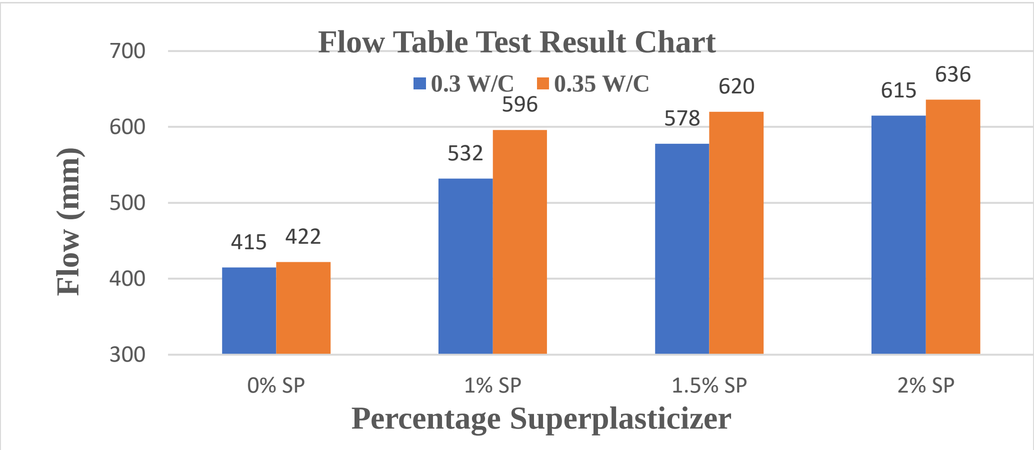

Figure10d: Flow Table Test for HPC

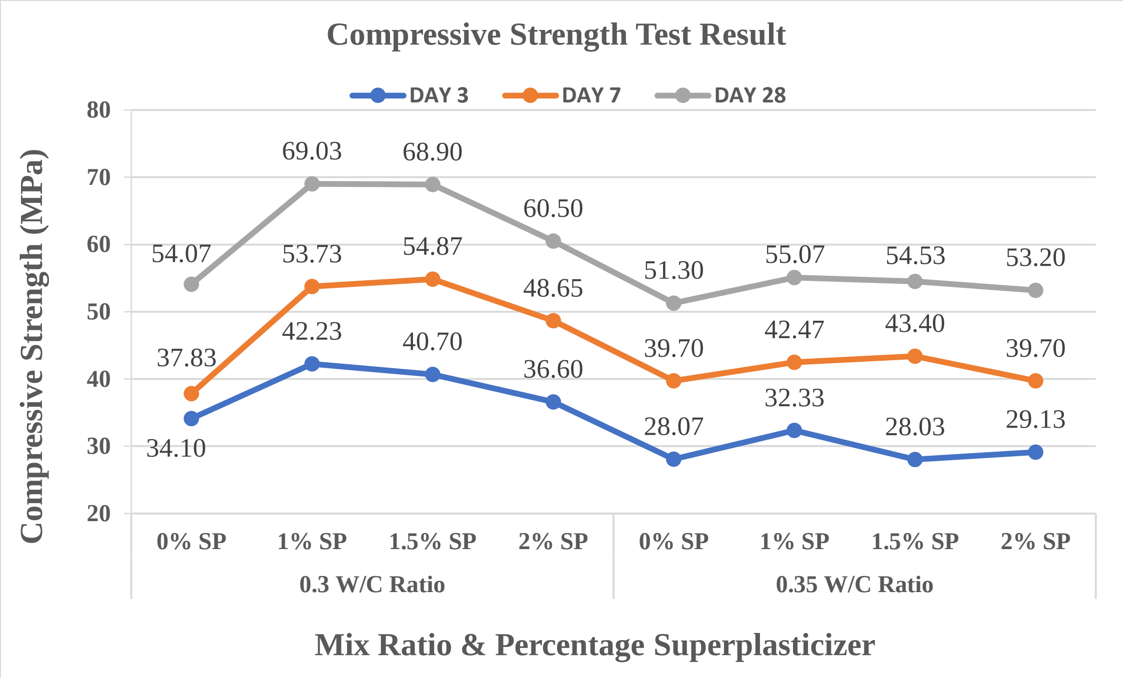

Figure 11: Compressive Strength of Concrete and Varying Water-cement Ratio and Superplasticizer.

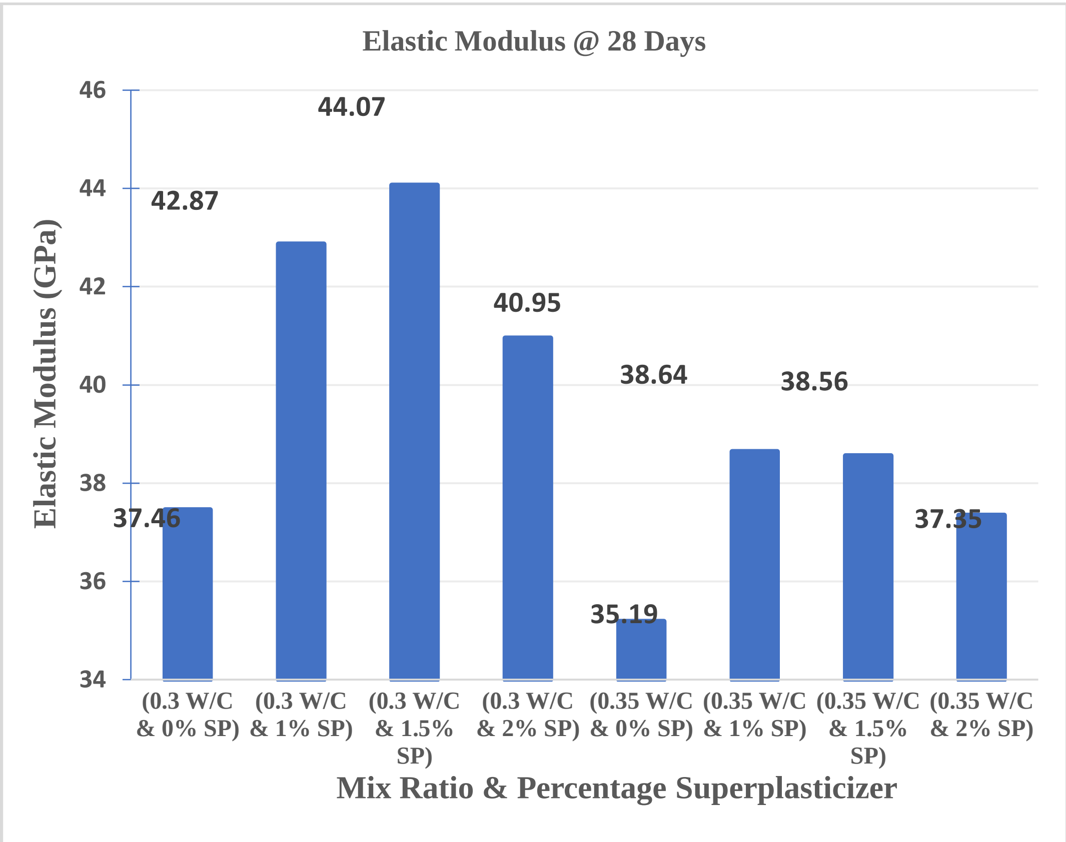

Figure 7: Elastic Modulus Curve at 28 Days for HPC-PCE

Table 8: Overall HPC-PCE Performance and Application

Mix	w/c	PCE %	Slump	CF	Flow (mm)	fc (MPa)	E (GPa)	ρ (kg/m³)	Penetration (mm)	Key Performance	Best Application
Mix 1	0.3	0	76	0.89	415	54.07	37.46	2412.25	4.41	Lowest slump/flow, low SP, moderate strength, high stiffness	High-strength priority
Mix 2	0.3	1	147	0.95	532	69.03	42.87	2432.79	4.25	Improved flow, higher strength than Mix 1, good stiffness	High-strength Structural Concrete
Mix 3	0.3	1.5	152	0.96	578	68.90	44.07	2479.41	3.87	Balanced flow and stiffness, high modulus	Maximum stiffness + SCC
Mix 4	0.3	2	166	0.97	615	60.50	40.95	2465.78	4.05	High strength, high flow, good compaction factor	High Stiffness + SCC
Mix 5	0.4	0	80	0.93	422	51.30	35.19	2354.47	4.65	Lower strength, very good workability and density	Economical + General Structural use
Mix 6	0.4	1	164	0.95	596	55.07	38.64	2447.8	3.80	Good strength-flow balance, low penetration	Economical + SCC
Mix 7	0.4	1.5	168	0.97	620	54.53	38.56	2452.05	3.53	Moderate strength, reduced penetration	Best impermeability + SCC
Mix 8	0.4	2	173	0.98	636	53.20	37.35	2420.35	4.32	Best penetration resistance, adequate strength	Impermeability Critical Structures

Discussion

The result of the experiment on the workability of fresh concrete for the HPC super-plasticized with PCE and control is represented in Figures 10a to 10d. From the experimental observations, it was found that mixes with a 0.30 w/c ratio, specifically Mix 1 (0% SP), had a slump of 76mm, indicating very low workability typical of stiff concrete. Mix 2 (1% SP), Mix 3 (1.5% SP), and Mix 4 (2% PCE) had slumps of 147, 152, and 166mm, respectively, showing increased workability and improvement over the control, with Mix 4 having the highest slump. For the 0.35 w/c ratio mixes, Mix 5 (0% PCE) exhibited a slump of 80mm, slightly better than Mix 1 due to the higher w/c ratio. Mix 6 (1% SP), Mix 7 (1.5% SP), and Mix 8 (2% PCE) showed slumps of 164, 168, and 173mm, respectively, with Mix 8 achieving the maximum workability, representing a 116.3% improvement over the control. This finding aligns with recent studies on the performance of polycarboxylate-based superplasticizers in HPC (Roberti *et al*., 2021; Zhou *et al.*, 2021; Zhang *et al*., 2021).

Evident strongly suggests that admixtures beyond 1.5% HPC-PCE, the rate of improvement drops significantly, suggesting a possible saturation of the cement particle surface by the superplasticizer molecules, which some authors posit leads to segregation, bleeding, and slow setting without significant gains in workability (Zhang *et al*., 2021; Zhao *et al*., 2021). In contrast, the addition of HPC-PCE dosage beyond 1.5% significantly improves the compactor factor beyond 0.95, which aligns with studies of Odeyemi *et al*. (2022) and Malamas (2023). Conversely, the flow diameter across all doses performs better with 0.35% than 0.30%, resulting in a notable difference of 64mm (12%), as shown in Figure 10d, which conforms to the study of Ahmed *et al*. (2021).

Experimental data clearly demonstrate that there is a strong influence of PCE in HPC, as the compressive strengths exceeded the target strength of 50MPa at 28 days, and early age strengths at 3 and 7 days of curing. Observation reveals that the mixes with a w/c ratio of 0.30 with 1 to 1.5% doses of PCE exceeded the target strength, with Mix 2 and Mix 3 reaching (compressive strengths of 65-75MPa after 28 days) nearly 70MPa. This aligns with Abrams' Law, which states that concrete strength is inversely proportional to the w/c ratio when other factors are held constant (Neville, 2019).

Recent studies by Liang *et al*. (2022), Sujay *et al*. (2020), and Khan *et al*. (2020) support the results shown in Figure 6, that a w/c of 0.30 with 1.5% PCE dosage produces maximum compressive strength at 28 days. This supports the idea that lower w/c ratios produce denser, less porous concrete with better mechanical properties. Aitcin & Flatt (2021) postulate that excess superplasticizer can cause delayed setting, segregation, and air entrainment, all reducing strength. Explained that excessive dispersion of cement particles leads to a less dense microstructure and hinders the development of strong hydration products. Figure 11 expatiate that a 0.35 w/c ratio with increased doses of PCE produces declined results, which was the claim of Liang *et al*. (2022), who observed that reducing w/c from 0.35 to 0.30 enhanced compressive strength by 20–30% due to decreased capillary porosity and improved interfacial transition zone (ITZ) between cement paste and aggregates.

For high-performance concrete applications, it is important to understand how compressive strength relates to elastic modulus to optimize structural efficiency. The results from tests measuring elastic modulus/Young's modulus are shown in Figure 7. Each of the eight mixes achieved elastic modulus values that range from 35.19 to 44.07 GPa, which is typical for normal-weight high-performance concrete. According to the classification set by BS EN 1992-1-1, Mixes

1, 5, 6, 7, and 8, which have elastic modulus values between 35.19 and 38.64 GPa, are considered to fall within the typical range for Grade 50 MPa high-performance concrete.

In contrast, mixes 2, 3, and 4, which have elastic modulus values ranging from 40.95 to 44.07 GPa, exhibit enhanced stiffness characteristics that are more typical of Grade 60+ MPa concrete. The higher elastic modulus values observed in the mixes with a water-to-cement ratio of 0.30 indicate that these mixes have better microstructural density and lower porosity when compared to the mixes with a water-to-cement ratio of 0.35. At a w/c ratio of 0.30, the elastic modulus reaches a peak of 44.07GPa at 1.5% content, and at a w/c ratio of 0.35, stiffness reaches its peak value of 38.64GPa. Doses greater than superplasticizer of 1.5% causes the elastic modulus of both series of w/c to decrease, which means that high doses of superplasticizer will lead to the inhibition of the elasticity of the concrete. Recent studies by Liang *et al.* (2022) regarding high-performance concrete (HPC) using polycarboxylate superplasticizer have put forth similar results.

The overall analysis of the performance of the mixes, in the predicted application as displayed by Table 8, produced several important observations. Mix 1, the one with the poorest slump-flow properties but moderate strength and high stiffness, is well selected to be used in high-priority applications of high-strength properties where dimensional stability and load-bearing capacity are of utmost value. Mix 2, which incorporates better flow properties at maximum compressive strength, is suitable in high-strength structural concrete projects that require sufficient workability and maximum mechanical properties.Mix . 3 is balanced, has high stiffness and modulus, and is the best suited to be used in work where the maximum stiffness and self-compacting concrete properties are needed. The overall combination of high strength (68.9 MPa), the highest elastic modulus (44.07 GPa), and the lowest penetration height (3.87 mm) at such a w/c ratio is representative of the complementary advantage relating to the 1.5% SP dosage.

Although Mix 4 had good strength and flow characteristics, it still showed performance a fraction less than that of Mixes 2 and 3, implying that a 2% SP dosage can be higher than that of this w/c ratio. Out of the 0.35 w/c mixes, Mix 5 yields less strength but excellent workability and density properties, which makes it convenient in low-cost and general structural applications in which moderate strength needs to be compensated in relation to costs. Mix 6 exhibits an appealing strength-flow balance and low penetration values, and therefore it may be used in cost-efficient applications that do not face overtly hostile conditions, especially in self-compacting construction situations. Mix 7 is moderate strength with the best overall penetration resistance (3.53 mm), and therefore it is the best to use where application requirements are maximum impermeability with self-compacting concrete properties, e.g., water retaining structures or even elements that face harsh conditions of the environment.

With the most favourable penetration resistance in the 0.35 w/c series, and with the necessary strength, Mix 8 displays qualities that would make it usable in high-performance critical structures that need the property of impermeability, e.g., basements, underground structures, or marine structures. The overall performance data that have been identified during this study indicate that when one is considering optimal mix design, it is not only important to consider the strength needs but also the demands of durability and the economic factors that must be taken into consideration in the context of an application.

Conclusion and Recommendation

The experimental study investigated the mechanical properties of HPC at a quantifying water and PCE, and confirmed the best mix designs for Grade 50MPa High Performance Concrete (HPC). The current study concludes that the application of HPC-PCE blended with eco-friendly material for sustainable construction is as follows:

i. Concrete mix without admixture, but 0.3w/c with poor slump-flow properties but moderate strength and high stiffness, is suitable to be used in high-priority applications of high-strength properties where dimensional stability and load-bearing capacity are of utmost value.
ii. HPC-PCE 1% admixture concrete at 0.3w/c has flow properties at 69.03MPa maximum compressive strength, implying that it is suitable for high-strength structural concrete projects that require sufficient workability and maximum mechanical properties.
iii. HPC-PCE of 1.5% admixture at 0.3 w/c mix has high stiffness and modulus 0f 44.07GPa. This implies that it is adequate to be used in work where the maximum stiffness and self-compacting concrete properties are required.
iv. Concrete mix 0.35w/c without PCE admixture yields less strength but excellent workability and density properties, implying that it is convenient in low-cost and general structural applications, in which moderate strength needs to be compensated in relation to costs.
v. Concrete mix with 1% HPC-PCE admixture at 0.35w/c exhibits an appealing strength-flow balance and low penetration values, and therefore could be used in cost-efficient applications that do not face overtly hostile conditions, especially in self-compacting construction situations.

The proposed future research directions will also improve the HPC technology, especially in terms of long-term durability, sustainability, and specialized usage. The principles established through this study will be used to create concrete formulations in the construction industry, which remain to be improved, to higher and more sustainable levels, with an increasing number of strict technical and environmental demands. Direct durability tests (Rapid Chloride Penetration, Carbonation, Alkali silica reaction, Creep and Shrinkage) were omitted, though highly suggested to be used subsequently in the research.

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