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Response Surface Methodology and Statistical Investigation of the Strength of Bituminous Sandcrete Blocks

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Abstract Spalling is a serviceability related defect in buildings that degrades their appearance and if unchecked, could be a threat to building sustainability and lead to structural failures. It is associated with the effect of moisture on the building especially the blockwall. This research focuses on the production of low water-absorption Sandcrete blocks. The water absorption and compressive strength of blocks using bitumen as a coat and as part of the sandcrete mix are investigated. In assessing the outcome, eight (8) different sets of Sandcrete blocks with varying bitumen contents were defined and nine (9) samples of standard six (6) inches blocks were produced for each set, with three (3) samples per set being tested at 7,14 and 28 days for water absorption and compressive strength respectively. The water sprinkling curing method was used at 24 hours intervals. The results acquired showed that the sets that contained bitumen showed reduced water absorption rates up to 4.06% at 28 days relative to the control samples. The analysis of the experimental result was done using response surface methodology, the percentage of bitumen replacement with sand and curing days was used as the independent variable. Multiple regression equation was obtained to predict investigated properties. Further analysis of the data shows that Sandcrete blocks coated externally with bitumen give the optimum performance in terms of compressive strength and water absorption.

Keywords Spalling, Sandcrete Blocks, Bitumen, Response Surface Methodology, Structural Integrity, Civil Engineering

1. Introduction

Sandcrete blocks are one of the most commonly used masonry units in the construction industry with about 90% of the homes in Nigeria utilizing them in their construction [1–6]. Sandcrete blocks can be categorized generally as solid and hollow blocks, hollow blocks are the most common of the two types [7]. In Nigeria, Sandcrete blocks are of two standard sizes ($450mm \times 225mm \times 225mm\ and\ 450mm \times 225mm \times 150mm$) while solid blocks are of 100mm and 150mm thicknesses [8–11]. From housing to fencing, Sandcrete blocks proffer various uses and applications in the construction industry [12–17]. Over the years, there has been an increment in the occurrence of construction failures in Nigeria, with an approximate number of 54 recorded building collapses in the space of 2012-2016 [18] and tens of others between 2016 and 2020 [19–25]. From investigations, it was suspected that some of the causes for the damage were due to the use of poor quality materials in the construction process [26–29]. Quality control in construction has become a major requirement for projects in the 21st century [30–39]. Lack of quality control in construction not only leads to an increase in maintenance cost and the general cost of these projects, but the projects also become risky to the wellbeing of the public [40–43]. Spalling is one of the main sandcrete block failures encountered in structures, spalling is a form of surface degradation that happens as materials such as concrete, brick or limestone are exposed to excess moisture, decay, weathering and much more [44]. Concrete spalling also known as concrete cancer is an eye-sore that can become a hazard if left untreated and exposed to the structural parts, it can cause extensive structural damage and may cause it to break away from the façade, potentially injuring the public and damaging property [45,46]. At earlier stages, Sandcrete blocks were produced without any form of regulation or requirement. To control the situation, the Standard Organization of Nigeria (SON) released NIS 87:2000[47] for the regulation of all construction activities which then created a specification, thereby ensuring quality control [48]. The compressive strength of the blocks is one of the main determinants for their application and should conform to the required standards [49], much so that according to the Nigerian Industrial Standard, hollows blocks should have a minimum strength of 1.8N/mm^2 at seven days and a minimum of 2.5N/mm^2 – 3.45N/mm^2 at twenty-eight days [1,47]. The key properties for Sandcrete blocks that affect their performance are their moisture content, compressive strength, water absorption rate and permeability [8] and it has been established that there is a relationship between the compressive strength and water absorption rate of Sandcrete blocks [50]. Spalling occurs when there is a dislodgment of aggregates from the surface of a concrete or Sandcrete material due to the continuous passage of water through such locations [51], hence the use of a water-resistant material like bitumen could help prevent spalling from occurring. Bitumen is the heaviest residue left behind after the destructive distillation of crude oil and is the most commonly used binding agent in the transportation industry [52–55]. Bitumen as a material possesses water-resistant qualities which work efficiently when used on the surface of Sandcrete blocks [56–59]. Previous studies have been carried out on the effects that occur due to the reactions between bitumen and cement for asphalt production [60-71] where it was observed that the two materials complement each other's properties under controlled conditions. This research seeks to investigate the performance of newly produced Sandcrete blocks when the bitumen is used as an additive in the mix itself rather than as an external coating. The response surface methodology was used to analyze experimental data obtained in respective to the mixing process. The independent variables considered in the analysis were the percentage of bitumen replacement with sand and curing days. The effect of these independent variables on the compressive strength and water absorption properties of sandcrete blocks was investigated. The RSM analysis aims to obtain a multiple regression equation that will predict investigated properties at curing days between 7 to 28 days and percentage bitumen replacement with sand between 0 and 10% regardless of the method of preparation.

2. Materials and Methods

Well-grained sharp sand was used for this research purpose mixed with the Dangote brand of Ordinary Portland cement. The properties of the bitumen used are as presented in Table 1. Industrial grade 6" Sandcrete blocks ($450mm\ x\ 150mm$) were produced. A mix ratio of 1(cement):6 (plaster sand) was used for the production of the blocks and a water-cement ratio of 0.9 is applied. The modified blocks were produced using variation in bitumen content by mass of the sand used in the blocks. Eight (8) variations were carried out during the production of the modified blocks with 9 blocks being produced per variation and all bitumen mixed in a hot state as shown in Table 2.

Table 1. Properties of Bitumen used.

Parameters	Average Value
Penetration (mm)	72
Softening (^{0}C)	58
Ductility (cm)	82
Viscosity (secs)	77
Flash Point (^{0}C)	275.67
Fire Point (^{0}C)	307.67
Specific Gravity	0.96
Loss on Heating (%)	0.86
Moisture Content (%)	0.00

Table 2. Experimental design

Block code	Mass of cement (kg)	Mass of sand (kg)	Mass of bitumen (kg)	Mass of water (kg)	Remark
C1	23	144	0	20.7	Control Sample
C2	23	144	0	20.7	Control Mix painted with Bitumen
R1	23	144	7.2	20.7	Bitumen (5% by weight of sand) mixed hot with half the quantity of the sand
R2	23	144	7.2	20.7	Bitumen (5% by weight of sand) mixed hot completely with sand
R3	23	144	14.4	20.7	Bitumen (10% by weight of sand) mixed hot with half the quantity of the sand
R4	23	144	14.4	20.7	Bitumen (10% by weight of sand) mixed hot completely with sand
PR1	23	144	2.07	18.63	10% of water replaced with Bitumen and mixed hot completely with sand
PR2	23	144	4.14	16.56	20% of water replaced with Bitumen and mixed hot completely with sand

Samples C1 are the control sample (industrial grade blocks) and C2are blocks coated externally with bitumen. R1 and R3 were produced with the bitumen mixed hot with half the quantity of the sand upon casting. The other half was mixed with cement before the two halves were finally mixed. Samples R2, R4, PR1 and PR2 were produced with the bitumen mixed hot completely with the sand. Mixing was carried out manually with the use of shovels. For samples containing bitumen, the emulsion was mixed with the sand first before other mixing occurred (Fig 1). A hand mould was used and mixing occurred manually. During production, compaction was done in two layers with the use of a trowel and by gravity (dropping the mould from a minimum height several times). The mould is made up of two parts, the receptacle and the prongs. After the mix was added into the mould and sufficient compaction had taken place, the whole mould was flipped over. The receptacle was carefully removed first ensuring that the block did not crumble in the process, then the prongs were also taken out to reveal the formed block. The curing process used was sprinkling. All blocks were placed on cellophane bags before curing. The blocks were sprinkled with water at 24-hour intervals. The Sandcrete blocks were tested for water absorption and compressive strength at 7, 14 and 28 days respectively.

(a)

(b)

Figure 1. (a) Hot Bitumen mixed with fine aggregate. (b) Sandcrete Blocks produced with sand mixed with bitumen

2.1. Water Absorption Test

The dry mass of the blocks was measured; this was achieved by leaving the blocks for 24hours to dry without exposure. The blocks were then kept in water for 24 hours after which they were taken out and weighed [72]. The water absorption of the blocks was determined by:

$$\text{Water absorption} = \frac{W_W - W_D}{V} X\, 100 \qquad (1)$$

Where W_w = wet weight of the block, W_D = dry weight of the block, V=volume of the block.

2.2. Compressive Strength Test

Each block was crushed using a 2000KN capacity compression machine. Wooden planks wide enough to encompass the gross area of the blocks were placed on the top and bottom of the blocks to facilitate uniform distribution of stress around the block area[73]. The metal plank placed atop the blocks provided a force of 4.6N. Compressive strength was calculated based on the Net and gross area of the block:

Based on the gross area, compressive strength$=\frac{P_x}{L \times B}$ (2)

Where P_x = as cast crushing load, L = the length and B is the breath

3. Results and discussion

3.1. Compressive Strength

The general trend observed was that there was an increment in the compressive strength of the eight sets of blocks with curing days. Overall, set C2 showed the highest compressive strength of the block sets. Blocks with bitumen mixed completely with sand containing (R2 and R4) showed the lowest compressive strength at 14 and 28 days, with set PR2 and PR1 showing similar strength characteristics with the control set C1 (Table 3). Blocks containing 5% bitumen generally showed the best performance in terms of compressive strength out of all the block sets modified with bitumen at 7,14 and 28 days. Generally, at 7 days, all block sets that contained bitumen internally except R1 expressed lower compressive strengths compared to the control samples at the same age. At 14 days there was an improvement in the compressive strength of the samples in which water was partially replaced with bitumen (PR1 and PR2). At 28 days, the control sets C1 and C2 had the highest compressive strength, although there was a noticeable increase in the compressive strength of the bitumen modified blocks. Overall blocks with 10% bitumen showed the lowest compressive strength. In general, there was a slower rate of strength development for blocks modified with bitumen compared with the control sets.

Table 3. Compressive strength of block sets

Block code	Average Compressive Strength (N/mm^2)		
	7 Days	14 Days	28 Days
C1	0.65	0.97	1.35
C2	1.27	1.48	1.51
R1	0.9	1.08	1.21
R2	0.68	0.67	1
R3	0.62	0.84	0.98
R4	0.61	0.71	0.8
PR1	0.52	1.04	1.2
PR2	0.64	0.92	1.09

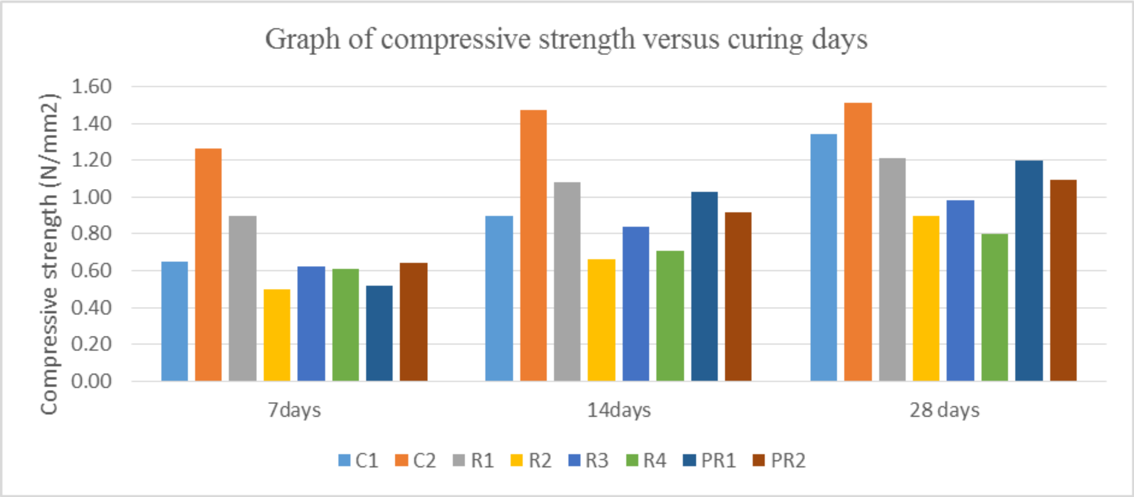

Figure 1. Variations in block compressive strength with curing days

3.2. Water Absorption

The general trend (Table 4) is that there is a reduction in water absorption rate with a corresponding increment in curing days. Overall, It is observed that block set C2 showed the best performance in terms of block water absorption at 7, 14 and 28 days. The block sets containing 5% and 10% bitumen (R1, R3 and R2, R4 respectively) showed better performance than the control and partial replacement sets (C1, PR1 and PR2 respectively). A significant increase in bitumen content does not appear to correspond to a similarly significant improvement in moisture content (Figure 2).

Table 4. Water absorption rate of block sets

Block code	Average Water Absorption (%)		
	7 Days	14 Days	28 Days
C1	10.79	6.86	6.65
C2	4.95	4.37	4.19
R1	6.6	5.21	4.68
R2	6.41	4.61	4.48
R3	6.77	4.58	4.23
R4	6.91	5.01	4.88
PR1	8.95	6.68	6.55
PR2	8.75	8.67	8.17

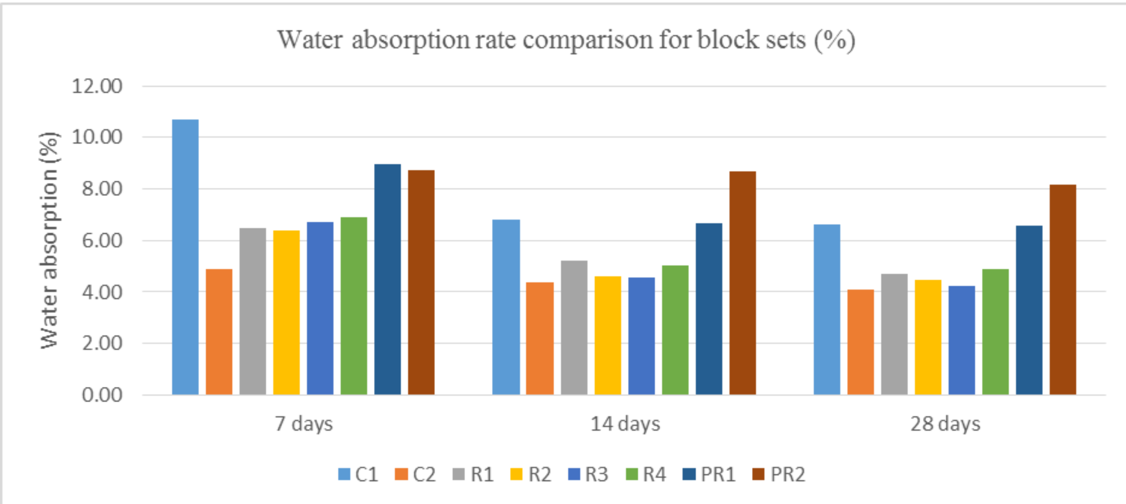

Figure 2. Variations in block water absorption with curing days.

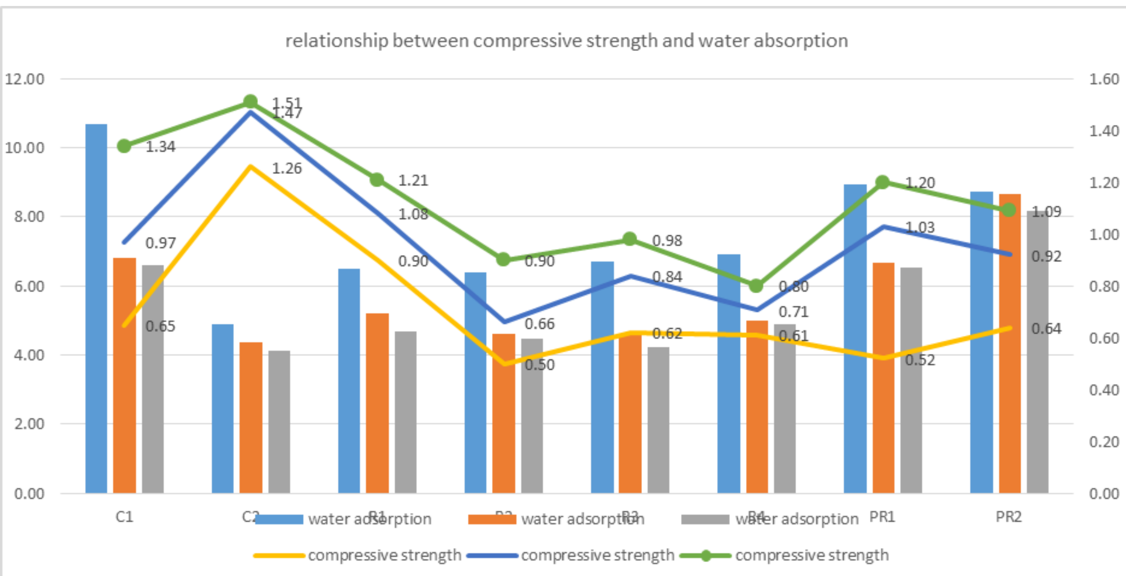

Figure 3. Relationship between compressive strength and water absorption for block sets.

3.3. Statistical Analysis

3.3.1. Compressive Strength and Water Absorption

When comparing the compressive strength of each block set to its respective water absorption rates (Figure 3), it was observed that there was a level of correlation between the water absorption and compressive strength of the Sandcrete blocks. Comparing the block sets to each other, however, this trend did not follow for the other sets of blocks, for example, set C1 which had the second-highest water absorption rate overall but still showed the second-highest compressive strength overall. The trend appeared to be random for the bitumen modified blocks of bitumen content 5% and 10% (R1,R2,R3,R4) which showed lower compressive strengths than the control and partial replacement sets (C1, C2 and PR1, PR2 respectively) even though they exhibited lower water absorption rates.

3.3.2. Compressive Strength and Bitumen Content

Pearson's correlation analysis was carried out for the variables compressive strength and bitumen content. At 7 days, a correlation coefficient of 0.27 was reported (Table 5), showing a weak positive linear correlation between compressive strength and bitumen content. At 14 days, a coefficient of -0.89 was calculated, which showed a strong negative linear correlation between compressive strength and bitumen content. At 28 days, a correlation coefficient of -0.98 was calculated which showed the strongest negative linear correlation between compressive strength and bitumen content. The Regression analysis for variables compressive strength (y) and bitumen content(x) is as given in figure 4.

3.3.3. Water Absorption and Bitumen Content

From the correlation and regression analysis (Table 6, Figure 5), it is observed that there is a medium negative linear correlation between water absorption and bitumen content for the water absorption at 14 days and 28 days, with each having correlation coefficients of -0.62 and -0.63 respectively. At 7 days it is observed that there is a strong negative linear correlation between water absorption and bitumen content, with a coefficient of -0.87.

Table 5. Statistical analysis for compressive strength and bitumen content

Bitumen %	Mean compressive strength at 7 days (N/mm²)	Mean compressive strength at 14 days (N/mm²)	Mean compressive strength at 28 days (N/mm²)
0.00	0.65	0.97	1.35
1.67	0.52	1.04	1.20
3.30	0.64	0.92	1.09
5.00	0.62	0.96	1.10
10.00	0.64	0.69	0.69
N	5	5	5
Pearson's coefficient of correlation	0.27	-0.89	-0.98
line of regression	$y = 0.0037x + 0.5992$	$y = -0.0309x + 1.0394$	$y = -0.0626x + 1.3354$
R^2	0.07	0.79	0.96

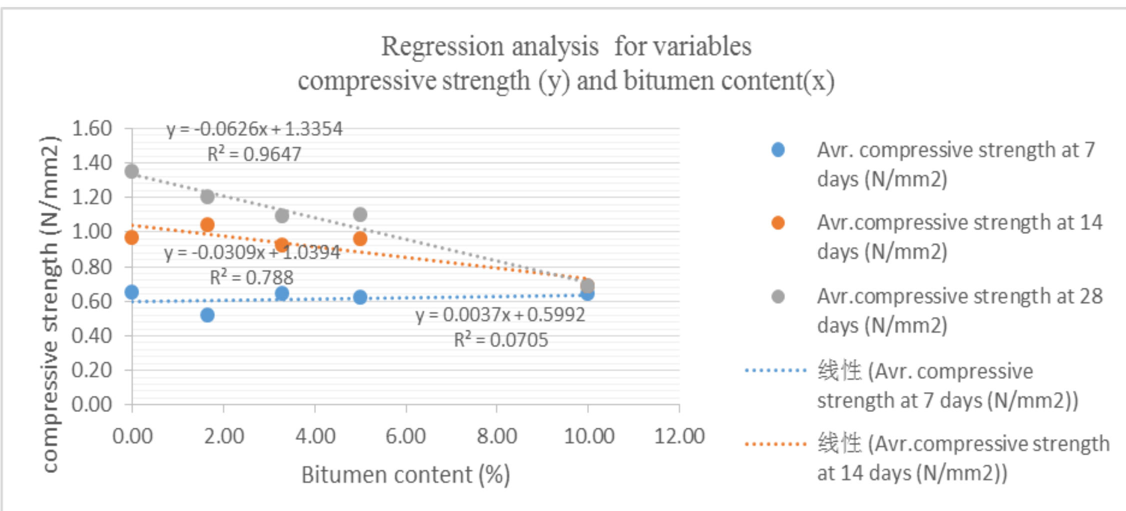

Figure 4. Scatter plot showing the relationship between compressive strength and bitumen content for block sets.

Table 6. Statistical analysis for water absorption and bitumen content

Bitumen %	Mean water absorption at 7 days (N/mm^2)	Mean water absorption at 14 days (N/mm^2)	Mean water absorption at 28 days (N/mm^2)
0.00	10.79	6.86	6.65
1.67	8.95	6.68	6.55
3.30	8.75	8.67	8.17
5.00	6.68	4.90	4.46
10.00	6.66	4.81	4.68
N	5	5	5
Pearson's correlation coefficient	-0.87	-0.62	-0.63
line of regression	$y = -0.3943x + 9.942$	$y = -0.252x + 7.1083$	$y = -0.2567x + 7.4084$
R^2	0.76	0.39	0.38

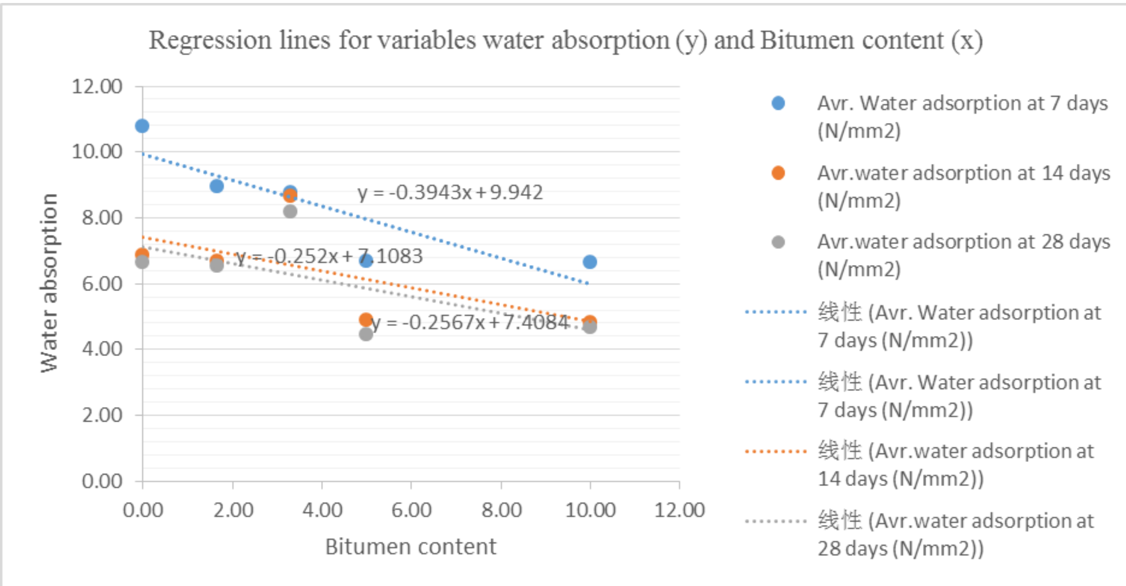

Figure 5. Scatter plot showing the relationship between water absorption and bitumen content for block sets.

3.4. Response Surface Methodology

3.4.1. ANOVA and Multiple Regression Equation for Investigated Properties

Tables 7 and 8 show the results of ANOVA analysis carried out on compressive strength and water absorption. The analysis of variance (ANOVA) is used to determine the contributions of the linear, interaction and quadratic terms[74,75]. The significance of each term was evaluated based on a confidence level of 95% [76]. To achieve this, model terms with probability values (p- values) of less than 0.05 were considered significant while those terms with p-values exceeding 0.05 were considered not significant. In the case of compressive strength, the significant model terms are A, B and A2 while for water absorption the significant model terms are A, B and B2. The interaction between A and B for both properties investigated was insignificant judging by the p- values obtained. All linear terms for compressive strength were significant with a confidence level of 99% and 96% for A and B respectively. The quadratic term of A was also significant at a confidence level of 96% while the quadratic term B was insignificant. A similar trend for linear terms was observed for water absorption however the quadratic term B was significant while the quadratic term A was insignificant. The interaction between A and B for both properties investigated was insignificant. It could be inferred from this analysis that the effect of percentage replacement of bitumen with sand was more significant on compressive strength than the curing days while for water absorption the reverse was observed. Furthermore, the lack of fit for compressive strength and water absorption were insignificant with P-values of 0.96 and 0.28 respectively. The coefficient of determination (R2) closest to one indicating a good positive relationship and R2 values above 0.8 and this implies that a sizable number of the points fell on the regression line with over 80% of the variation observed in the analysis adequately explained. For compressive strength and water absorption, the value obtained 0.88 and 0.92 respectively. Adequate precision

(AP) was also used in evaluating the performance of the model. According to Awolusi et al. [77], all values of AP greater than 4 indicate the ability of the models to navigate the space. For compressive strength and water absorption, the AP values are 9.35 and 10.74 respectively. The second-order multiple regression model for compressive strength and water absorption is presented in equation 3 and 4.

$$Compressive\ strength = +1.07460 - 0.15231A + 0.037712B + 8.40935E - 003A2 - 7.88829E - 004\ B2 + 2.24453E - 004AB \quad (3)$$

$$Water\ Absorption = +7.60056 + 0.33854A - 0.39555B - 0.015434A2 + 9.80567E - 003B - 5.80373E - 003AB \quad (4)$$

Table 7. ANOVA for Compressive strength

SoD	SoS	DoF	MS	F-value	P-value	Comment
Model	1.00	5	0.20	10.40	0.0039	R^2=0.88
A	0.76	1	0.76	39.52	0.0004	AP=9.35
B	0.11	1	0.11	5.87	0.0460	
A^2	0.13	1	0.13	6.68	0.0363	
B^2	0.016	1	0.016	0.82	0.3943	
AB	7.917E-004	1	7.917E-004	0.041	0.8447	
Residual	0.13	7	0.019			
Lack of Fit	9.555E-003	3	3.185E-003	0.10	0.9545	
Pure Error	0.12	4	0.031			

SoD: Source of data; SoS: Sum of squares; DoF: Degree of freedom; MS: mean square; R2: Coefficient of determination; AP: Adequate precision; A: Bitumen; B: Curing Day

Table 8. ANOVA for Water absorption

SoD	SoS	DoF	MS	F-value	P-value	Comment
Model	1.00	5	2.37	16.71	0.0009	R^2=0.92
A	1.25	1	1.25	8.71	0.0214	AP=10.74
B	5.90	1	5.90	41.12	0.0004	
A^2	0.43	1	0.43	3.00	0.1269	
B^2	2.44	1	2.44	16.98	0.0045	
AB	0.53	1	0.53	3.68	0.0963	
Residual	1.00	7	0.14			
Lack of Fit	0.59	3	0.20	1.86	0.2765	
Pure Error	0.42	4	0.10			

SoD: Source of data; SoS: Sum of squares; DoF: Degree of freedom; MS: mean square; R2: Coefficient of determination; AP: Adequate precision; A: Bitumen; B: Curing Days

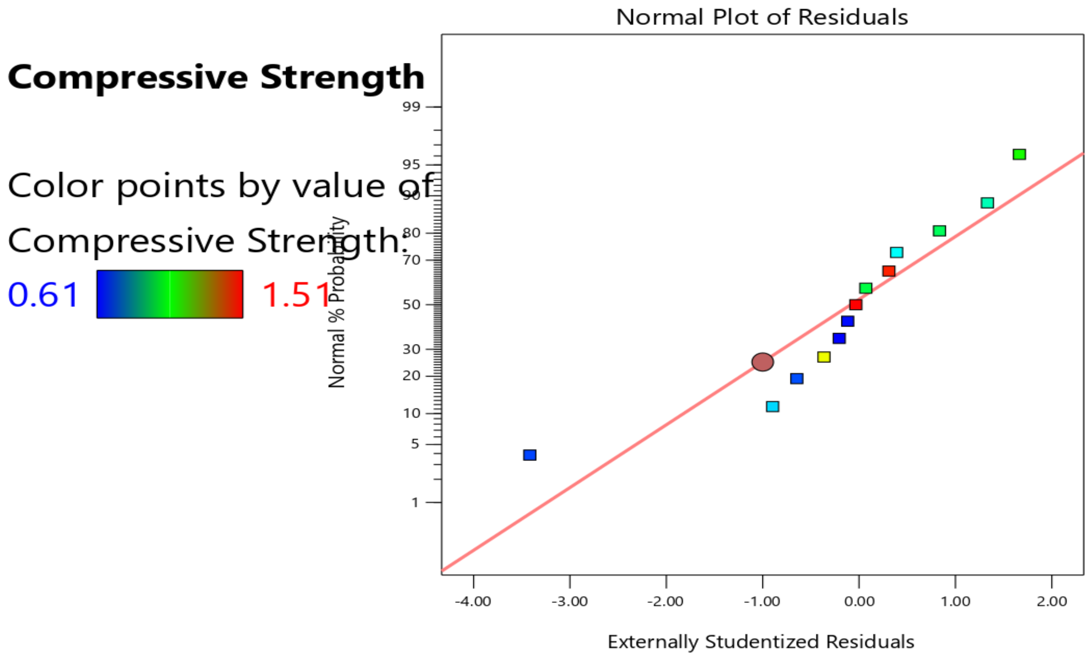

Figure 6. Normal probability distribution plot for compressive strength

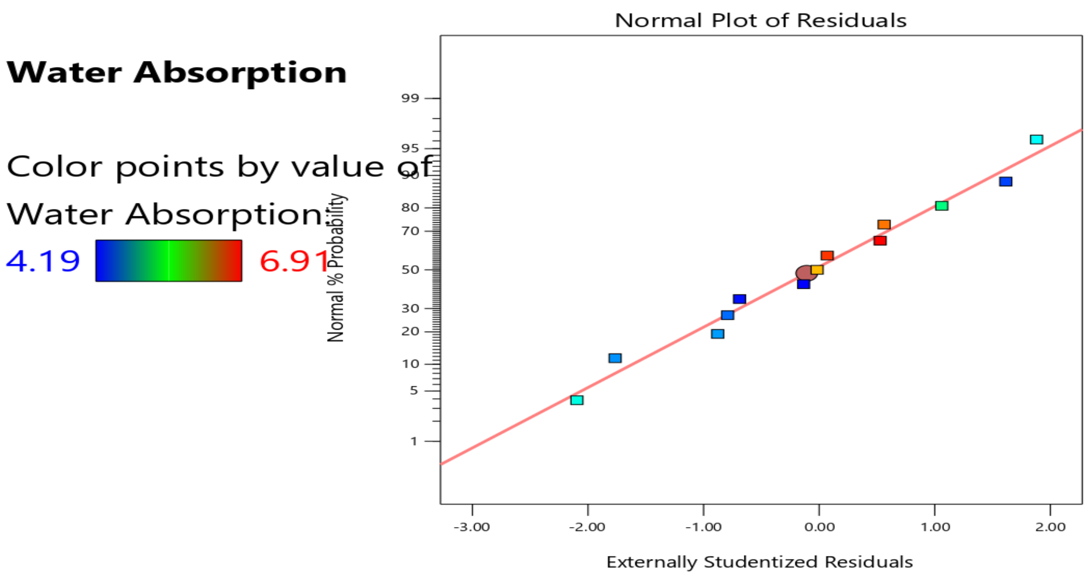

Figure 7. Normal probability distribution plot for water absorption

3.4.2. Normal Probability Plot

The normal probability plot for compressive strength and water absorption was carried out to check the normality of residuals. The plots presented in Figures 6 and 7 respectively show that normality has been satisfied since the plot majority of the plotted points fell very close to the distribution fitted line. This implies that the normal distribution plot was able to analyze interested responses. According to Bradley [78], a good estimated regression model is expected to explain the variation of the dependent variable in the sample and the normal probability plot is one of the tests used in evaluating the effectiveness of the model.

3.4.3. 2D and 3D Plots for Compressive Strength and Water Absorption Properties for Sandcrete Blocks

The plots illustrate the dependence of compressive strength and water absorption on the percentage bitumen replacement and curing days. The plots are usually drawn as a function of two independent variables to determine their effect on properties under investigation.

3.4.3.1. Effect of Percentage Bitumen Replacement and Curing days on Compressive Strength

For compressive strength, Figure 8 displays the 2D and 3D plots for A and B. From this Figure, it was observed that the compressive strength decreased with an increase in the percentage of A and increased with an increase in B. This implies that to achieve maximum compressive strength the bitumen content of the sandcrete blocks must be kept as low as possible.

3.4.3.2. Effect of Percentage Bitumen Replacement and Curing days on Water Absorption

For water absorption Figure 9 displays the 2D and 3D plots for A and B. From this Figure, it was observed that the increase in A and B will reduce water absorption. From this plot, it could be inferred that the initial water absorption of the sandcrete blocks is perceived to increase as the percentage bitumen replacement increases however with time (increasing curing days) the water absorption capacity of the blocks reduces. This implies that sandcrete blocks containing bitumen will exhibit low water absorption capacity in use.

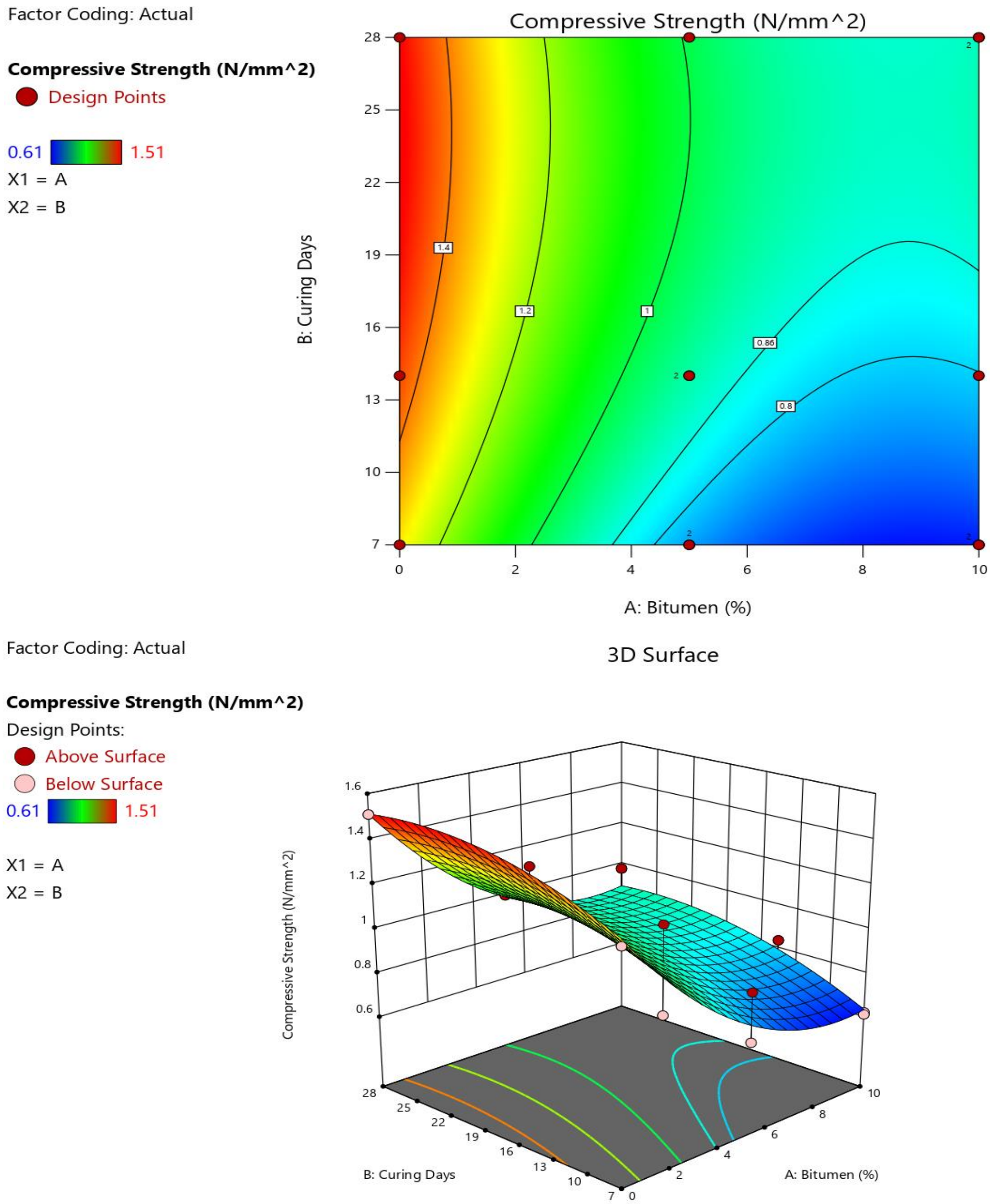

Figure 8. 2D and 3D plots for Compressive Strength

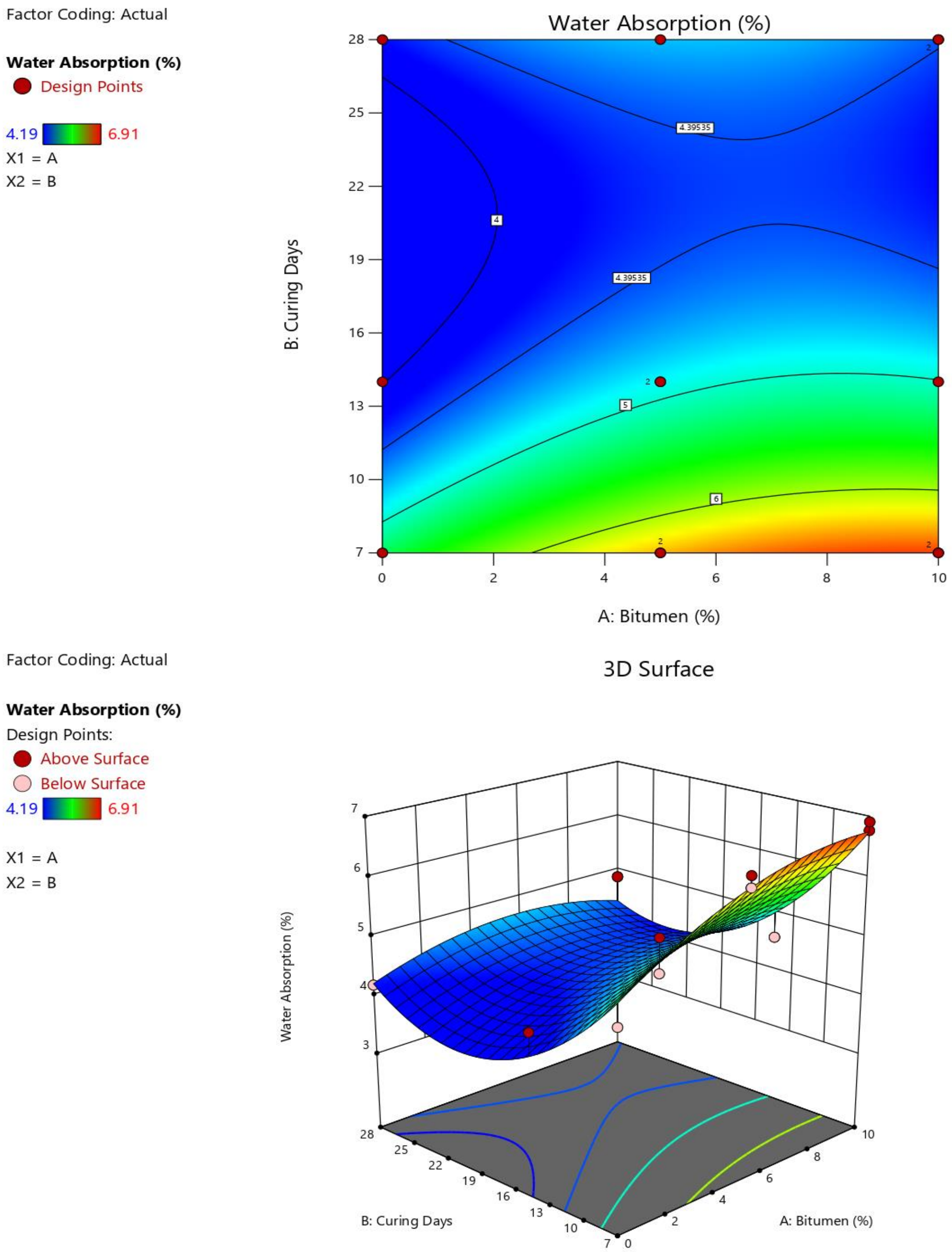

Figure 9. 2D and 3D plots for Water Absorption

4. Conclusions

The effect of the presence of bitumen in varying percentages on the compressive strength and water absorption rates of Sandcrete blocks was determined using pre-established testing methods. The following conclusions were drawn

- There is a reduction in the water absorption rate with the inclusion of bitumen spalling could be controlled with the use of bituminous sandcrete blocks.
- There is a positive linear correlation between water absorption rates and bitumen content for Sandcrete blocks
- The presence of bitumen in the aggregate-cement matrix contributes to the slow development of

compressive strength of Sandcrete blocks relative to industrial-grade blocks.

- The optimum bitumen content corresponding with the required compressive strength at 7 and 28 days lies between 5% and 10% of bitumen by mass of sand.
- The methodology in this research could be expanded to cover a high quantity of bitumen and other mixing methods in the development of Sandcrete blocks for no spalling effects.

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