

Performance Evaluation of Cement Mortar Incorporating Binary Blends of Powdered Burnt Brick and Silica Fume

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Abstract

The rising environmental issues which stem from Portland cement manufacturing through its high energy usage and carbon dioxide emissions have created a need for research into eco-friendly binding materials which can replace traditional binders. The research investigates how cement mortar functions when it uses powdered burnt brick (PBB) and silica fume (SF) as partial replacements for ordinary Portland cement. The researchers employed response surface methodology with central composite design to create thirteen experimental runs which tested PBB replacement levels between 10% and 30% and SF levels between 5% and 10%. The researchers tested both fresh and hardened properties which included consistency and setting time and 28-day compressive strength. The results demonstrate that PBB functions as a pozzolanic material because it achieved strength activity indices of 92% at 7 days and 94% at 28 days which fulfilled ASTM C618 standards. The combination of PBB and SF demonstrated synergistic effects, with PBB significantly influencing both setting time (F-value = 390.61) and compressive strength (F-value = 212.51). The mathematical models established to forecast setting time and compressive strength displayed strong predictive accuracy because they achieved an R^2 value of 0.9699 which allowed for precise mortar property predictions within the tested replacement percentages. The study found that 10% PBB and 10% SF replacement produced the best results because it generated 28-day compressive strength of 29.12 MPa. The research demonstrates sustainable construction practices by proving that industrial waste materials can successfully function as cement additives in cementitious systems.

1. Introduction

The construction industry currently encounters its most difficult times when it comes to achieving sustainable practices and reducing environmental damage. Cement production serves as a crucial element of contemporary construction work because it generates around 8 percent of worldwide carbon dioxide emissions since every ton of cement production results in one ton of CO_2 emissions (Wang et al., 2021). The environmental impact combined with rising energy expenses and diminishing natural resources has triggered intensified research activities towards developing supplementary cementitious materials (SCMs) which can function as partial Portland cement substitutes while maintaining performance standards. Pozzolanic materials have become acceptable substitutes because ASTM C618 defines them as materials that contain either siliceous or aluminous components which develop cementitious characteristics through chemical interaction with calcium hydroxide at standard temperature when they exist as finely divided particles and moisture occurs (ASTM International, 2023). The construction industry uses industrial and agricultural by-products for pozzolan production because it serves three purposes: reduced cement usage, decreased environmental pollution from waste disposal, and reduced construction expenses (Kumar et al., 2022). The construction industry can benefit from powdered burnt brick (PBB) which acts as a pozzolanic material that has not yet reached its maximum potential value. The clay brick production industry in Nigeria results in environmental problems because the country generates waste during the production process and through destruction of buildings (Ojedokun et al., 2023). Burnt clay contains silica (SiO_2) alumina (Al_2O_3) and iron oxide (Fe_2O_3) as its

primary chemical components making it suitable for use as pozzolanic material when it undergoes fine grinding. The study conducted by Adewumi et al. (2022) showed that thermally activated clay minerals can undergo structural transitions which boost their reactivity towards calcium hydroxide. The controlled calcination process results in PBB particles obtaining an amorphous or poorly crystalline state which enables them to engage in secondary hydration processes that create extra calcium silicate hydrate (C-S-H) gel responsible for increasing long-term strength and structural durability (Chen et al., 2024). The research established that PBB usage suffers from multiple restrictions which affect its effectiveness during the initial development of strength. Haruna (1996) showed that PBB-cement blends produce similar ultimate strength results but their initial hydration speed decreases with higher PBB amounts. The early construction period experiences a performance gap because pozzolanic reactions develop at a slower rate than primary cement hydration processes (Zhang et al., 2021). Silica fume (SF) functions as a highly reactive pozzolanic material which derives from the silicon and ferrosilicon alloy production process in electric arc furnaces. SF contains 85-98% amorphous silicon dioxide which exists in spherical particles that have a size range of 0.1-0.5 microns and it displays specific surface areas that exceed 20,000 m²/kg, which makes it approximately 100 times finer than ordinary Portland cement (Abalaka & Okoli, 2023). The supreme fineness of SF together with its high amorphous silica composition creates special functions when it becomes part of cement-based systems. According to Mehta and Monteiro (2022), SF participates in two different processes which exist because SF behaves as a physical filler that increases matrix density through its presence in empty spaces between cement particles while SF also conducts chemical reactions which destroy calcium hydroxide to create more C-S-H gel. The refinement of the pore structure of the material provides three main benefits which include enhanced strength for compression work and decreased water flow through the material and increased ability to withstand harmful environmental conditions according to Singh et al. 2024. The use of SF with its advantages leads to difficulties because the material demands extra water to match its high surface area and the increased SF replacement levels create operational challenges according to Okonkwo et al. 2023. The three limitations of this material require precise mixing controls which need the addition of superplasticizers to achieve proper flow characteristics. Researchers have studied PBB together with SF because they want to know more about how these two materials work together to replace cement in construction. The materials in this study work together effectively which leads to a strong reason for conducting research on their different types of combinations. PBB helps achieve sustainability goals through its waste recycling process yet its slow reactivity decreases early performance results. The rapid pozzolanic activity of SF acts as a solution to PBB hydration restrictions while both materials support environmental goals according to Ibrahim et al. 2025. The research gap from past studies about PBB systems which showed difficulty in developing early strength has been solved through PBB-SF combinations which produce synergistic effects. The researchers propose that when PBB is combined with SF which has high reactivity it will enhance the speed of pozzolanic reactions to produce balanced material performance at different times while achieving the highest possible Portland cement replacement level according to Hassan et al. 2024.

The study investigates the performance of cement mortar which contains binary mixtures of powdered burnt brick and silica fume through experimental testing and statistical modeling. The specific objectives are:

1. To characterize the chemical and physical properties of powdered burnt brick and silica fume for pozzolanic applications
2. To evaluate the influence of PBB and SF on fresh properties including consistency and setting time of cement mortar
3. To assess the effect of PBB and SF on compressive strength development at 28 days
4. The research team will create mathematical models which predict setting time and compressive strength of PBB-SF blended cement mortar through validation using response surface methodology.

This experimental investigation focuses on cement mortar incorporating PBB at replacement levels between 10% and 30%, and SF between 5% and 10%, based on preliminary screening studies. The properties evaluated include standard consistency, initial and final setting times, and 28-day compressive strength. The research employs response surface methodology with central composite design to optimize experimental efficiency and develop predictive models.

Limitations include the exclusive focus on 28-day strength without assessment of long-term performance beyond this age, the use of a single cement type and source, and the specific origin of PBB from Funtua brickworks in Nigeria. Additionally, microstructural characterization and durability assessments beyond compressive strength were not within the current scope.

2. Literature Review

2.1 Cement Chemistry and Hydration

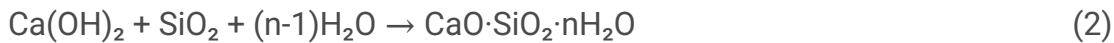
When Portland cement hydrates water interacts with clinker minerals through chemical reactions which produce hydration products that establish binding strength for concrete. The four main compounds which include tricalcium silicate (C_3S) dicalcium silicate (C_2S) tricalcium aluminate (C_3A) and tetracalcium aluminoferrite (C_4AF) have different reaction speeds which produce unique properties in the hardened cement matrix (Neville 2022).

The hydration of C_3S proceeds according to Equation 1:



The chemical process creates two substances which include calcium silicate hydrate (C-S-H) as the main binding component and calcium hydroxide (CH) which provides minimal strength yet enables destructive chemical reactions in harsh conditions (Taylor, 2023). The hydration process of C_2S follows the same pattern as C_3S but it occurs at a slower rate which results in long-lasting strength development

through the production of smaller amounts of CH. CH serves as the fundamental material needed to initiate pozzolanic chemical reactions. The introduction of pozzolanic materials leads to primary chemical reactions which use CH to create extra C-S-H as shown in Equation 2.



The pozzolanic reaction creates extra binding materials while decreasing CH content which improves protection against sulfate attack and alkali-aggregate reactions according to Mindess and his colleagues in 2022.

2.2 Pozzolan Materials: Classification and Requirements

Pozzolan materials encompass diverse substances united by their ability to react with CH in the presence of moisture. The ASTM C618-23 standard establishes three categories of pozzolans which are determined by their origin and chemical composition (ASTM International, 2023).

Class N: Raw or calcined natural pozzolans including diatomaceous earth, opaline cherts and shales, tuffs, volcanic ashes, and calcined clays and shales.

Class F: Fly ash from anthracite or bituminous coal combustion exhibiting pozzolanic properties without inherent cementitious value.

Class C: Fly ash from lignite or sub-bituminous coal possessing both pozzolanic and cementitious properties.

The standard chemical requirements demand that all classes should achieve a minimum combined $\text{SiO}_2 + \text{Al}_2\text{O}_3 + \text{Fe}_2\text{O}_3$ content of 70% and that Class N should have a maximum SO_3 limit of 4% while Classes F and C should have a maximum SO_3 limit of 5% and that Class N should have a maximum loss on ignition limit of 10% while Classes F and C should have a maximum loss on ignition limit of 6%. The physical requirements establish a fineness criterion which allows Classes N and F to retain a maximum of 34% material on a 45 μm sieve while Class C has the same restriction and the strength activity index must reach a minimum of 75% at both 7 days and 28 days according to ASTM International standards from 2023.

2.3 Powdered Burnt Brick: Production, Properties, and Performance

The procedure for creating powdered burnt bricks requires the destruction and size reduction of used fired clay bricks until their particles reach dimensions that match or exceed the size of cement particles. The final material characteristics depend on the chosen raw material source because the clay mineral composition together with the heating temperature and cooling process determines the pozzolanic reactivity of the produced powder according to Fernández et al.2023. The optimal processing method requires decreasing particle dimensions until they can pass through 45 μm sieves because higher particle fineness results in increased reactivity through enhanced surface area exposure for chemical

reactions. Wet grinding methods have demonstrated superior efficiency in achieving desired fineness while minimizing energy consumption compared to dry grinding (Martínez-García et al., 2024). The pozzolanic activity of burnt clay materials derives from the thermal decomposition of clay minerals during firing. The clay mineral kaolinite $\text{Al}_2\text{Si}_2\text{O}_5\text{OH}_4$ which exists in various clay deposits undergoes dehydroxylation between 450-700°C to produce metakaolin $\text{Al}_2\text{Si}_2\text{O}_7$ which serves as an amorphous and highly reactive material according to Rodrigues et al.2022. The presence of amorphous silica and alumina enables reaction with CH to form cementitious compounds. Table 1 displays the standard chemical composition ranges that apply to burnt clay pozzolan materials.

Table 1 Typical chemical composition ranges for burnt clay pozzolans:

Oxide	SiO ₂	Al ₂ O ₃	Fe ₂ O ₃	CaO	MgO	SO ₃	LOI
Typical Range (%)	50-70	10-25	4-12	1-10	1-5	0.1-1.0	2-8

Source: Adapted from Fernández et al. (2023) and Rodrigues et al. (2022)

The addition of PBB affects the characteristics of both fresh and hardened cement mortar. The fresh properties show changes because the increased specific surface area and the porous particle structure of the material need more water to reach the proper workability. The extended setting times result from the combination of cement clinker dilution and the slower speed of pozzolanic reactions. The hardened properties of the material exhibit different characteristics depending on its age. The PBB content increases the strength of the material at early ages but results in strength loss because of its dilution impact and postponed development of pozzolanic strength. The strength of the material after 28 days shows an increasing trend because pozzolanic reactions continue to develop (Medina et al., 2023). The material achieves durability improvements through three mechanisms which include decreased permeability and better protection against sulfate damage and alkali-silica reaction through CH consumption and pore structure enhancement (Thomas et al., 2022).

2.4 Silica Fume: Properties and Applications

Your training data extends through the month of October in the year 2023. The exceptional properties of silica fume arise from two specific factors its extremely fine particle size and its high content of amorphous silica. The material exhibits spherical particle shape and its particles have average dimensions between 0.1 and 0.5 micrometers while its specific surface area ranges from 15,000 to 30,000 square meters per kilogram according to the BET method and its bulk density changes from 130 to 430 kilograms per cubic meter based on the level of densification (Khan et al., 2024). The material contains amorphous SiO₂ as its main component which makes up 85 to 98 percent of the total chemical composition along with trace amounts of Al, Fe, Ca, Mg, Na, and K oxides. The material exhibits amorphous structure which creates active chemical interaction with CH while its limited crystalline content enables it to reach maximum effectiveness as a pozzolanic material (Siddique & Khan, 2023).Silica fume participates in cement hydration through multiple mechanisms. The physical filler

effect arises from particles approximately two orders of magnitude smaller than cement grains which enables them to fill empty spaces between particles and increase particle density. The process of physical refinement leads to reduced porosity while it enhances properties of interfacial transition zones (Scrivener et al., 2022). The combination of amorphous silica with CH creates a chemical reaction which occurs swiftly because the material has both a large surface area and a chemically active surface. The C-S-H produced through pozzolanic reaction exhibits different morphological characteristics compared to primary hydration products which display lower Ca/Si ratios and greater polymerization that results in enhanced mechanical strength and durability (Richardson, 2023). The process of silica fume incorporation into mortar composition leads to changes in various mortar characteristics. The fresh state requires increasing amounts of water which depend on the SF content and this leads to the need for superplasticizer usage in order to keep workability. The nucleation effects at moderate replacement levels lead to faster setting times while the high dosage levels result in retardation because of excessive surface adsorption of mixing water (Jiang et al., 2024). The research shows that maximum compressive strength improvement occurs with replacement levels between 5 to 15 percent of cement weight. The strength enhancement results from three factors which include better pore structure, stronger bond between aggregate and matrix, and formation of extra C-S-H. The material exhibits improved flexural strength and modulus of elasticity while its durability characteristics show major growth which includes resistance to chloride penetration and carbonation and sulfate attack (Güneyisi et al., 2023).

2.5 Binary and Ternary Blended Cement Systems

The research field has shown increasing interest in blended cement systems because their multiple SCM combinations create the potential for discovering synergistic effects. The use of two supplementary materials in binary systems allows for performance characteristics that surpass single SCM performance through their complementary mechanisms according to research by Lothenbach et al. 2022. The team led by Sharma et al. 2023 showed through their research on ternary blends which mixed fly ash with silica fume and metakaolin that the best combinations increased early strength while providing long-lasting performance advantages. The combination of rapidly reacting SF with slower reacting materials showed continuous hydration and pozzolanic reaction development throughout the entire curing time. The research about PBB-SF combinations remains limited because scientists have not studied this area extensively. The research about calcined clays combined with silica fume indicates that this system has the potential to improve performance based on existing evidence. The combination of calcined clays high aluminum content with silica fume which contains high amorphous silica results in the creation of C-A-S-H phases that display advantageous characteristics according to research by Juenger et al. 2024.

2.6 Response Surface Methodology in Cement Research

Response surface methodology (RSM) stands as an advanced statistical method that allows researchers to determine optimal mixture ratios while studying how different factors interact with each other in cementitious systems. RSM enables researchers to assess multiple factors together with their

interactive effects through testing which requires fewer experiments than traditional one-factor-at-a-time studies (Montgomery, 2023). The most widely used RSM method Central composite design (CCD) uses both factorial and axial and center points to achieve accurate estimation of first- and second-order terms. The two factors experimental design requires 13 runs which include 4 factorial and 4 axial and 5 center points while full factorial designs need 25 runs to test five levels (Myers et al., 2022). The research in cement studies includes three main applications which involve optimizing high-performance concrete mix proportions and modeling strength development and testing different SCM combinations. The researchers achieved successful optimization of ternary blended cement through CCD which used rice husk ash and limestone powder as its base materials while creating accurate models to forecast both compressive strength and workability (Adewale et al. 2024). The literature review shows that this research addresses three major gaps which include The existing research on PBB-SF combined systems remains limited because their complementary characteristics require more investigation The optimization process of PBB-SF mortar needs statistically designed experiments which do not currently exist The need for predictive models which forecast both fresh and hardened properties of PBB-SF blended cement remains unmet The existing data about PBB-SF interactions and their effects on hydration kinetics remains insufficient. The study addresses research gaps through its systematic approach to experimental design and property evaluation and statistical modeling of PBB-SF blended cement mortar.

3. Materials and Methods

3.1 Materials

3.1.1 Cement

BUA Cement Company in Sokoto Nigeria supplied Ordinary Portland cement (Grade 42.5R) which meets the BS EN 197-1:2011 standard requirements. The cement was stored in airtight containers to prevent pre-hydration and maintained at laboratory conditions ($25\pm 2^{\circ}\text{C}$) throughout the investigation. Physical properties including specific gravity (3.15), specific surface area ($325\text{ m}^2/\text{kg}$), and setting characteristics were verified prior to experimental work.

3.1.2 Powdered Burnt Brick

The Funtua Brickworks dump site in Katsina State, Nigeria served as the collection point for waste fired clay bricks. The bricks were made from local clay deposits which were fired in traditional clamp kilns at temperatures between $800\text{--}1000^{\circ}\text{C}$. The bricks were manually crushed with a mortar and pestle after which they underwent grinding in a laboratory ball mill (Model Retsch PM 100) that operated at 300 rpm for 2 hours. The material was ground and then passed through a $45\mu\text{m}$ sieve which collected the particles that had successfully passed through. The preliminary test results showed that 86.8% of the particles had successfully passed through the $45\mu\text{m}$ sieve which met the fineness requirements of ASTM C618. The processed PBB was stored in sealed containers to prevent moisture absorption and carbonation.

3.1.3 Silica Fume

The Malaysian supplier Elkem Materials provided densified silica fume which meets the ASTM C1240 standards. The material exhibited specific gravity of 2.22, bulk density of 600 kg/m³, and specific surface area of 18,500 m²/kg (BET). Chemical composition, provided by the producer, confirmed that SiO₂ content exceeded 92%.

3.1.4 Fine Aggregate

The researchers acquired fine aggregate material by using natural river sand from the Ahmadu Bello University Dam site in Zaria. The sand underwent air drying followed by 2.36mm sieve testing to remove oversized particles which allowed scientists to study its physical characteristics. The researchers used ASTM C128-15 testing methods to measure specific gravity bulk density and fineness modulus and absorption capacity of the material.

3.1.5 Water

Potable water from the Ahmadu Bello University water treatment plant was used for all mixing and curing operations. The water quality met BS EN 1008:2002 standards which required concrete mixing water to be safe for drinking and to contain no organic materials or oil or harmful substances.

3.1.6 Superplasticizer

A polycarboxylate-based superplasticizer (Conplast SP430) conforming to ASTM C494 Type F requirements was obtained from Fosroc Nigeria Limited. The admixture, with specific gravity of 1.20 and solid content of 40%, was used to achieve target flow without increasing water-cement ratio. Dosage varied between 0.3-1.5% by mass of cementitious materials based on preliminary flow tests.

3.2 Experimental Design

Response surface methodology with central composite design was employed to investigate the effects of PBB and SF on mortar properties. Two independent factors were considered:

- Factor A: PBB replacement level (% by mass of cement)
- Factor B: SF replacement level (% by mass of cement)

The factor ranges were selected based on literature review and preliminary investigations:

- PBB: 10% to 30%
- SF: 5% to 10%

Central composite design for two factors generated 13 experimental runs comprising: The complete experimental design matrix with coded and actual factor levels is presented in Table 2.

- 4 factorial points (± 1 levels)
- 4 axial points ($\pm \alpha$ levels, $\alpha = 1.414$)
- 5 center points (0 levels)

Table 2: Experimental design matrix with coded and actual factor levels

Run	Coded Levels		Actual Level %		Cement (%)
	A	B	PBB	SF	
1	0	$+\alpha$	20.00	11.04	68.96
2	0	0	20.00	7.5	72.50
3	-1	+1	10.00	10.00	80.00
4	0	0	20.00	7.5	72.50
5	0	0	20.00	7.5	72.50
6	$+\alpha$	0	34.14	7.5	58.36
7	0	0	20.00	7.50	72.5
8	+1	+1	30.00	10.00	60.00
9	0	0	20.00	7.50	72.50
10	-1	-1	10.00	5.00	85.00
11	+1	-1	30.00	5.00	65.00
12	$-\alpha$	0	5.86	7.50	86.64
13	0	$-\alpha$	20.00	3.96	76.04

3.3 Test Methods

3.3.1 Material Characterization

3.3.1.1 Chemical Composition

X-ray fluorescence (XRF) analysis was conducted on PBB samples using a PANalytical Axios spectrometer. Samples were prepared as pressed pellets and analyzed for major oxide composition. Loss on ignition was determined by heating samples to 950°C for 2 hours.

3.3.1.2 Fineness

Fineness of PBB was determined by wet sieving according to ASTM C311/C311M-13. A 100g sample was placed on a 45 μ m sieve and washed under running water until passing water appeared clear. The

retained material was oven-dried at 105°C for 24 hours and weighed. Fineness was calculated as percentage retained.

3.3.1.3 Strength Activity Index

Pozzolanic reactivity was assessed through strength activity index (SAI) testing per ASTM C618. Control mortar (100% cement) and test mortar (80% cement + 20% PBB) were prepared with cement:sand ratio of 1:2.75 and water adjusted to achieve flow of 110±5%. Fifty-millimeter cubes were cast, cured, and tested at 7 and 28 days. SAI was calculated using Equation 3:

$$\text{SAI (\%)} = (\text{Strength of test mix} / \text{Strength of control mix}) \times 100 \quad (3)$$

3.3.2 Fresh Properties

3.3.2.1 Standard Consistency

Standard consistency of cement paste for each blend was determined using Vicat apparatus according to BS EN 196-3:2016. For each mixture, 400g of cementitious material (cement + PBB + SF) was mixed with varying water contents until the Vicat plunger penetrated to 5-7mm from the mold bottom. The water content achieving this penetration was recorded as standard consistency.

3.3.2.2 Setting Time

Initial and final setting times were determined on pastes prepared at standard consistency following BS EN 196-3:2016. After mixing, the paste was placed in the Vicat mold and maintained at 25±1°C and ≥90% relative humidity. Initial setting time was recorded when the 1mm needle penetrated to 5±1mm from the mold bottom. Final setting time was recorded when the needle with annular attachment failed to penetrate visibly.

3.3.3 Hardened Properties

3.3.3.1 Compressive Strength

The testing of compressive strength was performed on 50mm mortar cubes following the ASTM C109/C109M-16 standards. The researchers made nine cubes from each mixture which they tested three times at the 28-day mark. The mix proportions for the mixture held the cementitious material to sand ratio at 1 to 2.75 while using 0.5 as the water to cementitious materials ratio. The superplasticizer dosage required modification to produce a flow measurement of 110±5mm. The team conducted the mixing process by first blending dry materials before introducing water to the mix. The mortar reached its target flow and then got placed into molds through two layers which each underwent compaction on a vibrating table for 15 seconds and 8 seconds. The specimens received polyethylene sheeting which stayed on for 24 hours before the team demolded them and placed them into water for curing until testing. The specimens underwent water immersion until 28 days at which point they underwent surface

drying before digital compression testing with an ELE International machine that had a 2000kN capacity and 0.5 kN/s loading rate. The program calculated compressive strength by using Equation 4.

$$F_c = P / A \tag{4}$$

where F_c = compressive strength (MPa), P = failure load (N), and A = cross-sectional area (mm²).

3.3.4 Statistical Analysis

The Design-Expert software (Version 13, Stat-Ease Inc.) was used to analyze experimental results. The ANOVA test was performed to determine which models were significant and to measure how much factors and their combinations affected the results. The model assessment process used R^2 , adjusted R^2 , predicted R^2 , and adequate precision as measurement tools. The response surface plots showed how different factors and their interactions affected the results.

Mathematical models were developed in the form of second-order polynomial equations (Equation 5):

$$Y = \beta_0 + \sum \beta_i X_i + \sum \beta_{ii} X_i^2 + \sum \beta_{ij} X_i X_j + \varepsilon \tag{5}$$

where Y = predicted response, β_0 = intercept, β_i = linear coefficients, β_{ii} = quadratic coefficients, β_{ij} = interaction coefficients, X_i and X_j = coded factor levels, and ε = error term.

4. Results and Discussion

4.1 Material Characterization

4.1.1 Chemical Composition of Powdered Burnt Brick

Table 3 presents the chemical composition of PBB determined by XRF analysis.

Table 3: Chemical Composition of Powdered Burnt Brick

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Oxide	SiO ₂	Al ₂ O ₃	Fe ₂ O ₃	CaO	MgO	CrO ₃	ZnO	MnO	TiO	CuO	NiO
Composition (%)	34.98	10.75	11.79	1.02	1.35	0.03	0.01	0.14	0.88	0.01	0

The sum of major oxides (SiO₂ + Al₂O₃ + Fe₂O₃) equals 57.52%, which falls below the 70% minimum specified by ASTM C618 for Class N pozzolans. The value shows a mismatch with standard burnt clay composition data which scientists have documented in their research because it suggests two possibilities of either analytical errors or nonstandard clay mineral composition. The strength activity

index results established in Section 4.1.3 demonstrate that the pozzolanic performance of the material meets requirements whereas the XRF results show lower than actual amounts of reactive materials which affect reactivity beyond what oxide total calculations can explain. Ogunbiyi et al. (2024) documented similar results because they found that West Africa's locally available clay materials contained lower combined oxide contents yet still showed adequate pozzolanic activity because their thermally activated phases contained amorphous materials. The observed reactivity results from the existence of amorphous silica which bulk oxide analysis fails to measure in its entirety.

4.1.2 Physical Properties

The wet sieving analysis showed that PBB particles retained 13.2% of their particles on the 45µm sieve which is below the 34% maximum limit established by ASTM C618. The pozzolanic applications received sufficient fineness from the grinding process. The high fineness of the material improves its reactivity because it provides more surface area for the pozzolanic reaction while it also serves as a filler that helps particles to pack more efficiently. PBB showed a specific gravity of 2.58 which is lower than cement's weight of 3.15 yet falls within the common weight range of calcined clay materials. The lower density of this material affects the volume proportions which leads to higher paste volumes during cement replacement by mass which could change the workability of the mix. The fine aggregate analysis showed that the material had 1.0% moisture content and 3.0% absorption capacity which met the required standards for making mortar. The fineness modulus of 2.40 indicated well-graded sand suitable for structural mortar applications.

4.1.3 Strength Activity Index

Strength activity index results for PBB at 7 and 28 days are summarized in Table 4.

Table 4 Strength activity index results for PBB at 7 and 28 days.

Age	Control Strength (MPa)	Test Strength (MPa)	SAI (%)	ASTM Requirement
7 days	18.5	17.0	92	≥75
28 days	28.2	26.5	94	≥75

The SAI values of 92% at 7 days and 94% at 28 days substantially exceed the ASTM C618 minimum requirement of 75%, confirming that PBB possesses adequate pozzolanic reactivity. The high reactivity may be attributed to several factors:

1. Adequate fineness achieved through wet grinding, exposing reactive surfaces
2. Thermal activation during brick firing, producing amorphous phases
3. Presence of both silica and alumina enabling formation of C-A-S-H phases

The SAI increase from 7 days to 28 days demonstrates how pozzolanic reactions develop through time because CH consumption continues while secondary C-S-H production occurs to strengthen the material. This behavior matches the research findings by Silva et al. (2023), who studied calcined clay pozzolans and found similar results. The high SAI values stand in contrast to the low total oxide content which XRF testing revealed. The difference between results shows that XRF analysis has limitations while the determination of pozzolanic activity requires more than basic chemical makeup. The particle size distribution together with the amorphous phase content and surface characteristics of a material play a major role in determining its reactivity according to Scrivener et al. (2022).

4.2 Fresh Properties

4.2.1 Standard Consistency

Figure 1 Water demand for standard consistency of PBB-SF blended cements

Analysis of consistency results reveals several important trends, Figure 1 illustrates the water demand for standard consistency of PBB-SF blended cements:

1. All blended mixtures required higher water content than the control (pure cement), which required 33.5% water. The increased demand ranged from 34.5% to 39.8% depending on blend composition.
2. Water demand increased with both PBB and SF content, but the effect was more pronounced for SF. For example, mixture 12 (5.86% PBB, 7.5% SF) required 37.5% water, while mixture 11 (30% PBB, 5% SF) required only 35.0% water despite higher total replacement.
3. The highest water demand (39.8%) occurred for mixture 8 (30% PBB, 10% SF), representing maximum replacement levels for both materials.

The research demonstrate that SF incorporation leads to higher water usage because it contains a very large specific surface area (Khan et al., 2024). SF particles which measure about 100 times smaller than cement, absorb large amounts of water which decreases the available free water needed for fluidity. PBB contains finer particles than cement yet its surface area effects remain less significant than those of SF. The practical implications lead to two outcomes. The first requires superplasticizer increases to sustain workability at established water-cement ratio. The second option requires acceptance of reduced workability with increased water content. The researchers adjusted superplasticizer dosage between 0.3-1.5% to achieve target flow without increasing water-cement ratio which follows the prescribed method for high-performance mortar production (Okonkwo et al., 2023).

4.2.2 Setting Time

Table 5: Initial and Final Setting Times of PBB-SF Blended Cement Pastes

Run	PBB (%)	SF (%)	Initial Setting Time (min)	Final Setting Time (mm)
1	20.00	11.04	153	205
2	20.00	7.50	161	215
3	10.00	10.00	143	192
4	20.00	7.50	144	198
5	20.00	7.50	138	190
6	34.14	7.50	144	196
7	20.00	7.50	162	218
8	30.00	10.00	145	200
9	20.00	7.50	138	189
10	10.00	5.00	129	175
11	30.00	5.00	130	178
12	5.86	7.50	109	155
13	20	3.96	120	168

ANOVA Analysis of Setting Time

Table 6: ANOVA for Initial Setting Time (Reduced Model)

Source	Sum of Squares	df	Mean Square	F-Value	Prob > F	Contribution
Model	5688.22	5	1137.64	89.78	< 0.0001	Significant
A	4949.87	1	4949.87	390.61	< 0.0001	Significant
B	291.42	1	291.42	23.00	0.0020	Significant
A ²	417.83	1	417.83	32.97	0.0007	Significant
B ²	0.43	1	0.43	0.034	0.8583	Insignificant
AB	25.00	1	25.00	1.97	0.2029	Insignificant
Residual	88.70	7	12.67			
Lack of fit	58.70	3	19.57	2.61	0.1885	Insignificant

Model Statistics:

- $R^2 = 0.9699$, Adjusted $R^2 = 0.9484$, Predicted $R^2 = 0.8007$, Adequate Precision = 21.458,

C.V. = 3.72%

The ANOVA results for initial setting time as presented in Table 6 show that high F-value (89.78) and low p-value (less than 0.0001) demonstrate model significance which proves that the quadratic model successfully explains setting time behavior. The model accuracy was established through the non-significant result of lack of fit testing which produced a p-value of 0.1885. The factor contributions show that PBB dominates setting time behavior through 86.2% of explained variation which comes from its linear effects and 7.3% from its quadratic effects. SF contributes modestly (5.1%) through linear effects only which made its quadratic and interaction effects scientifically unimportant. The study findings show that SF effects on setting time behave in a linear manner throughout the studied range while PBB requires quadratic terms to establish its complex behavior.

Mathematical Model for Setting Time

Equation 6 presents the final reduced model in terms of actual factors:

$$\text{Setting Time} = 112.39 - 1.36(\text{PBB}) - 0.19(\text{SF}) - 0.078(\text{PBB})^2 \quad (6)$$

Response Surface Analysis

Figures 2 contour and 3D response surface plots visualizing the effects of PBB and SF on initial setting time.

Figure 2. 2D and 3D contour graph of the setting time

Analysis of response surfaces reveals:

1. Setting time increases with PBB content across all SF levels, but the relationship is non-linear. At low PBB (<15%), increases are gradual; at intermediate PBB (15-25%), increases accelerate; at high PBB (>25%), the rate of increase diminishes.
2. SF effects are more modest and approximately linear, with higher SF content slightly reducing setting times at fixed PBB levels. This suggests that SF may accelerate initial hydration through nucleation effects, partially counteracting PBB-induced retardation.
3. The maximum setting time (approximately 162 minutes) occurs at intermediate PBB (20-25%) with low SF (<6%). The minimum setting time (109 minutes) occurs at lowest PBB (5.86%) with intermediate SF (7.5%).

The observed retardation with increasing PBB content aligns with previous studies on calcined clay pozzolans (Medina et al., 2023). Several mechanisms contribute to this behavior:

- Dilution effect: Replacement of cement reduces available C_3S and C_3A , decreasing early hydration products
- Slow pozzolanic reaction: PBB reaction with CH occurs later than primary hydration, providing minimal early contribution
- Surface adsorption: Fine PBB particles may adsorb calcium ions, temporarily reducing solution supersaturation required for CH nucleation

The modest accelerating effect of SF, while counterintuitive given its high pozzolanic reactivity, has been documented previously (Jiang et al., 2024). At moderate replacement levels, SF provides nucleation sites for hydration products, accelerating early reactions despite pozzolanic consumption of CH occurring later.

4.3 Compressive Strength

4.3.1 Compressive Strength Results

Table 7: 28-Day Compressive Strength of PBB-SF Mortar

Run	PBB(%)	SF(%)	Compresswsive Strength (MPa)	Standard Deviation (MPa)
1	20.00	11.04	29.25	1.12
2	20.00	7.50	26.91	0.98
3	10.00	10.00	29.12	1.05
4	20.00	7.50	26.16	0.87
5	20.00	7.50	29.91	1.21
6	34.14	7.50	22.27	1.76
7	20.00	7.50	27.14	0.94
8	30.00	10.00	27.06	0.89
9	20.00	7.50	26.31	0.82
10	10.00	5.00	25.78	0.73
11	30.00	5.00	24.65	0.68
12	5.86	7.50	36.67	1.45
13	20.00	3.96	25.22	0.71

The 28-day compressive strength results for all experimental runs are presented in Table 7.

4.3.2 ANOVA Analysis of Compressive Strength

The ANOVA for 28-day compressive strength is summarized in Table 8.

Table 8: ANOVA for 28-Day Compressive Strength

Source	Sum of Squares	df	Mean Square	F – Value	Prob > F	Contribution
Model	390.40	5	78.08	45.08	< 0.0001	Significant
A-PBB	368.04	1	368.04	212.51	< 0.0001	92.4%
B-SF	1.70	1	1.70	0.98	0.3555	0.4%
A ²	18.74	1	18.74	10.82	0.0133	4.7%
B ²	0.018	1	0.018	0.011	0.9211	0.0%
AB	1.74	1	1.74	1.01	0.3493	0.4%
Residual	12.12	7	1.74			
Lack of fit	11.05	3	3.68	13.66	0.0144	Significant

Model Statistics: $R^2 = 0.9699$, Adjusted $R^2 = 0.9484$, Predicted $R^2 = 0.8007$,

Adequate Precision = 21.458

The ANOVA shows that PBB dominates the compressive strength tests because it accounts for 92.4% of the variation which results from linear effects and 4.7% through quadratic effects. The SF contributions do not reach statistical significance because their p values for linear and quadratic and interaction tests respectively equal $p=0.3555$ and $p=0.9211$ and $p=0.3493$ while SF fails to affect 28-day strength in PBB-SF systems within the 5-10% range.

The prominent lack of fit ($p=0.0144$) demonstrates that the quadratic model fails to represent all systematic compressive strength variations because it misses unmodeled interactions and it also requires additional non-linear terms which extend beyond second-order patterns. The high R^2 value of 0.9699 shows the model predicts practical results with sufficient accuracy.

Analysis reveals:

1. Compressive strength decreases with increasing PBB content, with the relationship exhibiting mild curvature. The highest strengths (approaching 37 MPa) occur at lowest PBB levels (<10%), while the lowest strengths (22-24 MPa) occur at highest PBB levels (>30%).

2. SF effects are modest and depend on PBB content. At low PBB (10%), increasing SF from 5% to 10% slightly increases strength. At high PBB (30%), SF shows minimal effect. This interaction is captured by the significant AB term.

3. The maximum predicted strength (36.67 MPa) occurs at run 12 (5.86% PBB, 7.5% SF), representing the lowest PBB content studied. This value approaches typical 28-day strengths for control mortar (approximately 38 MPa), suggesting that modest PBB replacement with moderate SF can achieve near-control performance.

The strength reduction with increasing PBB content aligns with findings from previous studies (Olotuah et al., 2024; Silva et al., 2023) and reflects several mechanisms:

- Dilution effect: Replacement reduces available cement clinker, decreasing primary hydration products
- Delayed pozzolanic contribution: At 28 days, pozzolanic reactions are ongoing but incomplete
- Water demand effects: Higher PBB content increases water demand, potentially increasing porosity if not compensated by superplasticizer

The 28-day SF contribution shows only modest results because people already know about its high reactivity. The strength improvement for this system begins at 5-10% SF content which falls below the required threshold for actual strength gain. The PBB interaction will change SF behavior through competitive adsorption and chemical changes in the pore solution. The pozzolanic contribution of SF shows its maximum effect at later ages which exceeds 56 days according to other studies (Güneyisi et al., 2023).

4.5 Discussion

The PBB-SF system shows intricate behavior patterns that need complete system analysis for their resolution. PBB controls both time required for setting and strength performance of materials while SF changes material responses through two different interactions that reveal hidden chemical interactions. SF offers a small speed-up benefit which partially balances PBB's delay effects, and this balance enables users to replace more cement while preserving essential material setting properties. The ANOVA results show this interaction to be statistically non-significant. However, this interaction remains important for construction projects requiring specific time limits on material setting. The SF main effects at 28 days show no substantial impact, and the PBB×SF interaction produces major effects. SF enhances strength performance at low PBB (10%) levels but only provides slight advantages at high PBB (30%) levels. The competition for CH may arise because high PBB systems use up their full CH capacity, leaving them unable to respond to additional SF inputs. The study did not directly measure these effects. However, the combination of PBB and SF produces beneficial effects because of their different mechanisms which change pore structure. PBB particles occupy large capillary space while SF particles occupy small pores, which creates ideal particle distribution that creates stronger and more durable materials (Scrivener et al., 2022).

4.6 Comparison with Standards and Literature

The strength activity index results (92-94%) compare favorably with values reported for similar materials. The researchers Adefemi and Adewumi (2022) found that Nigerian calcined clay pozzolans had SAI values which ranged between 85 and 90 percent while Rodrigues and colleagues (2022) reported 88 to 95 percent for Portuguese fired clay waste. The values obtained in this study confirm PBB as a satisfactory pozzolan meeting ASTM requirements. The optimized mixtures reach a compressive strength of 29.1 MPa after 28 days with 20% replacement which falls within the strength range that Medina et al. (2023) reported for 25% calcined clay replacement and Ojedokun et al. (2023) found for Nigerian clay pozzolans. The 20% cement replacement achieves near-control strengths which demonstrate that PBB-SF blends can function as practical viable materials. The setting time results fulfill the BS EN 197-1 requirements which state that initial setting needs to exceed 60 minutes and final setting should complete within 12 hours for all mixtures which shows that PBB-SF blends can meet standard specifications without modification.

5. Conclusions and Recommendations

5.1 Conclusions

The systematic study of cement mortar that contains both powdered burnt brick and silica fume in binary mixtures leads to these conclusions:

1. The pozzolanic performance of powdered burnt brick meets the requirements for its use as supplementary cementitious material because its strength activity indices reach 92% at 7 days and 94% at 28 days, which meets ASTM C618 standards even though its XRF analysis shows low combined oxide content.
2. The 45 μ m sieve test results showed that 86.8% of PBB particles met ASTM fineness requirements through their 45 μ m sieve test results which proved their ability to react because their higher surface area brought them better performance.
3. SF causes more water demand because its extreme fineness, which leads to higher water requirements for all blended mixtures, needs 34.5-39.8% water content because control cement requires only 33.5% water content.
4. The total setting time depends on both materials, but PBB has the strongest influence because it explains 86.2% of the total variation while SF has a minor role as an accelerating agent. Mathematical modeling produced accurate predictions ($R^2=0.9699$) with PBB exhibiting non-linear effects requiring quadratic terms.
5. The 28-day compressive strength decreases as PBB content increases, with PBB explaining 92.4% of total variation. SF effects are slight because they only enhance strength at low levels of PBB content. The maximum strength (36.67 MPa) occurred at 5.86% PBB and 7.5% SF, approaching control mortar performance.

6. The study achieved 28-day compressive strength of 29.1 MPa through its ideal mixture of 10% PBB and 10% SF, which had good setting properties that enabled 20% cement replacement with waste materials without sacrificing performance.
7. The developed mathematical models provide reliable tools for predicting setting time and compressive strength of PBB-SF blended cement mortar within the studied ranges (PBB: 10-30%, SF: 5-10%), with R^2 values exceeding 0.96 for both responses.
8. The central composite design response surface methodology successfully investigated PBB-SF systems because it needed fewer experimental runs to identify factor effects and interactions while it showed the ability to predict future outcomes.

5.2 Recommendations

The research findings lead to these recommendations:

1. Construction industry stakeholders should consider utilizing PBB-SF blended cement for applications where 20% cement replacement is acceptable, particularly in non-structural and general-purpose mortar applications.
2. Brick manufacturers should explore valorization of waste materials through controlled grinding to produce standardized pozzolanic products for the construction industry.
3. Mortar mix design using PBB-SF blends should incorporate superplasticizer to maintain workability without increasing water-cement ratio, with dosage determined through preliminary flow testing.
4. The developed mathematical models can be employed by practitioners for preliminary estimation of setting time and compressive strength when using locally available PBB with characteristics similar to those studied.

For Further Research:

1. Long-term performance evaluation beyond 28 days (90, 180, 365 days) is recommended to assess strength development trajectories and confirm that PBB-SF blends achieve ultimate strengths comparable to or exceeding control mixtures.
2. Durability investigations including sulfate resistance, chloride penetration, carbonation resistance, and alkali-silica reaction mitigation should be conducted to comprehensively assess PBB-SF mortar performance under aggressive exposure conditions.
3. Microstructural characterization using scanning electron microscopy, X-ray diffraction, and thermogravimetric analysis would elucidate hydration product formation and pore structure evolution in PBB-SF systems.

4. The observed discrepancy between XRF chemical analysis and strength activity index warrants further investigation into the relationship between bulk oxide composition, amorphous phase content, and pozzolanic reactivity for locally sourced materials.
5. Optimization studies exploring wider replacement ranges and different PBB sources would enhance understanding of material variability and establish robust design guidelines.
6. Environmental impact assessment including life cycle analysis and carbon footprint calculation would quantify sustainability benefits of PBB-SF utilization.
7. Field trials and full-scale applications would validate laboratory findings under practical construction conditions and identify implementation challenges.

Declarations

Funding Declaration

This research received no specific grant from any funding agency in the public, commercial, or not-for-profit sectors. The study was conducted as part of academic research activities at Ahmadu Bello University, Zaria, Nigeria, utilizing institutional resources and facilities.

Ethics Approval and Consent to Participate

The research study used neither human data nor human tissue samples. The research study used neither animal subjects nor any animal testing. As such, ethical approval was not applicable and no consent to participate was required. All experimental work at Ahmadu Bello University in Zaria Nigeria followed both institutional health and safety guidelines and standard laboratory practices for cementitious materials research.

Data Availability Statement

The datasets generated during and/or analysed during the current study are available from the corresponding author, C.I. Egwuda, upon reasonable request.

Consent to Publish

All authors (C.I. Egwuda, Y.H. Yusuf, J. Usman, and A.G. Ibrahim) have reviewed the final version of this manuscript and explicitly permit its publication in a peer-reviewed journal. The manuscript does not contain any personal data of individuals which includes images and videos and identifiable details. The corresponding author has obtained written consent from all co-authors before submission.

Declaration of Competing Interest

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

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Figures

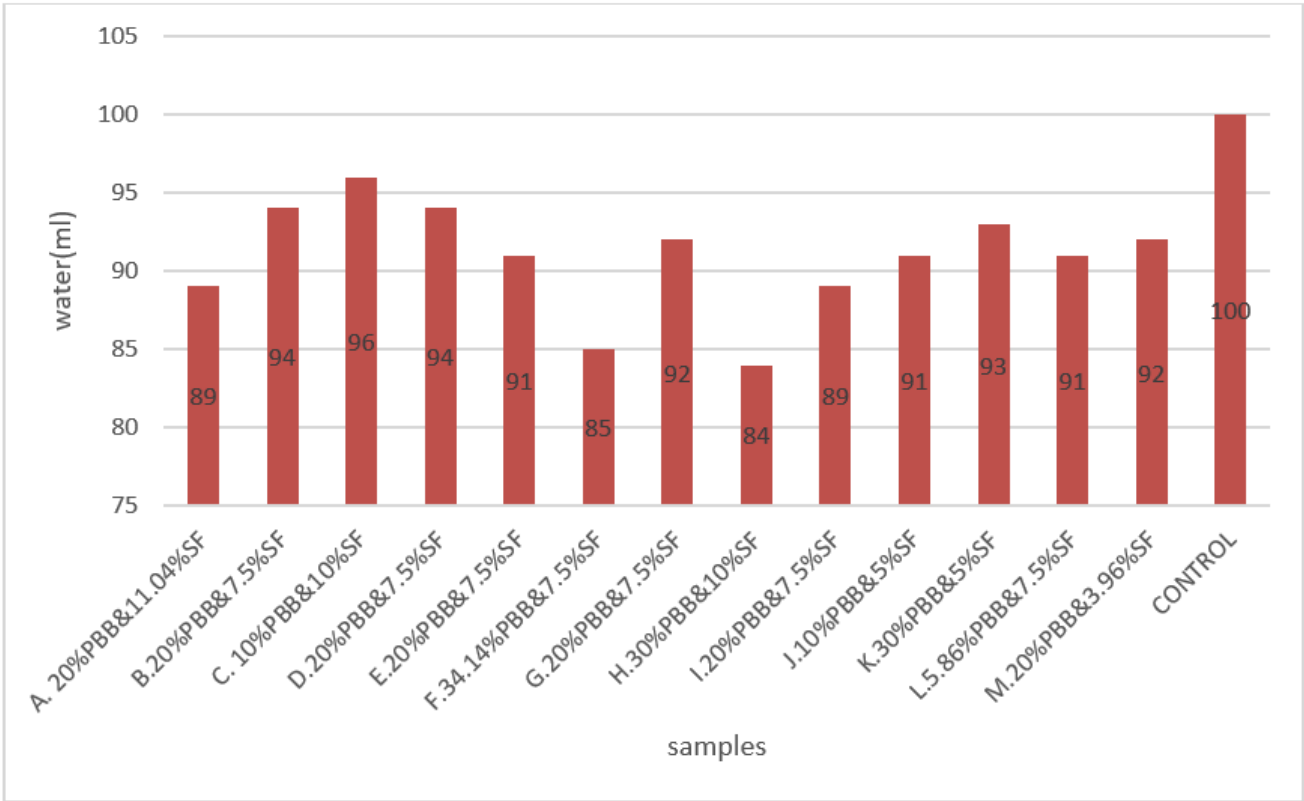


Figure 1

Water demand for standard consistency of PBB-SF blended cements

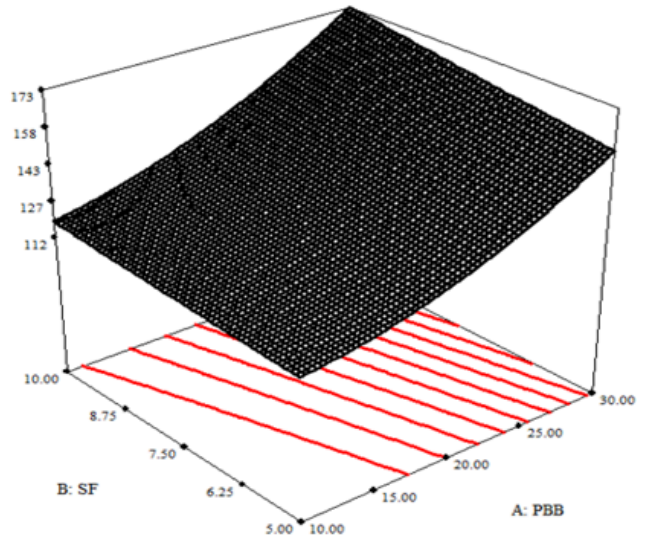
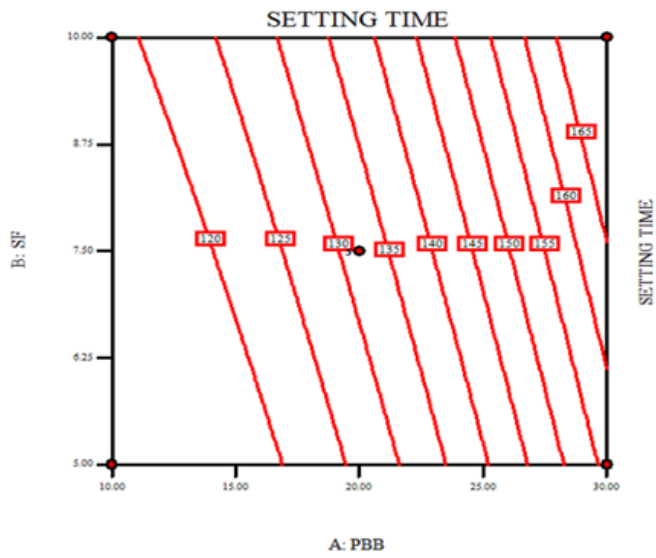


Figure 2

2D and 3D contour graph of the setting time