RESEARCH PAPER

Fresh and Mechanical Performance of Nano-Silica-Bacillus subtilis Concrete: An Experimental Investigation

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Abstract

Hybrid modification of concrete with nano-silica (NS) and Bacillus subtilis is of interest because the two additions may influence cementitious performance through different pathways, yet formulation-level evidence across fresh behavior and multiple mechanical properties remains less consistent than evidence for either modifier alone. Six formulations were compared at an effective water-to-binder ratio of 0.40: control concrete (CC), 1.5% nano-silica (NS1.5), B. subtilis at 10^6 CFU/mL (B6), 1.0% nano-silica with B6 (NS1.0B6), 1.5% nano-silica with B6 (NS1.5B6), and 1.5% nano-silica with 10^7 CFU/mL bacteria (NS1.5B7). Slump, fresh density and air content were measured; compressive-strength development was followed from 7 to 90 days; and 28-day split tensile strength, flexural strength and static elastic modulus were compared. Slump ranged from 68 to 94 mm, whereas fresh density and air content varied over narrower absolute ranges. NS1.5B6 gave the highest measured 28-day means for compressive strength (46.2 ± 0.8 MPa), split tensile strength (3.38 ± 0.20 MPa), flexural strength (5.35 ± 0.27 MPa) and static elastic modulus (34.8 ± 0.6 GPa), corresponding to mean increases of 19.7%, 9.4%, 9.2% and 3.3% relative to CC. Raising the bacterial suspension concentration from B6 to B7 at 1.5% NS did not increase the measured mechanical means. Because PCE dosage varied among formulations, the matrix lacks NS1.0-only, B7-only and nutrient-only controls, and specimen-level replicate data and replicate counts were not available for inferential analysis, the results are interpreted as descriptive formulation-level responses rather than proof of statistical superiority or nano-silica-bacteria synergy.

Keywords: nano-silica concrete; Bacillus subtilis; bacterial concrete; workability; compressive strength; split tensile strength; flexural strength; static elastic modulus

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1. Introduction

Nano-silica is widely studied in cementitious materials because its high specific surface area and reactivity can promote nucleation, pozzolanic consumption of calcium hydroxide and refinement of the pore system. Recent work on nano-silica sol has shown that these effects can increase strength and durability while also reducing workability, with the response depending on nano-silica type, dosage and dispersion [6,7]. These mechanisms provide a plausible basis for strength enhancement, but they also make mixture rheology and admixture dosage important experimental variables.

Bacterial concrete uses microorganisms such as Bacillus species to induce or facilitate mineral precipitation within the cementitious matrix. Bacillus subtilis has been investigated for mechanical improvement and self-healing because of its tolerance to alkaline environments and its ability to participate in calcium-carbonate-forming pathways when suitable nutrients and calcium sources are available [1-5]. Studies using B. subtilis with calcium lactate have reported improvements in mechanical and durability indicators, although the magnitude of response depends strongly on bacterial concentration, nutrient system, curing condition and specimen design [4,15].

Combined nano-silica-bacterial systems are less standardized in the literature than studies of either modifier alone. Damodaran and Mayilsamy [13] investigated a bacterial concrete containing 2% nano-silica together with 1% steel fibre, so the response cannot be attributed to a two-component nano-silica-bacteria system alone. Shandel [14] examined a hybrid containing 4% nano-silica and 10^6 cells/mL with emphasis on self-healing and microstructural evidence, whereas Saitheja and Palanivel [16] studied B. subtilis with calcium lactate across 0.5-1.5% nano-silica in M40 concrete. The published systems therefore differ in nano-silica dosage, bacterial condition, auxiliary constituents, endpoints and control structure. This variability supports formulation-specific comparison and cautions against treating reported hybrid improvements as universally transferable or automatically synergistic.

1.1 Research gap and contribution

The present study addresses a narrower formulation question by comparing low nano-silica replacement levels (1.0-1.5%) and B. subtilis suspension concentrations of 10^6 and 10^7 CFU/mL across fresh-state behavior, long-age compressive strength, split tensile strength, flexural strength and static elastic modulus within one six-mixture programme. Its contribution is an integrated formulation-level performance comparison rather than a mechanistic demonstration of synergy. The matrix is not fully factorial and therefore cannot uniquely decompose nano-silica, bacterial, nutrient and interaction effects; accordingly, the study identifies the highest measured response within the tested set while separating observed trends from causal or statistically demonstrated claims. Table 1 positions the present design relative to the most directly relevant hybrid studies cited in this manuscript.

Table 1. Positioning of the present formulation matrix relative to directly relevant nano-silica/bacterial studies cited in this manuscript.

Study	NS dosage	Bacterial condition	Additional scope / design feature	Relevance to present study
Damodaran and Mayilsamy [13]	2%	Bacterial concrete	Includes 1% steel fibre; mechanical and characterization study	Auxiliary fibre prevents isolation of a two-component NS-bacteria response
Shandel [14]	4%	10^6 cells/mL	Self-healing assessment with SEM-supported interpretation	Higher NS level and different endpoint emphasis
Saitheja and Palanivel [16]	0.5-1.5%	B. subtilis + calcium lactate	M40 concrete; low-dose NS range	Closest cited low-dose range, but matrix and endpoints differ
Present study	1.0-1.5%	10^6 and 10^7 CFU/mL	Fresh properties + 7-90 d compression + three 28 d mechanical indicators	Integrated six-formulation comparison; not a full factorial interaction design

1.2 Objectives of the study

1. To report the measured baseline properties of cement, fine aggregate and coarse aggregate included in the experimental programme.
2. To quantify formulation-level differences in slump, fresh concrete density and air content across the selected control, nano-silica, bacterial and combined mixtures.
3. To determine compressive-strength development at 7, 28, 56 and 90 days for the selected control, nano-silica, bacterial and combined mixtures.
4. To compare the 28-day split tensile strength, flexural strength and static elastic modulus of the selected mixtures and identify the highest measured mechanical response without implying statistical superiority unless supported by inferential analysis.

2. Materials and Methods

2.1 Cement and aggregates

Ordinary Portland cement, natural river sand and crushed 20 mm coarse aggregate were used as the principal concrete constituents. Cement specific gravity was measured in the laboratory. Fine aggregate was evaluated for fineness modulus, grading zone and water absorption, while coarse aggregate was evaluated for crushing value, impact value and water absorption. These measured properties form the constituent-material baseline used in this study. The retained experimental record did not include the cement product designation, grade, manufacturer, chemical composition or fineness, or the aggregate source identifiers; these omissions limit independent reproduction and are treated explicitly as methodological limitations rather than being inferred.

2.2 Nano-silica and bacterial addition

Nano-silica was incorporated as a percentage replacement of total binder mass. Bacillus subtilis ATCC 6633 was used in the bacterial and combined formulations. B6 denotes a bacterial suspension concentration of 10^6 CFU/mL and B7 denotes 10^7 CFU/mL. In bacterial mixtures, 8 L/m3 of bacterial suspension replaced an equal quantity of mixing water, while calcium lactate and urea were each added at 0.50% of binder mass. The retained dataset did not include supplier-level nano-silica properties (physical form, purity, SiO2 content, particle-size distribution or specific surface area) or bacterial culture-medium, incubation, concentration-verification and suspension-pH records. Consequently, the dosage labels are used as formulation descriptors, and particle-scale or microbiological mechanisms are not claimed as directly verified in this study.

2.3 Selected concrete mixtures and design basis

Six formulations were used for the fresh-property and mechanical comparison: control concrete (CC), 1.5% nano-silica concrete (NS1.5), bacterial concrete at 10^6 CFU/mL (B6), 1.0% nano-silica with B6 (NS1.0B6), 1.5% nano-silica with B6 (NS1.5B6), and 1.5% nano-silica with 10^7 CFU/mL bacteria (NS1.5B7). The effective water-to-binder ratio was maintained at 0.40. The selected nano-silica levels interrogate a low-dose range consistent with recent nano-silica/bacterial investigations [13,16], while B6 and B7 provide an order-of-magnitude concentration comparison. Concrete proportioning was referenced to the general framework of IS 456 [8] and IS 10262 [9].

The PCE dosage was formulation-dependent rather than constant: 3.20, 4.18, 3.32, 3.97, 4.30 and 4.42 kg/m3 for CC, NS1.5, B6, NS1.0B6, NS1.5B6 and NS1.5B7, respectively. With a total binder content of 400 kg/m3, these values correspond to approximately 0.80%, 1.05%, 0.83%, 0.99%, 1.08% and 1.11% of binder mass. The retained mix-design record does not state a fixed target slump or the trial-based rule used to adjust PCE dosage. PCE variation is therefore treated as a formulation-level confounder, particularly for fresh-property comparison; observed slump differences are not attributed exclusively to nano-silica or bacterial concentration.

Table 2. Selected concrete mix proportions (kg/m³ except bacterial solution in L/m³).

Mix	Cement	NS	Batch water	Bact. soln.	Ca-lactate	Urea	FA	CA	PCE	w/b

Mix	Cement	NS	Batch water	Bact. soln.	Ca-lactate	Urea	FA	CA	PCE	w/b
CC	400.0	0.0	160.0	0.0	0.0	0.0	675	1110	3.20	0.40
NS1.5	394.0	6.0	160.0	0.0	0.0	0.0	675	1110	4.18	0.40
B6	400.0	0.0	152.0	8.0	2.0	2.0	675	1110	3.32	0.40
NS1.0B6	396.0	4.0	152.0	8.0	2.0	2.0	675	1110	3.97	0.40
NS1.5B6	394.0	6.0	152.0	8.0	2.0	2.0	675	1110	4.30	0.40
NS1.5B7	394.0	6.0	152.0	8.0	2.0	2.0	675	1110	4.42	0.40

2.4 Mixing and specimen preparation

Aggregates and cement were dry-mixed for 60 s. Nano-silica was pre-dispersed in approximately 25% of the mixing water containing half of the polycarboxylate ether (PCE) admixture using high-shear mixing for 3 min. The remaining water and PCE were introduced over 90 s. In bacterial mixtures, the bacterial suspension was added during the final 60 s at low mixer speed. The effective water content included the water present in the bacterial suspension so that the stated water-to-binder ratio remained unchanged. Mixer type and capacity, specimen dimensions, mould filling and compaction procedure, demoulding age, curing medium and temperature, specimen conditioning, testing-machine details and loading rates were not available in the retained experimental record; this prevents full procedural reproduction and is acknowledged in Section 3.9.

2.5 Experimental test matrix

The experimental programme comprised constituent-property measurements, fresh-state evaluation and hardened mechanical testing. Compressive and flexural testing were aligned with IS 516 [10], splitting tensile strength with IS 5816 [11], and static elastic modulus with ASTM C469/C469M [12]. Table 3 distinguishes reported test information from metadata that are not available in the retained record. No unreported specimen geometry, replicate count, fresh-property test standard or loading rate has been inferred.

Table 3. Experimental test matrix and available reporting metadata.

Property	Reference standard	Specimen / test unit	Replicate n	Test age	Reporting status
Cement specific gravity	NR	Material sample	NR	Initial	Single measured value
Fine aggregate fineness / grading / absorption	NR	Material sample	NR	Initial	Single measured values
Coarse aggregate crushing / impact / absorption	NR	Material sample	NR	Initial	Single measured values
Slump	NR	Fresh concrete	NR	Fresh	Single measured value
Fresh density	NR	Fresh concrete	NR	Fresh	Single measured value
Air content	NR	Fresh concrete	NR	Fresh	Single measured value
Compressive strength	IS 516 [10]	Geometry NR	NR	7, 28, 56, 90 d	Mean ± SD plotted; 28 d tabulated
Split tensile strength	IS 5816 [11]	Geometry NR	NR	28 d	Mean ± SD
Flexural strength	IS 516 [10]	Geometry NR	NR	28 d	Mean ± SD
Static elastic modulus	ASTM C469/C469M [12]	Geometry NR	NR	28 d	Mean ± SD

Note: NR = not reported in the retained experimental record. These missing metadata limit full reproducibility and are included in the study limitations.

2.6 Data treatment and interpretation

Mechanical results are presented as mean ± standard deviation where those statistics are available in the retained dataset. Percentage changes and normalized comparisons are calculated directly from reported mixture means. Specimen-level replicate values, replicate count (n), batch identifiers and inferential-test outputs were not available; therefore ANOVA, post-hoc comparisons, confidence intervals dependent on n and batch-to-batch variance could not be computed. No p-values are reported, and no difference between mixtures is described as statistically significant. Terms such as "optimum", "superior" and "synergistic" are avoided; "highest measured mean" refers only to descriptive ranking within the investigated formulations.

3. Results and Discussion

3.1 Cement and aggregate characterization

The measured constituent properties are summarized in Table 4. Cement specific gravity was 2.70. Fine aggregate recorded a fineness modulus of 3.182, Zone III grading and 0.85% water absorption; coarse aggregate exhibited a crushing value of 15.47%, an impact value of 13.90% and water absorption of 1.35%. These values provide the measured baseline for the mixtures. The cement specific-gravity value of 2.70 is retained as experimentally reported but is not interpreted further because cement grade, manufacturer data and repeat-test records are unavailable in the retained dataset.

Table 4. Experimental cement and aggregate characterization results.

Test	Measured result	Result unit / classification
Cement specific gravity	2.70	dimensionless
Fine aggregate fineness modulus	3.182	dimensionless
Fine aggregate grading / zone	Zone III	grading zone
Fine aggregate water absorption	0.85%	%
Coarse aggregate crushing value (ACV)	15.47%	%
Coarse aggregate impact value (AIV)	13.90%	%
Coarse aggregate water absorption	1.35%	%

3.2 Fresh concrete properties

The fresh-property results show the clearest formulation-level change in slump. CC produced a slump of 94 mm and B6 91 mm, whereas NS1.5, NS1.0B6, NS1.5B6 and NS1.5B7 produced 73, 77, 70 and 68 mm, respectively. This pattern is consistent with the higher water demand and rheological sensitivity commonly reported for nano-silica-containing concrete [6,7,14]. However, PCE dosage also increased across the nano-silica formulations; therefore, the observed slump values represent the combined effect of the complete mix designs and cannot be used to isolate a nano-silica effect independently of admixture dosage.

Fresh density varied from 2390 to 2413 kg/m3, while air content ranged from 1.90% to 2.14%. In absolute terms these shifts are modest relative to the change in slump. Replicate information for the fresh-property measurements is not available, so the data are reported as measured formulation-level values without assigning statistical significance to the density or air-content differences.

Table 5. Experimental fresh concrete properties.

Mix	Slump (mm)	Fresh density (kg/m³)	Air content (%)
CC	94	2390	1.90
NS1.5	73	2408	2.02
B6	91	2395	2.02
NS1.0B6	77	2407	2.10
NS1.5B6	70	2413	2.14
NS1.5B7	68	2413	2.14

3.3 Compressive strength development

All investigated mixtures showed progressive compressive-strength development from 7 to 90 days in the plotted dataset (Figure 1). At 28 days, CC reached 38.6 ± 1.0 MPa, NS1.5 reached 43.5 ± 0.7 MPa and B6 reached 40.5 ± 1.0 MPa. The combined formulations recorded 44.7 ± 1.0 MPa for NS1.0B6, 46.2 ± 0.8 MPa for NS1.5B6 and 44.0 ± 1.2 MPa for NS1.5B7. NS1.5B6 therefore exhibited the highest measured 28-day mean compressive strength within the six-formulation set.

Relative to CC, the 28-day measured mean compressive-strength increases were 12.7% for NS1.5, 4.9% for B6, 15.8% for NS1.0B6, 19.7% for NS1.5B6 and 14.0% for NS1.5B7. Figure 1 shows a similar ordering of the plotted means at later ages. Exact 7-, 56- and 90-day numerical means are not reconstructed from the figure, and replicate counts are unavailable; consequently, age-development interpretation is restricted to the plotted trajectories and the exact 28-day values retained in tabular form.

Table 6. Experimental 28-day compressive strength results (mean ± SD; replicate n not available in the retained record).

Mix	28-day compressive strength (MPa)
CC	38.6 ± 1.0
NS1.5	43.5 ± 0.7
B6	40.5 ± 1.0
NS1.0B6	44.7 ± 1.0
NS1.5B6	46.2 ± 0.8
NS1.5B7	44.0 ± 1.2

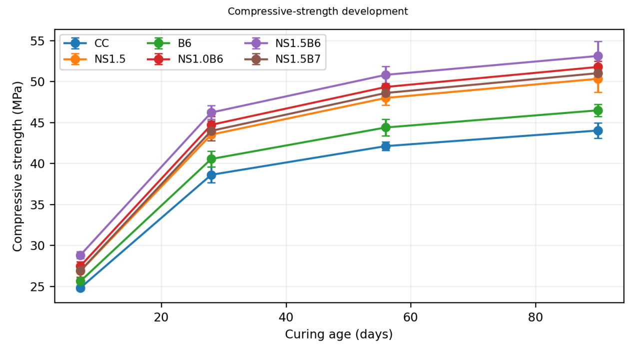

Figure 1. Experimental compressive-strength development of the selected mixtures at 7, 28, 56 and 90 days; error bars show specimen standard deviation.

3.4 Split tensile strength

CC recorded a 28-day split tensile strength of 3.09 ± 0.19 MPa. The measured means for NS1.5, B6, NS1.0B6, NS1.5B6 and NS1.5B7 were 3.28 ± 0.20, 3.17 ± 0.19, 3.33 ± 0.20, 3.38 ± 0.20 and 3.30 ± 0.20 MPa, respectively. NS1.5B6 therefore exhibited the highest measured mean, corresponding to a 9.4% increase relative to CC. The difference between NS1.5B6 and NS1.0B6 is small relative to the reported standard deviations; consequently, the present data presentation does not establish statistical superiority between these formulations.

Table 7. Experimental 28-day split tensile strength results (mean ± SD).

Mix	Split tensile strength (MPa)
CC	3.09 ± 0.19
NS1.5	3.28 ± 0.20
B6	3.17 ± 0.19
NS1.0B6	3.33 ± 0.20
NS1.5B6	3.38 ± 0.20
NS1.5B7	3.30 ± 0.20

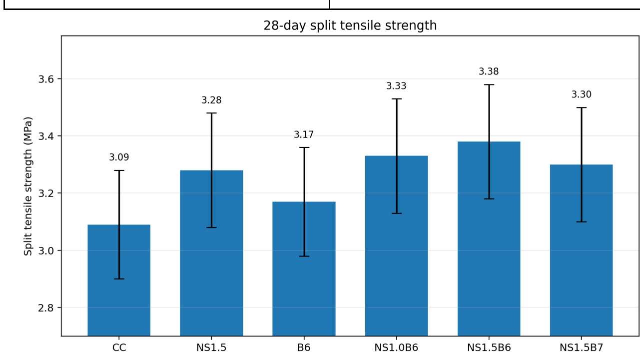

Figure 2. Experimental 28-day split tensile strength of the selected mixtures; error bars show specimen standard deviation.

3.5 Flexural strength

Flexural strength showed a similar descriptive ordering. CC recorded 4.90 ± 0.24 MPa, compared with 5.19 ± 0.26 MPa for NS1.5, 5.02 ± 0.25 MPa for B6, 5.26 ± 0.26 MPa for NS1.0B6, 5.35 ± 0.27 MPa for NS1.5B6 and 5.22 ± 0.26 MPa for NS1.5B7. NS1.5B6 had the highest measured mean, approximately 9.2% above CC. This agreement in the direction of the compressive, tensile and flexural mean responses suggests a consistent mechanical trend, but statistical testing is required before describing the small differences among the combined formulations as significant.

Table 8. Experimental 28-day flexural strength results (mean ± SD).

Mix	Flexural strength (MPa)
CC	4.90 ± 0.24
NS1.5	5.19 ± 0.26
B6	5.02 ± 0.25
NS1.0B6	5.26 ± 0.26
NS1.5B6	5.35 ± 0.27
NS1.5B7	5.22 ± 0.26

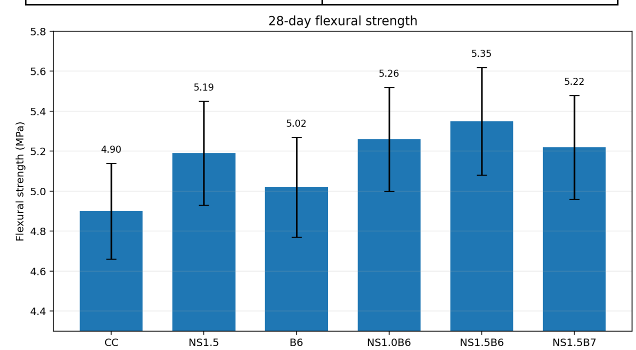

Figure 3. Experimental 28-day flexural strength of the selected mixtures; error bars show specimen standard deviation.

3.6 Static elastic modulus

The measured 28-day static elastic modulus ranged from 33.7 ± 0.6 GPa for CC to 34.8 ± 0.6 GPa for NS1.5B6. NS1.5, B6, NS1.0B6 and NS1.5B7 recorded 34.4 ± 0.6, 34.0 ± 0.6, 34.6 ± 0.6 and 34.5 ± 0.6 GPa, respectively. The maximum measured mean increase was therefore approximately 3.3%, substantially smaller than the corresponding compressive-strength change. Because differences such as 34.8 versus 34.6 GPa are small compared with the reported standard deviation, the modulus results are best interpreted as a limited stiffness shift rather than evidence of a distinct statistically proven ranking.

Table 9. Experimental 28-day static elastic modulus results (mean ± SD).

Mix	Static elastic modulus (GPa)
CC	33.7 ± 0.6
NS1.5	34.4 ± 0.6
B6	34.0 ± 0.6
NS1.0B6	34.6 ± 0.6
NS1.5B6	34.8 ± 0.6
NS1.5B7	34.5 ± 0.6

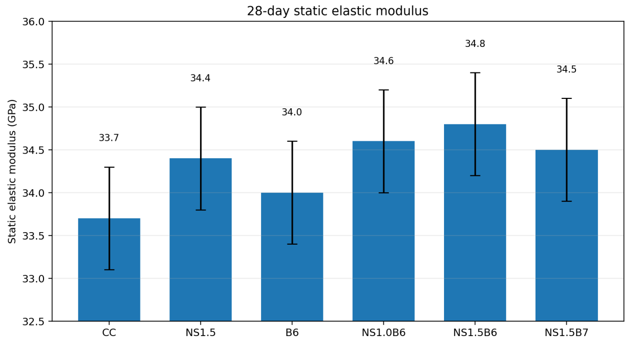

Figure 4. Experimental 28-day static elastic modulus of the selected mixtures; error bars show specimen standard deviation.

3.7 Comparative performance analysis

The fresh and hardened results were further examined using normalized values and a workability-strength comparison calculated directly from the reported mixture means. These are descriptive derived metrics; they do not replace replicate-level statistical analysis or introduce additional experimental evidence.

3.7.1 Relative improvement with respect to control

Table 10 expresses the 28-day mean changes relative to CC. NS1.5B6 has the largest measured mean increase in each reported mechanical property: +19.7% in compressive strength, +9.4% in split tensile strength, +9.2% in flexural strength and +3.3% in static elastic modulus. Figure 5 shows that the proportional response is strongest in compressive strength and smaller for tensile, flexural and stiffness measures. These percentages describe effect magnitude relative to the control mean; they should not be interpreted as statistically significant differences until replicate-level testing is completed.

Table 10. Relative change in 28-day mechanical properties with respect to the control concrete (CC); calculated from measured mean values.

Mix	Compressive Δ (%)	Split tensile Δ (%)	Flexural Δ (%)	Elastic modulus Δ (%)
CC	0.0	0.0	0.0	0.0
NS1.5	12.7	6.1	5.9	2.1
B6	4.9	2.6	2.4	0.9
NS1.0B6	15.8	7.8	7.3	2.7
NS1.5B6	19.7	9.4	9.2	3.3
NS1.5B7	14.0	6.8	6.5	2.4

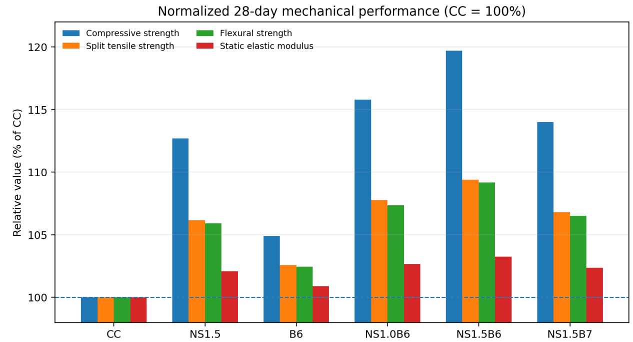

Figure 5. Normalized 28-day mechanical performance of the investigated mixtures, with CC defined as 100%.

3.7.2 Workability-strength trade-off

The measured formulations show a practical workability-strength trade-off: mixtures containing nano-silica generally occupy the region of higher 28-day compressive strength and lower slump. NS1.5B6 combines the highest measured 28-day compressive mean (46.2 MPa) with a 70 mm slump, whereas CC has the highest slump (94 mm) and the lowest 28-day compressive mean (38.6 MPa). Figure 6 is intentionally descriptive. With only six formulations and formulation-dependent PCE dosage, the plotted trend should not be interpreted as a universal causal or constitutive relationship.

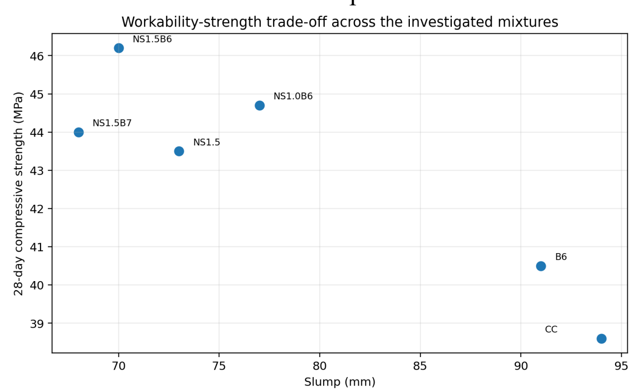

Figure 6. Measured slump versus 28-day compressive strength for the six investigated mixtures, illustrating the observed workability-strength trade-off.

3.7.3 Overall measured mechanical response

Taken together, the reported means identify NS1.5B6 as the formulation with the highest measured 28-day compressive, split tensile and flexural strengths and static elastic modulus within the investigated set. Nano-silica-containing formulations also exhibit lower slump. At the same 1.5% NS level, NS1.5B7 does not exceed NS1.5B6 in any reported mechanical mean and also has the lowest measured slump. This non-monotonic concentration response is an experimentally relevant observation: increasing the bacterial suspension label from 10^6 to 10^7 CFU/mL did not translate into higher measured strength or stiffness in this matrix. However, the absence of B7-only and nutrient-only controls, together with missing inferential statistics, prevents attribution of this pattern uniquely to bacterial concentration. The result is therefore presented as a formulation-level trend, not as a statistically proven optimum.

3.8 Literature-based interpretation

The observed reduction in slump for nano-silica-containing formulations is consistent with literature reporting greater rheological sensitivity and water demand as nano-silica content increases [6,7]. Chen et al. [6] linked nano-silica-related strength development to nucleation, pozzolanic reaction and pore refinement using XRD, SEM and pore-structure evidence. Comparable mechanisms are plausible in the present mixtures, but no microstructural or hydration measurements were performed; the current mechanical trends are therefore described as consistent with, rather than caused by, those mechanisms.

The magnitude of the present mechanical response lies within the broad range reported for related nano-bio systems, but direct numerical equivalence is not appropriate because mixture designs differ. Damodaran and Mayilsamy [13] reported increases of 14.17%, 8.69% and 12.16% in compressive, split tensile and flexural strength for bacterial concrete containing 2% nano-silica and 1% steel fibre. Shandel [14] reported larger gains for a hybrid containing 4% nano-silica and 10^6 cells/mL and supported the interpretation with SEM evidence. The present NS1.5B6 formulation gives measured mean gains of 19.7%, 9.4% and 9.2% in the corresponding properties, but differences in nano-silica dosage, auxiliary constituents, curing, controls and test design prevent direct ranking across studies.

Bacterial-only literature further demonstrates why control design matters. Sahani et al. [15] reported mechanical improvement for B. subtilis concrete containing calcium lactate and supported their interpretation using FESEM/EDS/XRD evidence of calcite-related change. In the present study, every bacterial formulation also contains calcium lactate and urea, while corresponding nutrient-only controls are absent. The measured differences must therefore be interpreted as responses of bacteria-plus-nutrient formulations and cannot be assigned uniquely to viable bacterial activity. For the same reason, the available matrix cannot establish a unique nano-silica-bacteria synergy.

Across the four mechanical indicators, the proportional 28-day gain is largest for compressive strength and progressively smaller for split tensile strength, flexural strength and static elastic modulus. This pattern indicates that the formulation changes affect the measured strength response more strongly than the measured stiffness response. The lower means for NS1.5B7 relative to NS1.5B6 may reflect formulation-dependent effects involving suspension content, workability, void structure or dispersion, but none of these mechanisms was measured directly; they remain hypotheses for future targeted testing.

3.9 Limitations and future work

The findings are limited to six formulations and a primarily mechanical test scope. The matrix lacks NS1.0-only, B7-only and nutrient-only controls, so additive and interaction effects are not fully isolated. PCE dosage varies by formulation and confounds direct attribution of fresh-state differences. Several reproducibility-critical metadata are absent from the retained record, including specimen geometry, replicate count, selected fresh-property standards, curing details, loading rates and bacterial-culture preparation/verification. The absence of specimen-level replicate data prevents inferential statistical testing. In addition, no SEM/EDS, XRD, TGA or pore-structure measurements were performed to verify proposed nano-silica or bacterial mechanisms, and durability/self-healing indicators such as sorptivity, permeability, chloride resistance, shrinkage, crack closure and bacterial viability were outside the dataset. Future work should use a factorial control matrix, a constant or explicitly target-based PCE strategy, independent-batch replication with specimen-level ANOVA/post-hoc analysis, verified bacterial concentration and culture records, microstructural characterization, and durability/self-healing testing.

4. Conclusions

1. Within the investigated formulations, nano-silica-containing mixtures showed the principal fresh-state trade-off as reduced slump (68-77 mm versus 94 mm for CC), while fresh density and air content varied over narrower ranges. Because PCE dosage also varied, these fresh-state differences are interpreted as formulation-level responses rather than isolated nano-silica effects.
2. NS1.5B6 exhibited the highest measured 28-day means for compressive strength (46.2 ± 0.8 MPa), split tensile strength (3.38 ± 0.20 MPa), flexural strength (5.35 ± 0.27 MPa) and static elastic modulus (34.8 ± 0.6 GPa). Relative to CC, the corresponding measured mean increases were 19.7%, 9.4%, 9.2% and 3.3%.
3. Compressive strength increased with curing age for all mixtures in the plotted dataset, and Figure 1 shows NS1.5B6 maintaining the highest plotted mean trajectory through 90 days. Because exact 7-, 56- and 90-day tabulated values and replicate counts are unavailable, later-age differences are interpreted descriptively rather than inferentially.
4. NS1.5B7 did not exceed NS1.5B6 in any reported mechanical mean, indicating that the measured response was not monotonic with the bacterial suspension concentration label within the 1.5% NS formulations. Without replicate-level inference and the missing B7-only and nutrient-only controls, this observation cannot be interpreted as a statistically demonstrated concentration optimum.
5. The study supports a descriptive formulation-level comparison, not a unique nano-silica-bacteria synergy. A stronger causal assessment requires NS1.0-only, B7-only and nutrient-only controls, controlled PCE strategy, independent-batch replication with inferential statistics, and direct microstructural and durability/self-healing verification.

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