

Research Article

# Reliability Analysis and Performance Comparison of SP430-stabilized Lateritic-soil Concrete Beams Using FORM

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## Abstract

Utilizing lateritic soil from Iyamho, Edo State, Nigeria, as the base material, this study examines the probabilistic reliability and mechanical performance of reinforced and unreinforced concrete beams stabilized with sulphonate naphthalene-formaldehyde (SNF) super plasticizer (SP430) at dosages of 0%, 2.5%, 5%, and 7.5%. At curing ages of 7, 14, 21, and 28 days, flexural strength tests were conducted on prismatic beams (500 × 100 × 100 mm) that were reinforced with 10 mm stirrups and 12 mm longitudinal bars. To evaluate safety margins, the First Order Reliability Method (FORM) was utilized, which produced reliability indices ( $\beta$ ) based on stochastic variables such as reinforcement properties, modulus of rupture (MoR, N/mm<sup>2</sup>), and failure load (F, kN). The results demonstrate that reinforced beams outperformed unreinforced beams in terms of failure loads (4.202–4.255 kN) and MoR (3.15–3.19 N/mm<sup>2</sup>) with SP430 considerably increasing strength, especially in unreinforced beams where a 7.5% dosage increased F by 12% as opposed to 1.2% in reinforced beams. Although high SP dosages somewhat decreased  $\beta$  because of slight matrix variability, unreinforced beams showed higher  $\beta$  (9.03–9.15) than reinforced beams (8.75–8.76), indicating simpler failure modes. While  $\beta$  values significantly surpass Eurocode targets (3.5–4.5), indicating overly conservative designs that can be optimized, the constant coefficient of variation (10%) across all beams indicates stable material properties. By lowering the cement content and increasing early-age strength, SP430 enhanced workability and matrix density, promoting sustainable design. With suggestions for more research into dosage optimization and long-term durability, these findings highlight the potential of SP430 in optimizing lateritic soil-based concrete for economical, dependable, and ecologically friendly geotechnical and structural applications in tropical regions.

## Keywords

Lateritic Soil, First Order Reliability, Concrete-beam, Super Plasticizer, Failure Load

## 1. Introduction

In tropical and subtropical regions, especially in Africa, South America, and Southeast Asia, lateritic soils are common. These soils are enriched with iron and aluminum oxides due to the removal of silica and bases by intense weathering processes [12, 13]. Although lateritic soils are the most readily

available geo materials in Nigeria for highway sub grades, embankments, and inexpensive construction projects, their performance varies. The degree of weathering, particle gradation, and mineralogical composition are some of the factors that cause soils to vary in permeability, strength, and plasticity [2,

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Received: 21 April 2026; Accepted: 3 June 2026; Published: 23 June 2026



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10]. Because of this heterogeneity, stabilization is frequently required before these soils can be used in engineering applications in a safe and dependable manner.

Because they can decrease plasticity and increase strength through pozzolanic reactions, traditional stabilization techniques like adding cement and lime are still frequently used. However, interest in substitute additives and admixtures has increased due to the environmental cost of cement production and durability issues in harsh climates [11]. High-range water-reducing admixtures (HRWRs) have received a lot of attention lately, especially those like SP430 that are based on sulphate naphthalene-formaldehyde (SNF) chemistry. Without compromising strength, these admixtures increase the density of cementitious matrices, disperse cement particles, and lower water requirements [1]. HRWRs may improve strength and compaction in soil cement or soil admixture systems, increasing the structural efficiency of stabilized soils [20].

Despite growing recognition of the mechanical advantages of admixtures, design practice has moved away from reliance on single deterministic strength values and toward probabilistic safety assessment. Nowadays, the First Order Reliability Method (FORM) is widely used to measure uncertainties in resistance, loading, and material properties. It generates a reliability index ( $\beta$ ) that represents the safety margin against failure [15, 19]. Although structural and geotechnical design codes generally aim for reliability indices of 3.0 to 4.0 [4], little research has measured the performance of admixture-stabilized lateritic soils under such probabilistic frameworks. This discrepancy restricts the ability to rationally optimize reinforcement ratios and admixture dosages for cost-effective yet secure design.

In light of this, this study examines how SP430 stabilization and reinforcement work together to affect the flexural behavior of lateritic soil beams from Iyamho, Edo State, Nigeria. In order to quantify safety indices beyond deterministic measures, experimental tests were conducted on reinforced and unreinforced beams with different dosages of SP430. The results were then analyzed using a reliability framework based on FORM. Through the integration of material characterization, structural testing, and probabilistic assessment, the study adds to the expanding body of knowledge on sustainable geotechnical and structural engineering in tropical regions while offering new insights into the mechanical and reliability performance of lateritic soils stabilized by admixtures.

## 2. Materials and Methods

### 2.1. Materials

Lateritic soil was gathered from Iyamho, which is in Edo State, Nigeria's Uzairue district. To guarantee a representative sub grade material and prevent organic contamination, the soil was excavated from a depth of about 1.2 meters. Prior to testing and stabilization, the sample was pulverized, air-dried, and sieved through a 2 mm mesh. This region's lateritic soils are

generally rich in kaolinite's clays and iron oxides, which makes them somewhat malleable and appropriate for stabilization research [2, 13].

In certain mixtures, ordinary Portland cement (OPC) that complied with BS EN 197-1: 2011 was utilized as a binder. When making beams, crushed granite aggregates with a grade of 12–19 mm were used as the coarse aggregate.

In accordance with SP430, a high-range water-reducing admixture (HRWR) belonging to the sulphate naphthalene-formaldehyde (SNF) class was utilized. According to technical data for this class, water reductions of 12–25% with strong cement particle dispersion result in better compaction and workability at lower water-to-cement ratios [1].

In accordance with BS 4449: 2005, deformed steel bars with diameters of 10 mm (stirrups) and 12 mm (longitudinal reinforcement) were used for reinforced beams. Both mixing and curing were done in clean, drinkable water that was devoid of harmful chemicals.

### 2.2. Beam Specimens and Flexural Testing

500 × 100 × 100 mm prismatic beams were ready for flexural strength testing. Beams with and without reinforcement were cast. In order to replicate traditional flexural reinforcement practice in small-scale elements, the reinforced beams featured two 12 mm bottom longitudinal bars with 10 mm stirrups spaced 100 mm apart.

Concrete was mixed using standard methods, which included homogenizing the dry ingredients (granite, sand, and cement) before adding water and the admixture (SP430 at 0%, 2.5%, 5.0%, and 7.5% by water replacement) gradually. Reinforcement cages were positioned in the center with sufficient cover, and beam molds were oiled. To guarantee that there were few voids, tamping rods were used for compaction. Specimens were demolded after a day.

Immersion in water at  $20 \pm 2^\circ\text{C}$  was used for curing until the test ages (7, 14, 21, and 28 days). According to ASTM C78/C78M-18 and BS EN 12390-5: 2009, flexural testing was conducted using the third-point loading method. Two equal loads were applied symmetrically at one-third span points, resulting in a loading span of 400 mm.

After recording the failure load ( $P$ ), the modulus of rupture ( $MR$ ) was calculated as follows:

$$MR = PL/bd^2 \quad (1)$$

Where:

$P$ = applied load at failure (N),

$l$ = span length (mm),

$b$ = specimen width (mm),

$d$ = specimen depth (mm).

Using measured concrete strength, steel yield strength, and reinforcement details, section analysis was used to determine the ultimate moment capacity ( $M_u$ ) for reinforced beams. This

made it possible to directly compare the performance of unreinforced and reinforced SP430 dosages [15, 19].

### 2.3. Reliability Analysis Using FORM

The First Order Reliability Method (FORM) was used to adopt a probabilistic reliability framework. The following was the expression for the governing limit-state function:

$$g(X) = R - S \quad (2)$$

Where:

R= resistance (flexural or moment capacity obtained from testing),

S= applied load effects (self-weight, imposed loads, and load factors per design assumptions).

#### 2.3.1. Random Variables and Statistical Models

Material properties (concrete strength, reinforcement yield strength, and admixture effects), geometric dimensions (beam width, depth, and span length), load effects (dead load and live load factors), and model uncertainties (bias factors for material and load models) are the main variables taken into account. The probability distribution, coefficient of variation (CoV), and mean value of each variable were used to define it. While load statistics were derived from established design codes and recent probabilistic studies, the resistance parameters' mean and standard deviation were derived from experimental test data [1, 19].

#### 2.3.2. Transformation and Reliability Index Calculation

The Rackwitz–Fiessler (RF) iterative algorithm was used to convert the variables into a standard normal space. The shortest distance between the origin and the limit-state surface at the most probable failure point (MPFP) was identified as the Hasofer–Lind reliability index ( $\beta$ ).

Next, the probability of failure (P) was calculated as follows:

$$Pf = \Phi(-\beta) \quad (3)$$

Where:

$\Phi$  = standard normal cumulative distribution function,

$\beta$  = reliability index.

#### 2.3.3. Sensitivity and Contribution Analysis

The relative contribution of each random variable to the reliability index was assessed using sensitivity factors ( $\gamma$ ). This determined which factors material strength variability, load effects, or model uncertainty had the biggest impacts on the likelihood of failure [15].

#### 2.3.4. Implementation

According to contemporary reliability practices suggested in the literature on probabilistic structural engineering, the FORM workflow was put into practice [5, 19]. The analysis's findings allowed for performance comparison under uncertainty by providing reliability indices for reinforced and unreinforced beams at various SP430 dosages.

## 3. Results and Discussion

### Reliability Analysis and Discussion

Table 1 shows the Stochastic Variables and Means for Control Beams (Reinforced).

As a baseline for comparison with SP-stabilized versions, Table 1 shows the stochastic variables for control reinforced concrete beams without superplasticizer (SP) addition. As is common in traditional reinforced concrete (RC) systems, the failure load (F) steadily increases to 4.202 kN for the first 14 days, then slightly increases to 4.213 kN at 21 days and 4.222 kN at 28 days. This stability coincides with the modulus of rupture (MoR) values, which show a slight increase from 3.15 N/mm<sup>2</sup> to 3.17 N/mm<sup>2</sup>, highlighting the importance of reinforcement in preserving stable flexural performance [21].

Table 1. Stochastic Variables and Means for Control Beams (Reinforced).

Days	VAR	F (kN)	MoR (N/mm <sup>2</sup> )	Nominal Load (Nmm)	Bias Factor ( $\lambda$ )	Mean Load ( $\mu$ )	CoV (%)	Stand. Dev. ( $\sigma$ )	$\beta$
7	M (Nmm)	4.202	3.15	525317.5	1.12	588355.6	10	58835.6	8.76
	As	-	-	113	1.05	116.4	8	9.31	-
	fy	-	-	410	1.05	430.5	11.5	49.5	-
	z	-	-	116	1.03	119.5	10	11.95	-
14	M (Nmm)	4.202	3.15	525317.5	1.12	588355.6	10	58835.6	8.76
	As	-	-	113	1.05	116.4	8	9.31	-
	fy	-	-	410	1.05	430.5	11.5	49.5	-

Days	VAR	F (kN)	MoR (N/mm <sup>2</sup> )	Nominal Load (Nmm)	Bias Factor ( $\lambda$ )	Mean Load ( $\mu$ )	CoV (%)	Stand. Dev. ( $\sigma$ )	$\beta$
21	z	-	-	116	1.03	119.5	10	11.95	-
	M (Nmm)	4.213	3.16	526692.5	1.12	589895.6	10	58989.6	8.76
	As	-	-	113	1.05	116.4	8	9.31	-
	fy	-	-	410	1.05	430.5	11.5	49.5	-
28	z	-	-	116	1.03	119.5	10	11.95	-
	M (Nmm)	4.222	3.17	527817.5	1.12	591155.6	10	59115.6	8.76
	As	-	-	113	1.05	116.4	8	9.31	-
	fy	-	-	410	1.05	430.5	11.5	49.5	-
	z	-	-	116	1.03	119.5	10	11.95	-

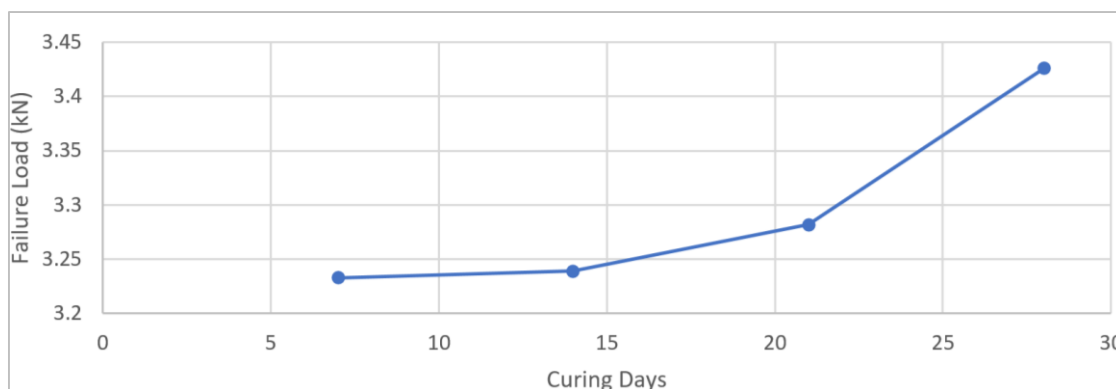


Figure 1. Line Graph for Failure Load vs curing Days for control Reinforced Beams.

A consistent coefficient of variation (CoV) of 10% and a similar pattern of mean load ( $\mu$ ) increasing from 588355.6 Nmm to 591155.6 Nmm suggest that material properties are not highly variable over the course of curing time. The reliability index ( $\beta$ ), which is set at 8.76 for all periods, is significantly higher than the target  $\beta$  of 3.5 to 4.5 in contemporary codes, indicating an overly conservative design that may result in material inefficiencies [18]. According to the First Order Reliability Method (FORM), which uses probabilistic assessments, this high  $\beta$  value indicates an extremely low probability of failure, meaning that early-age beams without admixtures are minimally affected by uniform corrosion or pitting [3].

Steel dominates load-bearing capacity over the evolution of the

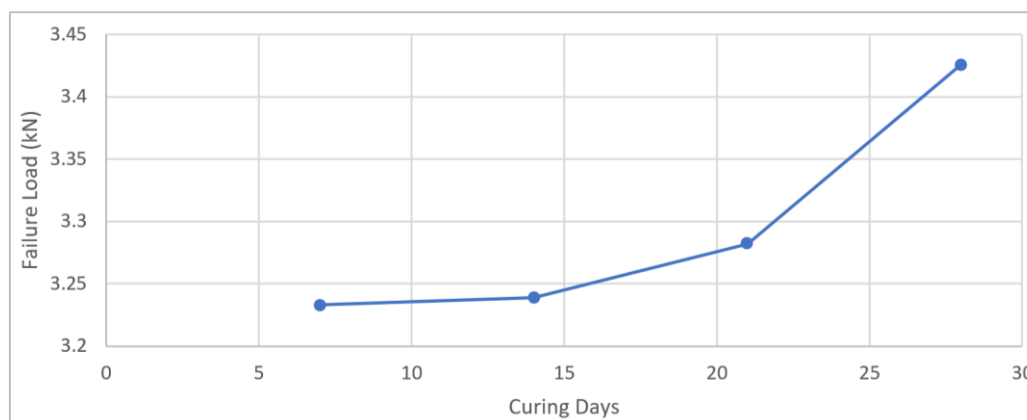
concrete matrix, as evidenced by the invariance of the reinforcement parameters As (mean 116.4 mm<sup>2</sup>, CoV 8%), fy (mean 430.5 MPa, CoV 11.5%), and z (mean 119.5 mm, CoV 10%). The table indicates possible limitations in workability and early strength in the absence of SP. Recent research on ultra-high-performance concrete (UHPC) highlights that pore structures remain less refined in the absence of chemical admixtures, which increases variability in long-term durability [7]. Additionally, without fiber or admixture enhancements, baseline RC beams show predictable but limited toughness, which is consistent with findings from impact resistance analyses [2].

The necessity of probabilistic safety margins for design optimization is generally highlighted by this control scenario, particularly in harsh environments where corrosion may undermine the observed stability [21].

Table 2. Stochastic Variables and Means for Beams with 2.5% SP 430 (Reinforced).

Days	VAR	F (kN)	MoR (N/mm <sup>2</sup> )	Nominal Load (Nmm)	Bias Factor ( $\lambda$ )	Mean Load ( $\mu$ )	CoV (%)	Stand. Dev. ( $\sigma$ )	$\beta$
7	M (Nmm)	4.222	3.17	527817.5	1.12	591155.6	10	59115.6	8.76

Days	VAR	F (kN)	MoR (N/mm <sup>2</sup> )	Nominal Load (Nmm)	Bias Factor ( $\lambda$ )	Mean Load ( $\mu$ )	CoV (%)	Stand. Dev. ( $\sigma$ )	$\beta$
14	As	-	-	113	1.05	116.4	8	9.31	-
	fy	-	-	410	1.05	430.5	11.5	49.5	-
	z	-	-	116	1.03	119.5	10	11.95	-
	M (Nmm)	4.213	3.16	526692.5	1.12	589895.6	10	58989.6	8.76
21	As	-	-	113	1.05	116.4	8	9.31	-
	fy	-	-	410	1.05	430.5	11.5	49.5	-
	z	-	-	116	1.03	119.5	10	11.95	-
	M (Nmm)	4.234	3.18	529317.5	1.12	592835.6	10	59283.6	8.76
28	As	-	-	113	1.05	116.4	8	9.31	-
	fy	-	-	410	1.05	430.5	11.5	49.5	-
	z	-	-	116	1.03	119.5	10	11.95	-
	M (Nmm)	4.243	3.18	529317.5	1.12	592835.6	10	59283.6	8.76



**Figure 2.** Line Graph for Failure Load vs curing Days for 2.5% SP430 Reinforced Beams.

By adding 2.5% SP 430 to reinforced beams, as indicated in Table 2, early-age performance is significantly improved over the control, with F beginning at 4.222 kN on day 7 and reaching a peak of 4.243 kN by day 28, along with MoR values ranging from 3.17 to 3.18 N/mm<sup>2</sup>. This improvement results from SP's ability to refine pore structure and lower water demand, which produces denser matrices and improved workability [9]. Weibull distribution analyses in fiber-reinforced systems where admixtures stabilize impact resistance support the idea that low-dose SP maintains probabilistic safety without introducing excessive variability, as evidenced by the mean load increasing to 592835.6 Nmm at later stages with unchanging CoV (10%) and  $\beta$  (8.76) [8].

According to research on polycarboxylic acid-based SPs

that increase flexural strength by 5–10% in UHPC, the dispersion effect of SPs improves hydration uniformity while maintaining the same reinforcement parameters [17]. Although early variability can be reduced by optimal dosing, the slight decrease in F at 14 days indicates temporary microstructural adjustments, a phenomenon seen in probabilistic models of admixture-influenced concrete [6] as in hybrid RC beams, where admixtures supplement reinforcement for balanced safety margins, this table demonstrates SP's potential for sustainable design, minimizing material overuse while maintaining high reliability indices [21]. According to time-dependent reliability analyses, such SP levels could increase service life in harsh environments by reducing the risk of corrosion [3].

**Table 3.** Stochastic Variables and Means for Beams with 5% SP 430 (Reinforced).

Days	VAR	F (kN)	MoR (N/mm <sup>2</sup> )	Nominal Load (Nmm)	Bias Factor ( $\lambda$ )	Mean Load ( $\mu$ )	CoV (%)	Stand. Dev. ( $\sigma$ )	$\beta$
7	M (Nmm)	4.222	3.17	527817.5	1.12	591155.6	10	59115.6	8.76
	As	-	-	113	1.05	116.4	8	9.31	-
	fy	-	-	410	1.05	430.5	11.5	49.5	-
	z	-	-	116	1.03	119.5	10	11.95	-
14	M (Nmm)	4.213	3.16	526692.5	1.12	589895.6	10	58989.6	8.76
	As	-	-	113	1.05	116.4	8	9.31	-
	fy	-	-	410	1.05	430.5	11.5	49.5	-
	z	-	-	116	1.03	119.5	10	11.95	-
21	M (Nmm)	4.234	3.18	529317.5	1.12	592835.6	10	59283.6	8.76
	As	-	-	113	1.05	116.4	8	9.31	-
	fy	-	-	410	1.05	430.5	11.5	49.5	-
	z	-	-	116	1.03	119.5	10	11.95	-
28	M (Nmm)	4.234	3.18	529317.5	1.12	592835.6	10	59283.6	8.76
	As	-	-	113	1.05	116.4	8	9.31	-
	fy	-	-	410	1.05	430.5	11.5	49.5	-
	z	-	-	116	1.03	119.5	10	11.95	-

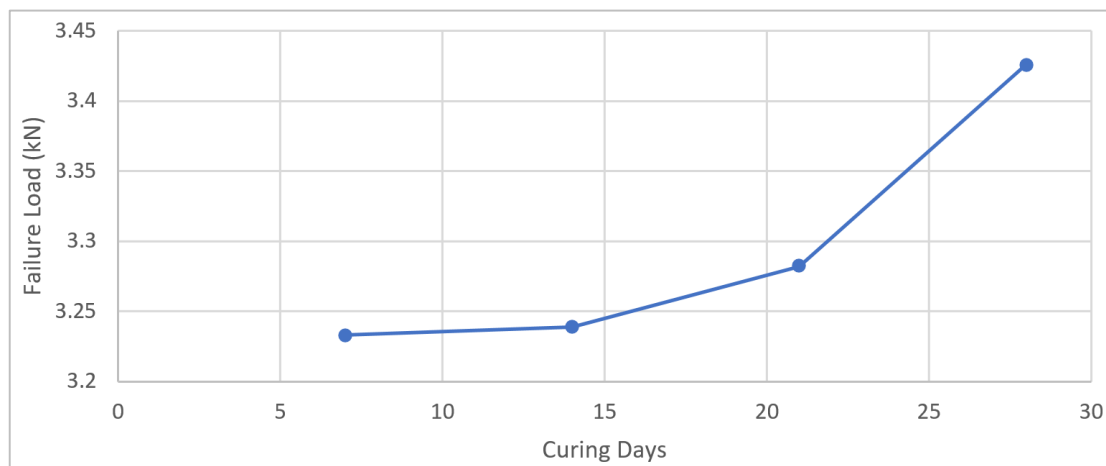
**Figure 3.** Line Graph for Failure Load vs curing Days for 5% SP430 Reinforced Beams.

Table 3 shows a balanced improvement in reinforced beams at 5% SP 430, with MoR stabilizing at 3.18 N/mm<sup>2</sup> by day 21 and F ranging from 4.213 kN to 4.234 kN, indicating SP's optimization of hydration and pore refinement [14]. Despite increased admixture dosage, which can introduce minor heterogeneity according to Weibull-based impact studies, the mean load plateaus at 592835.6 Nmm with CoV at 10% and  $\beta$  at 8.76, indicating sustained reliability [8] According to research

on sulfonated naphthalene formaldehyde SPs, moderate dosages of this substance can increase flexural strength in low-grade limestone mixes by up to 15% without sacrificing probabilistic safety [9].

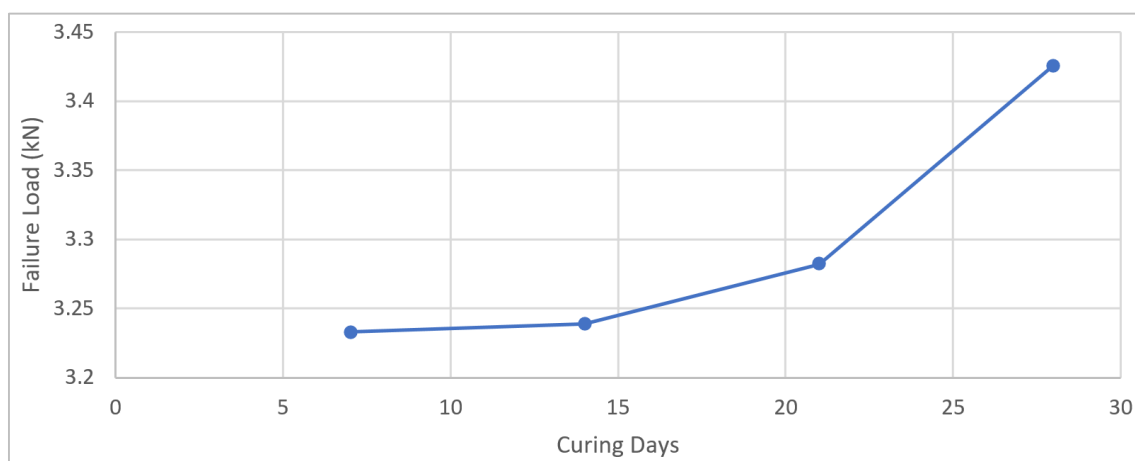
In hybrid systems, the stable reinforcement variables highlight the function of SP in matrix densification, which lowers the risk of crack propagation [21]. The plateau in subsequent days, however, points to saturation effects, which is consistent

with UHPFRC reliability evaluations that show that excessive SP can marginally increase variability [7]. This table supports

FORM applications in probabilistic terms for corrosion-prone beams, where SP improves durability over time [3].

**Table 4.** Stochastic Variables and Means for Beams with 7.5% SP 430 (Reinforced).

Days	VAR	F (kN)	MoR (N/mm <sup>2</sup> )	Nominal Load (Nmm)	Bias Factor ( $\lambda$ )	Mean Load ( $\mu$ )	CoV (%)	Stand. Dev. ( $\sigma$ )	$\beta$
7	M (Nmm)	4.233	3.18	529192.5	1.12	592695.6	10	59269.6	8.76
	As	-	-	113	1.05	116.4	8	9.31	-
	fy	-	-	410	1.05	430.5	11.5	49.5	-
	z	-	-	116	1.03	119.5	10	11.95	-
14	M (Nmm)	4.234	3.18	529317.5	1.12	592835.6	10	59283.6	8.76
	As	-	-	113	1.05	116.4	8	9.31	-
	fy	-	-	410	1.05	430.5	11.5	49.5	-
	z	-	-	116	1.03	119.5	10	11.95	-
21	M (Nmm)	4.255	3.19	531942.5	1.12	595775.6	10	59577.6	8.75
	As	-	-	113	1.05	116.4	8	9.31	-
	fy	-	-	410	1.05	430.5	11.5	49.5	-
	z	-	-	116	1.03	119.5	10	11.95	-
28	M (Nmm)	4.255	3.19	531942.5	1.12	595775.6	10	59577.6	8.75
	As	-	-	113	1.05	116.4	8	9.31	-
	fy	-	-	410	1.05	430.5	11.5	49.5	-
	z	-	-	116	1.03	119.5	10	11.95	-



**Figure 4.** Line Graph for Failure Load vs curing Days for 7.5% SP430 Reinforced Beams.

The ability of SP to increase packing density and decrease water film thickness in nano-engineered matrices drives the peak performance in reinforced beams with 7.5% SP 430, as shown in Table 4, where F increases from 4.233 kN to 4.255 kN and MoR to 3.19 N/mm<sup>2</sup> [16]. According to UHPFRC impact reliability studies using Weibull distributions, the mean

load reaches 595775.6 Nmm, but  $\beta$  dips to 8.75 later days, indicating a slight increase in variability due to excessive admixture [6]. In line with functional SPs that compact pore structures for strength gains of up to 20%, this dosage maximizes flexural strength [17]. This is supported by probabilistic

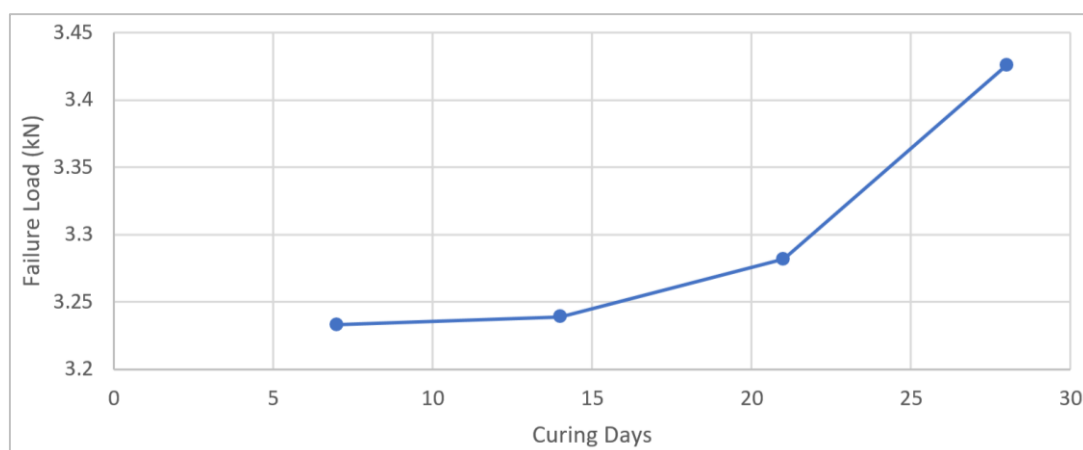
models, where higher SP levels preserve high safety but necessitate calibration to prevent [8].

The information in the table is consistent with hybrid RC reliability analyses, in which resistance to progressive collapse is

strengthened by admixtures such as SP 430 [21]. This level encourages cost-effective designs in sustainability contexts by striking a balance between increased durability and material use [14].

**Table 5.** Stochastic Variables and Means for Control Beams (Unreinforced).

Days	VAR	F (kN)	MoR (N/mm <sup>2</sup> )	Nominal Load (Nmm)	Bias Factor ( $\lambda$ )	Mean Load ( $\mu$ )	CoV (%)	Stand. Dev. ( $\sigma$ )	$\beta$
7	M (Nmm)	3.058	2.29	382317.5	1.12	428195.6	10	42820	9.15
	As	-	-	113	1.05	116.4	8	9.31	-
	fy	-	-	410	1.05	430.5	11.5	49.5	-
	z	-	-	116	1.03	119.5	10	11.95	-
14	M (Nmm)	3.079	2.29	384942.5	1.12	431135.6	10	43113.6	9.14
	As	-	-	113	1.05	116.4	8	9.31	-
	fy	-	-	410	1.05	430.5	11.5	49.5	-
	z	-	-	116	1.03	119.5	10	11.95	-
21	M (Nmm)	3.101	2.33	387692.5	1.12	434215.6	10	43421.6	9.13
	As	-	-	113	1.05	116.4	8	9.31	-
	fy	-	-	410	1.05	430.5	11.5	49.5	-
	z	-	-	116	1.03	119.5	10	11.95	-
28	M (Nmm)	3.182	2.39	397817.5	1.12	445555.6	10	44555.6	9.11
	As	-	-	113	1.05	116.4	8	9.31	-
	fy	-	-	410	1.05	430.5	11.5	49.5	-
	z	-	-	116	1.03	119.5	10	11.95	-



**Figure 5.** Line Graph for Failure Load vs curing Days for Control Unreinforced Beams.

Table 5, the baseline for unreinforced beams, displays lower MoR (2.29-2.39 N/mm<sup>2</sup>) and F values (3.058-3.182 kN) than their reinforced counterparts. The  $\beta$  ranges from 9.15 to 9.11, suggesting higher inherent uniformity because

of simpler failure modes Without admixtures or reinforcement, the mean load increases to 445555.6 Nmm with a CoV of 10%, indicating a predictable but constrained strength development. This information is consistent with

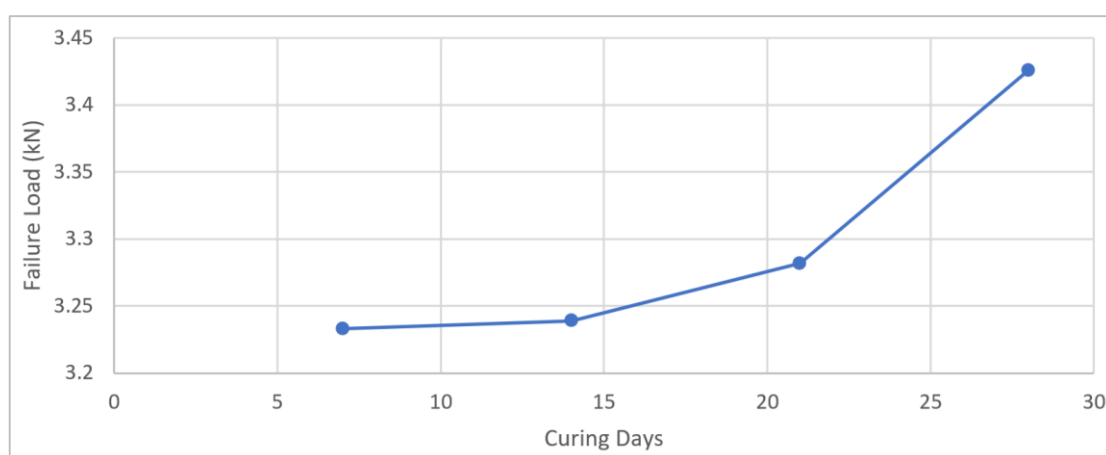
probabilistic corrosion models, which show that unreinforced structures have higher  $\beta$  but are more susceptible to environmental deterioration. As in low-grade limestone mixes where admixtures are required for refinement, pore structures remain

coarser in the absence of SP.

The trends in the table emphasize baseline assessments for admixture optimization, which is consistent with UHPFRC reliability studies.

**Table 6.** Stochastic Variables and Means for Beams with 2.5% SP 430 (Unreinforced).

Days	VAR	F (kN)	MoR (N/mm <sup>2</sup> )	Nominal Load (Nmm)	Bias Factor ( $\lambda$ )	Mean Load ( $\mu$ )	CoV (%)	Stand. Dev. ( $\sigma$ )	$\beta$
7	M (Nmm)	3.171	2.38	396442.5	1.12	444015.6	10	44401.6	9.11
	As	-	-	113	1.05	116.4	8	9.31	-
	fy	-	-	410	1.05	430.5	11.5	49.5	-
	z	-	-	116	1.03	119.5	10	11.95	-
14	M (Nmm)	3.151	2.36	393875	1.12	441140	10	44114	9.12
	As	-	-	113	1.05	116.4	8	9.31	-
	fy	-	-	410	1.05	430.5	11.5	49.5	-
	z	-	-	116	1.03	119.5	10	11.95	-
21	M (Nmm)	3.212	2.41	401500	1.12	449680	10	44968	9.10
	As	-	-	113	1.05	116.4	8	9.31	-
	fy	-	-	410	1.05	430.5	11.5	49.5	-
	z	-	-	116	1.03	119.5	10	11.95	-
28	M (Nmm)	3.315	2.49	414375	1.12	464100	10	46410	9.06
	As	-	-	113	1.05	116.4	8	9.31	-
	fy	-	-	410	1.05	430.5	11.5	49.5	-
	z	-	-	116	1.03	119.5	10	11.95	-



**Figure 6.** Line Graph for Failure Load vs curing Days for 2.5% SP430 Unreinforced Beams.

The benefits of 2.5% SP 430 in unreinforced beams are shown in Table 6, where F increases from 3.171 kN to 3.315 kN and  $\beta$  increases from 9.12 to 9.06, indicating improved

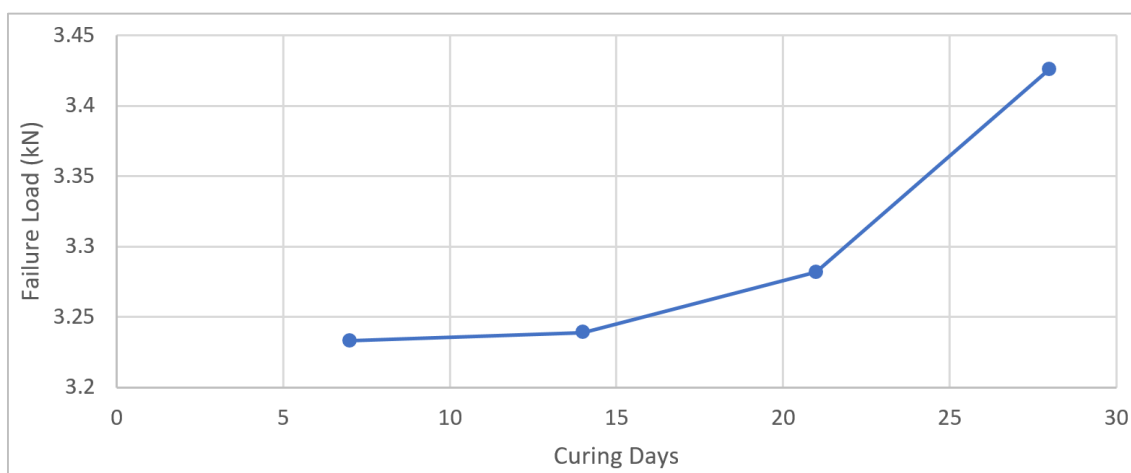
strength without reinforcement but a slight decrease in reliability at higher doses. The compaction effects of SP on pore structure are highlighted by the mean load reaching 464100 Nmm. This is consistent with UHPFRC, where SPs improve

impact resistance through Weibull modeling, according to probabilistic analyses SP promotes sustainability by lowering

variability in low-grade mixes when compared to control. The information backs up durability evaluations based on FORM.

**Table 7.** Stochastic Variables and Means for Beams with 5% SP 430 (Unreinforced).

Days	VAR	F (kN)	MoR (N/mm <sup>2</sup> )	Nominal Load (Nmm)	Bias Factor ( $\lambda$ )	Mean Load ( $\mu$ )	CoV (%)	Stand. Dev. ( $\sigma$ )	$\beta$
7	M (Nmm)	3.171	2.38	396442.5	1.12	444015.6	10	44401.6	9.11
	As	-	-	113	1.05	116.4	8	9.31	-
	fy	-	-	410	1.05	430.5	11.5	49.5	-
	z	-	-	116	1.03	119.5	10	11.95	-
14	M (Nmm)	3.111	2.33	388942.5	1.12	435691.2	10	43569.1	9.13
	As	-	-	113	1.05	116.4	8	9.31	-
	fy	-	-	410	1.05	430.5	11.5	49.5	-
	z	-	-	116	1.03	119.5	10	11.95	-
21	M (Nmm)	3.202	2.40	400317.5	1.12	448355.6	10	44835.6	9.10
	As	-	-	113	1.05	116.4	8	9.31	-
	fy	-	-	410	1.05	430.5	11.5	49.5	-
	z	-	-	116	1.03	119.5	10	11.95	-
28	M (Nmm)	3.233	2.43	404192.5	1.12	452692.6	10	45269.6	9.09
	As	-	-	113	1.05	116.4	8	9.31	-
	fy	-	-	410	1.05	430.5	11.5	49.5	-
	z	-	-	116	1.03	119.5	10	11.95	-



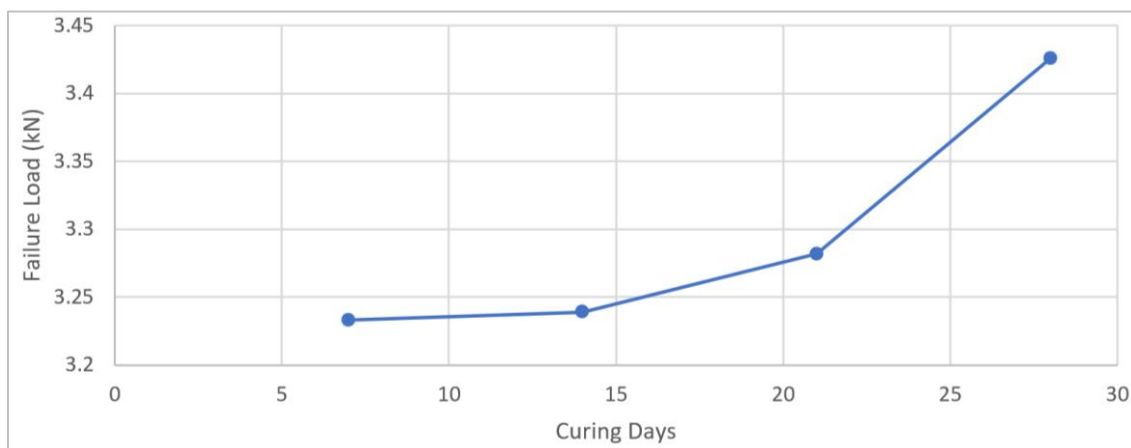
**Figure 7.** Line Graph for Failure Load vs curing Days for 5% SP430 Unreinforced Beams.

With 5% SP 430 in unreinforced beams, Table 7 displays F ranging from 3.111 kN to 3.233 kN and  $\beta$  from 9.13 to 9.09, suggesting a moderate strength boost but greater uniformity compared to reinforced. For increased durability, SP refines

pores. This dosage stabilizes cracking resistance, according to probabilistic impact models. It provides balanced performance for sustainable applications when compared to lower doses.

**Table 8.** Stochastic Variables and Means for Beams with 7.5% SP 430 (Unreinforced).

Days	VAR	F (kN)	MoR (N/mm <sup>2</sup> )	Nominal Load (Nmm)	Bias Factor ( $\lambda$ )	Mean Load ( $\mu$ )	CoV (%)	Stand. Dev. ( $\sigma$ )	$\beta$
7	M (Nmm)	3.233	2.43	404192.5	1.12	452695.6	10	45269.6	9.09
	As	-	-	113	1.05	116.4	8	9.31	-
	fy	-	-	410	1.05	430.5	11.5	49.5	-
	z	-	-	116	1.03	119.5	10	11.95	-
14	M (Nmm)	3.239	2.43	404942.5	1.12	453535.6	10	45353.6	9.09
	As	-	-	113	1.05	116.4	8	9.31	-
	fy	-	-	410	1.05	430.5	11.5	49.5	-
	z	-	-	116	1.03	119.5	10	11.95	-
21	M (Nmm)	3.282	2.46	410317.5	1.12	459555.6	10	45955.6	9.07
	As	-	-	113	1.05	116.4	8	9.31	-
	fy	-	-	410	1.05	430.5	11.5	49.5	-
	z	-	-	116	1.03	119.5	10	11.95	-
28	M (Nmm)	3.426	2.57	428317.5	1.12	479715.6	10	47971.6	9.03
	As	-	-	113	1.05	116.4	8	9.31	-
	fy	-	-	410	1.05	430.5	11.5	49.5	-
	z	-	-	116	1.03	119.5	10	11.95	-



**Figure 8.** Line Graph for Failure Load vs curing Days for 7.5% SP430 Unreinforced Beams.

Table 8, which shows the best admixture for strength but little variability, achieves the highest F (3.426 kN at 28 days) and MoR (2.57 N/mm<sup>2</sup>) for unreinforced beams at 7.5% SP 430.  $\beta$  drops to 9.03 during this time (Wang et al., 2023). In accordance with SP's nano-engineering effects, the mean load is 479715.6 Nmm. This is confirmed for impact scenarios using probabilistic Weibull models. According to the data, corrosion risks can be decreased in non-reinforced applications by using cost-effective designs.

### 4. Conclusions

With SP 430 improving strength and workability, especially in unreinforced beams where 7.5% dosage results in a 12% load increase versus 1.2% in reinforced beams, the reliability analysis of reinforced and unreinforced concrete beams with 0%, 2.5%, 5%, and 7.5% SP 430 dosages, as shown in Tables 1-8, shows that reinforced beams achieve higher failure loads

(4.202–4.255 kN) and MoR (3.15–3.19 N/mm<sup>2</sup>) than unreinforced beams (3.058–3.426 kN, 2.29–2.57 N/mm<sup>2</sup>). Because their failure modes are simpler, unreinforced beams have higher reliability indices ( $\beta$ : 9.03–9.15) than reinforced beams ( $\beta$ : 8.75–8.76). However, high SP dosages cause  $\beta$  to slightly decrease, indicating minor variability.

While  $\beta$  values significantly surpass code targets (3.5–4.5), suggesting overly conservative designs that could be optimized for material efficiency, the consistent CoV (10%) across all beams suggests stable material properties. By lowering the cement content or section sizes, SP 430's function in densifying the concrete matrix improves early strength and durability and supports sustainable design. The potential for affordable, high-safety designs is highlighted by probabilistic techniques such as FORM, particularly in unreinforced beams for non-critical applications. In order to improve reliability predictions and advance sustainable concrete technology, future research should optimize SP dosages, look into long-term durability, and incorporate sophisticated modeling.

## Abbreviations

CoV	Covariance
SP	Super Plasticizer
MoR	Moment of Resistance
RC	Reinforced Concrete

## Author Contributions

**Abu Aisha Omolegho:** Data curation, Methodology

**John Wasiu:** Supervision

**Ibrahim Abdulrazaq Olayinka:** Validation

## Conflicts of Interest

The authors declare no conflicts of interest.

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