Heliyon 7 (2021) e08565

Contents lists available at ScienceDirect

Heliyon

journal homepage: www.cell.com/heliyon

Research article

Response surface methodology-based optimisation of cost and compressive strength of rubberised concrete incorporating burnt clay brick powder

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ARTICLE INFO

Keywords:
Cost assessment
Response surface methodology
Central composite design
Rubberised concrete
Burnt clay brick powder
Compressive strength

ABSTRACT

Modified concrete is increasingly being produced by substituting concrete constituents with waste materials. Among waste materials are powder from waste clay bricks replacing Ordinary Portland Cement and Waste Tire Rubber (WTR) replacing natural coarse aggregate. However, the use of modified concrete is controlled by its cost-performance balance. This paper investigates the cost advantages of using rubberised concrete incorporated with Burnt Clay Brick Powder (BCBP) where findings are evaluated in comparison with conventional concrete. In this study, compressive strength of rubberised concrete containing BCBP was investigated using mixes generated by Response Surface Methodology (RSM). Central Composite Design (CCD) based on RSM was used to assess the influence of replacement variables of BCBP (0–5%) and WTR (0–20%) on concrete production cost and concrete compressive strength responses. First order and second order mathematical models were developed by RSM with findings from experimental design. The accuracy of the mathematical models established by CCD was tested using Analysis of Variance (ANOVA). Desirability analysis was then employed to optimise BCBP and WTR contents yielding maximum compressive strength at lower cost. Moreover, under the established optimum conditions, the performance of the optimum independent variables was experimentally verified by testing 6 cubes. Production cost of concrete containing these waste materials reduced up to 4.23% compared to conventional concrete. RSM evaluation demonstrated that the empirical findings were well suited into linear and quadratic models for cost and compressive strength responses respectively. The coefficients of determination of greater than 0.85 for all responses established that the models were capable of explaining variability in the responses. 5% BCBP and 6.875% WTR were optimum contents establishing maximum 7-days compressive strength of 27.607 MPa at lower cost of KSh 13 718.43. Optimisation of cost and 28-days compressive strength from desirability analysis gave 5% BCBP and 5.844% WTR contents as optimum values. This optimum combination resulted to maximum compressive strength of 33.970 MPa and lower cost of KSh 13 734.64. Verification of the model findings indicated considerable agreement with the verified values. From the findings, it was confirmed that a reasonable cost-performance balance for modified concrete can be achieved using BCBP and WTR.

1. Introduction

Huge amounts of materials are being manufactured, and along with them are the waste products that are being generated due to the extensive growth of industries [1]. Waste utilisation is considered as an essential aspect in the construction sector in relation to sustainability [2]. The use of waste materials in concrete is found to address the unacceptable negative impacts occasioning from the waste dumping of such non-biodegradable materials [3]. Some researchers [4, 5], have highlighted on the reduction of concrete production cost when Burnt Clay Brick Powder (BCBP) is used as partial substitute of cement. Meanwhile, the systematic usage of BCBP in concrete also yields significant economic and social benefits in addition to decreasing site cleaning and disposal cost [6]. In contrast, tire rubber aggregates have been reported to cost more than normal aggregates [7]. Investigations on sustainable construction are intended at development of an eco-friendly concrete and incorporating Waste Tire Rubber (WTR) and BCBP in concrete has potential in accomplishing this intention [8, 9, 10, 11].

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https://doi.org/10.1016/j.heliyon.2021.e08565
Received 2 October 2021; Received in revised form 16 November 2021; Accepted 3 December 2021

However, determination of BCBP and WTR contents yielding maximum compressive strength at lower cost has received little attention in literature.

The rapid escalation of waste materials dumping to sustain the requirements of the ever increasing population has supported sustainable construction through the use of waste materials in concrete [12]. The massive use of natural aggregates is also receiving increasing criticisms due to natural resources depletion. It is known that each year millions of tires are disposed, cast off or concealed across the world, posing an extreme threat to the ecological system [13]. By the year 2030, it is expected that the quantity of tires ending their life would reach 1200 million in a year [14]. The general public therefore needs to pursue economic development measures to mitigate environmental dilapidation and extensive use of natural aggregate. On the other hand, although rubberised concrete has illustrated improvement in ductility [8, 15, 16], the use of chipped and crumb rubber aggregates in concrete has limitations in relation to durability and strength [13, 14, 17, 18, 19]. Moreover, water absorption and drying shrinkage of rubberised concrete are reported to increase compared to control concrete [20, 21, 22]. This has been attributed to increased porosity occasioning from hydrophilic nature of tire rubber [20, 23, 24].

There have been growing concerns on the increased cost of concrete which has occasioned an increase in the total construction cost. Ordinary Portland Cement (OPC) production is characterised by emission of CO_2 which is regarded as a greenhouse gas that causes global warming [10, 25]. Waste from building industry constitutes up to 25% of the entire disposal of solid wastes [26]. The global red clay brick and concrete block production was estimated to be around 1900 billion in 2020 [27]. Use of BCBP as an artificial pozzolanic material has been observed to lower the consumption of energy and emissions of CO_2 during cement production apart from reducing the production cost of concrete [6, 28]. Compared with conventional concrete, inclusion of BCBP in concrete is observed to reduce compressive strength of concrete at lower curing periods [10], because of reduced levels of $Ca(OH)_2$ to react with SiO_2 [29]. However, other studies [5, 30], have reported increased compressive strength even at lower curing periods. This has been attributed to very fine particles of brick powder effectively filling voids thereby resulting in dense concrete microstructure. Partial cement replacement with 10% brick powder is also noted to reduce Portland cement consumption without negatively affecting concrete performance for huge projects [31]. The adoption of use of BCBP and WTR in concrete production could be beneficial for various reasons: a successful method of conserving the environment, concrete production cost benefits, decreasing concrete density and minimising the natural resources consumption [9, 32, 33, 34]. To help encourage the construction sector to use BCBP and WTR in concrete, their contents are to be optimised to give good compromise between maximising compressive strength and minimising cost.

Response Surface Methodology (RSM) uses efficient theoretical, statistical and numerical procedures to create models for optimisation of independent parameters [35, 36]. The methodology allows numerous considerations to influence one or several responses [37]. The method employs partial factorial designs including Central Composite Design (CCD) [38]. It also offers an enormous benefit by outweighing one factor at a time method which is time consuming and lacks capacity for factor interaction consideration [39]. More concretely, RSM is aimed at proposing sequential strategies of conducting experimentation and verifying the agreement between the experimental data and constructed models [40]. Numerous extensions of RSM have been used to determine the superior compromise among several responses. Desirability analysis is one of the most prominent methods used to optimise multi-response characteristics [41, 42]. The use of RSM is seen to have potential in determining optimised contents of BCBP and WTR in concrete yielding maximised compressive strength at lower cost.

RSM is increasingly gaining prominence in studies for optimality of several practices including concrete production [37, 43]. RSM uses Design of Experiment software packages and some of them include Design Expert and Minitab. The software packages are capable of generating best experimental designs, regression analysis and appropriate statistical tests [44, 45]. RSM as partial factorial design has been found to reduce number of experiments than full factorial design [46]. For instance, examination of five variables at five distinct levels necessitates 3125 experiments in full factorial design whereas RSM demands exactly 48 experiments [46]. It is also known that experimenters may very often not have enough resources and sufficient time to conduct full factorial experiments and may opt for partial factorial designs which are regularly used [45]. A conclusion could be drawn that RSM manifests tremendous savings in the terms of effort, length of time and expenditure.

This research captures the cost effectiveness of rubberised concrete containing BCBP. The unique contribution of this research is on optimisation of BCBP and WTR contents establishing maximum compressive strength of concrete at lower cost. The applicability of this research is demonstrated through reduced cost due to inclusion of BCBP and WTR in concrete. Hence, it highlights the potential cost benefits offered by rubberised concrete incorporated with BCBP which can prompt individuals or companies to embrace these sustainable construction materials.

2. Materials and methods

2.1. Materials

Fragmented clay bricks were obtained from Kenya Clay Products to generate BCBP of specific gravity of 2.69 using ball mill. At this factory, clay bricks were burnt at 950 °C. The fragmented bricks were ready to be disposed as waste materials. BCBP in this study showed the sum of SiO_2, Fe_2O_3 and Al_2O_3 of 85.93% and this BCBP was therefore established as class N pozzolan according to ASTM C618 [47]. Ordinary Portland Cement (OPC) CEM I in accordance with BS EN 197-1 [48], and with specific gravity of 3.12 was substituted by BCBP passing through 75 μm sieve. The chemical compositions of BCBP and cement are shown in Table 1. Waste tires were locally sourced and feasible innovative aggregates were achieved by adjusting their sizes to accommodate the required maximum size of 20 mm. Cement, fine aggregates and coarse aggregates were purchased within Kenya. Coarse aggregate of specific gravity of 2.55 was partially substituted by WTR with specific gravity of 1.14. The percentage of voids and bulk density of WTR were 49.33% and 567.55 kg/m^3 respectively. WTR revealed water absorption value of 0.98% whilst coarse aggregate showed water absorption value of 3.39%. In this study, fine aggregate of water absorption of 1.11% and specific gravity of 2.59 was river sand in conformance with requirements in BS 882 [49]. Coarse aggregate and WTR of sizes ranging from 5-20 mm were used in conformance with specifications in BS 882 [49]. The percentage of voids and compacted bulk density of coarse aggregate were determined as 39.99% and 1440.20 kg/m^3 respectively. In contrast, fine aggregate revealed percentage of voids and compacted bulk density values of 39.14% and 1564.10 kg/m^3 respectively. Figure 1 shows BCBP and WTR used in this study to partially replace OPC and coarse aggregate respectively. Portable water from Jomo Kenyatta University of Agriculture and Technology (JKUAT) was used for specimen preparation.

2.2. Methods

2.2.1. Experimental design

The Class 20 mix design based on British Research Establishment (BRE) was conducted in this research. Generation of experimental runs using CCD of response surface methodology resulted in a sum of thirteen runs. Adopting this number of runs represents accurate optimum values and illustrates significant experimental data [46]. 13 mix designs with different quantities of cement, sand, coarse aggregate, BCBP and WTR are shown in Table 2. The numerical factors were adjusted within the five levels of the center point (mid-level), plus Alpha (+α), minus Alpha (-α), +1 (high level) (axial/star points) and -1 (low level) (factorial points). These factors are shown Table 3. The independent variables consisting of

Table 1. The chemical compositions of cement and BCBP.

Material	SiO_2	Fe_2O_3	Al_2O_3	CaO	MgO	Na_2O	K_2O	TiO_2	MnO	P_2O_5	Ba	S	LOI
Cement	15.45	4.55	2.81	62.45	-	0.48	1.01	0.47	0.12	1.29	0.05	2.75	7.47
BCBP	64.36	12.86	8.71	2.00	-	1.82	3.05	2.13	0.68	1.18	1.18	-	0.97

Figure 1. Feasible innovative construction materials (a) BCBP (b) WTR.

BCBP and WTR were introduced in the design and were expressed in a coded form as A (BCBP) and B (WTR). Responses denoted as R1, R2 and R3 represented the cost, 7 and 28-days compressive strengths respectively.

2.2.2. Cost assessment

Cost assessment depended heavily on the expenses of generating one cubic metre of conventional concrete and modified concrete. This was achieved by breaking down material expenses and identifying unit rates of the material required for concrete production. The comparison was established based on the cost savings for normal and modified concrete. The unit costs of each material for labour and transportation were accessed in the Kenyan market. The quantities of cement and coarse aggregates varied under the influence of partial replacements for these materials. Expenses associated with procurement and transportation of fine and coarse aggregates were computed in compliance with the local distributors' rates while water costs were accessed from Nairobi City Water and Sewerage Company. Monetising the cost values of tire rubber per kg was conducted in accordance with values in a report [50]. Shredding aggregates of sizes up to 25.4 mm was found to range from 1 to 3 KSh per kg. However, the adopted value in this study demonstrates current prices. In this research, costs emanating from production of innovative aggregates from tire rubber using manual labour were neglected as these proved to be higher than those from machine. All unit costs and expenses for 1-cubic meter concrete volume are in Kenyan Shillings Currency.

Table 3. Coded parameter levels for BCBP and WTR.

Independent variables	Code	Unit	Coded parameter levels		
			-1	0	+1
Burnt clay brick powder	A	%	0	2.5	5
Waste tire rubber	B	%	0	10	20

Table 2. Mix proportions with quantities of raw materials of rubberised concrete containing BCBP.

Mix	Cement (kg/m^3)	BCBP (kg/m^3)		Sand (kg/m^3)	WTR		Coarse aggregate (kg/m^3)	Water (kg/m^3)
		%	(kg/m^3)		%	(kg/m^3)		
1	301.36	2.5	7.73	633.90	10	50.87	1158.31	170
2	293.64	5.0	15.45	633.90	20	101.74	1029.61	170
3	301.36	2.5	7.73	633.90	10	50.87	1158.31	170
4	301.36	2.5	7.73	633.90	10	50.87	1158.31	170
5	309.09	0.0	0.00	633.90	10	50.87	1158.31	170
6	293.64	5.0	15.45	633.90	10	50.87	1158.31	170
7	293.64	5.0	15.45	633.90	0	0.00	1287.01	170
8	301.36	2.5	7.73	633.90	10	50.87	1158.31	170
9	309.09	0.0	0.00	633.90	20	101.74	1029.61	170
10	309.09	0.0	0.00	633.90	0	0.00	1287.01	170
11	301.36	2.5	7.73	633.90	10	50.87	1158.31	170
12	301.36	2.5	7.73	633.90	20	101.74	1029.61	170
13	301.36	2.5	7.73	633.90	0	0.00	1287.01	170

2.2.3. Experimental procedure

The experimental design of concrete for all the thirteen (13) runs was generated by RSM using Design Expert 12. Casting of concrete containing waste materials was carried out using manual mixing. Addition of water into the mix and mixing procedure undertaken for approximately 8 min ensured homogeneity in the concrete matrix. Following blending of all the constituent materials, fresh concrete was placed in lubricated moulds. Thereafter, fresh concrete was compacted using a poker vibrator until uniform compaction was attained. The specimens were then left for 24 h before demoulding. After demoulding, all specimens for compressive strength were cured for 6 and 27 days.

2.2.4. Measurement of compressive strength

Measurements of cubic compressive strengths were performed on 100 × 100 × 100 mm cube specimens in accordance with ASTM C109-11 [51]. Testing was conducted after 7 and 28 days of curing. Three cube specimens were prepared for every mix. The compressive strength test was performed using a 1500 kN universal testing machine at a loading rate of 0.5 kN/s.

2.2.5. Response surface methodology

RSM predicted the influence of quantities of BCBP and WTR as independent variables on cost and compressive strength responses. It covered optimisation aspect by obtaining the optimum values of cost and compressive strength. RSM design has the capacity to ascertain linear interaction and quadratic influences of the independent variables on properties of concrete [37]. The research optimised the combined outcomes of these factors to minimise or maximise desired outputs. Eqs. (1) and (2) illustrate linear and quadratic functions respectively.

$$Y = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \ldots\ldots + \beta_i x_i + \varepsilon \tag{1}$$

$$Y = \beta_0 + \sum_{i=1}^{k} \beta_i x_i + \sum_{i=1}^{k} \sum_{j=1}^{k} \beta_{ij} x_i x_j + \sum_{i=1}^{k} \beta_{ii} x_{ii}^2 + \varepsilon \tag{2}$$

According to the equations, Y represents response, $ß_0$ is a constant, $ß_i$, $ß_{ii}$ and $ß_{ij}$ are coefficients of linear influence and double interactions, x_i, x_j are the independent factors and ϵ is the error.

2.2.6. Optimisation and validation procedures

Optimisation process was aimed at obtaining optimum values of the two independent parameters generating desirable response variables purpose. Response models visualisation using graphical optimisation led to the understanding of influence of BCBP and WTR on concrete production cost and concrete compressive strength. The overall goals in numerical optimisation were to maximise compressive strength and minimise cost. Desirability analysis as a multiple optimisation technique was employed to combine these goals. This technique sought to optimise the cost and compressive strength to obtain economically viable parameters of BCBP and WTR. Verification of experimental data and predicted values was carried out in order to evaluate the efficiency and appropriateness of the predicted response surface models.

3. Results and discussion

3.1. Cost implication

Tables 4 and 5 highlight the estimated production costs associated with production of conventional and modified concrete mixes respectively. The extent of beneficial significance for adopting the usage of rubberised concrete incorporated with BCBP over normal concrete was also explored in this research (see Table 6).

The production cost of rubberised concrete containing BCBP reduced consequently in comparison to conventional concrete. The cost of binder (cement + BCBP) reduced by 2.5% for concrete containing BCBP compared to cement cost in control concrete. It is obvious that inclusion of BCBP was responsible at slight cost reduction of rubberised concrete compared to control concrete. From this perspective, widespread challenges of pollution and dumping of fragmented clay bricks can be alleviated once BCBP is used in concrete production. Equivalent quantities of fine aggregate and water were established for both conventional and modified concrete and no comparable benefit of using these materials was anticipated.

As expected, WTR and coarse aggregates in modified concrete showed 8.14% cost increment compared to coarse aggregates in normal concrete. However, concerns of increment of overall concrete cost due to inclusion of WTR were eliminated by the volume replacement method of rubber and introduction of BCBP. Although cost of tire rubber per kilogram is greater than the corresponding cost of coarse aggregate per kilogram, volume replacement was found to result in reduced cost. Such findings were anticipated considering that the bulky density of tire rubber in this study decreased by 60.47% compared to that of coarse aggregate. Meanwhile, higher maintenance costs and reliability challenges are addressed by rubberised concrete which forms an essential basis of adopting this sustainable construction [52]. On a basis of propagating dynamic performance of structures, tire rubber incorporation in concrete leads to cost effective maintenance, construction and design [53].

3.2. Fitting the model

The influence of independent parameters (BCBP and WTR) on cost and compressive strength of concrete was assessed. Computations of polynomial coefficients from experimental data predicted both response variables. Analysis of Variance (ANOVA) findings demonstrated that cost and compressive strength responses could be illustrated with linear and quadratic models respectively. Regression equations generated for all responses using response surface methodology are illustrated in Eqs. (3), (4), and (5).

$$Cost = 13810.71 - 141.41A - 157.19B \tag{3}$$

$$7 - days\ compressive\ strength = 25.13 + 1.27A - 4.25B - 0.10AB - 0.11A^2 - 2.72B^2 \tag{4}$$

$$28 - days\ compressive\ strength = 32.64 + 0.16A - 6.53B + 0.04AB - 1.26A^2 - 1.57B^2 \tag{5}$$

3.3. Effect of independent factors on responses

3.3.1. Production cost

Figures 2a and 2b show the contour plots and 3-D response model plotted for cost response respectively. Table 7 shows the diagnostic case statistics report for cost response. The figure visualises the influence of each variable on cost of rubberised concrete incorporated with BCBP. Two-dimensional plane from a contour plot reveals the response surface

Table 4. Cost estimates of producing one cubic metre of control concrete (0P0T/Run 10).

Material description	Unit price per kg (Kenyan Shillings)	Quantity (kg)	Total price (Kenyan Shillings)
Ordinary Portland Cement	28.00	309.09	8654.52
Fine aggregate	2.50	633.90	1584.75
Coarse aggregate	3.00	1287.01	3861.03
Water	0.053	170.00	9.01
Total			14109.31

Note: Current exchange rate is 1 USD = KSh 107.81 and 1 kg of water is equivalent to 1 L.

Table 5. Cost estimates of producing one cubic metre of modified concrete (5P20T/Run 2).

Material description	Unit price per kg (Kenyan Shillings)	Quantity (kg)	Total price (Kenyan Shillings)
Ordinary Portland Cement	28.00	301.36	8222.79
BCBP	9.70	15.45	149.91
Fine aggregate	2.50	633.90	1584.75
Coarse aggregate	3.00	1029.61	3088.82
Water	0.053	170	9.01
WTR	4.50	101.74	457.80
Total			13512.12

Note: Current exchange rate is 1 USD = KSh 107.81 and 1 kg of water is equivalent to 1 L.

where all similar response positions generated contour profiles of same responses. A 3-D surface graph represents a three-dimensional outlook which facilitates response surface interpretation. As expected, the R^2 and R^2_{adj} were both at 100% thereby demonstrating complete correlation.

Table 6. Experimental design, experimental parameters and recorded response values.

Run	Independent variables		Response values		
	A: BCBP (%)	B: WTR (%)	Cost (KSh)	7- days compressive strength (MPa)	28-days compressive strength (MPa)
1	2.5	10	13810.7	24.3325	34.12
2	5	20	13512.1	19.121	23.8252
3	2.5	10	13810.7	25.4719	34.33
4	2.5	10	13810.7	25.8085	31.155
5	0	10	13952.1	24.439	28.7885
6	5	10	13669.3	26.94	31.155
7	5	0	13826.5	28.0394	36.5124
8	2.5	10	13810.7	24.7052	33.2
9	0	20	13794.9	16.7535	24.4445
10	0	0	14109.3	25.265	37.2785
11	2.5	10	13810.7	24.41	33.21
12	2.5	20	13653.5	18.8316	22.842
13	2.5	0	13967.9	26.8763	36.488

Response surface plots illustrate interaction of parameters which can be applied to optimise the effectiveness of responses [54, 55]. It is clear that the production cost slumps due to inclusion of BCBP and WTR illustrating that these waste materials beneficially contribute to concrete cost reduction. From Figure 2b, the production cost is observed to rise sharply with the reduction of these replacement materials where the maximum cost is seen with normal concrete. Low cost of BCBP per kg compared to cement cost per kg is observed to lower overall production cost of modified concrete. The lowest cost is observed for 5P20T concrete mixture. Volume replacement of coarse aggregate by tire rubber is considered as a technique contributing towards the reduction in production cost of modified concrete. The overall diagnostic case statistics report for the cost response in Table 7 illustrates complete correlation.

3.3.2. 7-Days compressive strength

Table 8 shows the ANOVA for 7-days compressive strength results. Figures 3a and 3b show the contour plot and corresponding response surface of compressive strength respectively. The normal probability versus externally studentised residuals plot for 7-days compressive strength is illustrated in Figure 4a. The diagnostic plot of residuals versus predicted is given in Figure 4b. In addition, Table 9 shows the diagnostic case statistics report for 7-days compressive strength response. From Table 9, the overall diagnostic case statistics analyses indicate that the model is adequate. However, the two values of Difference in Fits (DFFITS) exceed the limits of ±2.0381 for run orders 2 and 9. Notwithstanding this anomaly, the two data points did not significantly affect the outcome of model.

High values of R^2 and R^2_{adj} estimated as 0.9787 and 0.9636 respectively, demonstrated the competence of the model. The lack of fit is not significant and F-test illustrates higher significance ($p < 0.001$) for the selected model. The F-value and P-value are observed to be the crucial parameters in evaluating the model significance [56]. The coefficients of determination coupled with statistical tests guaranteed that the model was capable of explaining the variability in the response. Acceptable goodness of fit of the model exists between the normal probability and the externally studentised residuals as shown in Figure 4a. A linear relationship is considerably observed in this figure. This observation confirms that the constructed model is normally distributed capable of predicting the experimental findings. It is reported that a good model should be normally distributed [56]. The signal to noise ratio of 24.56 indicates a sufficient signal. The model is therefore capable of navigating

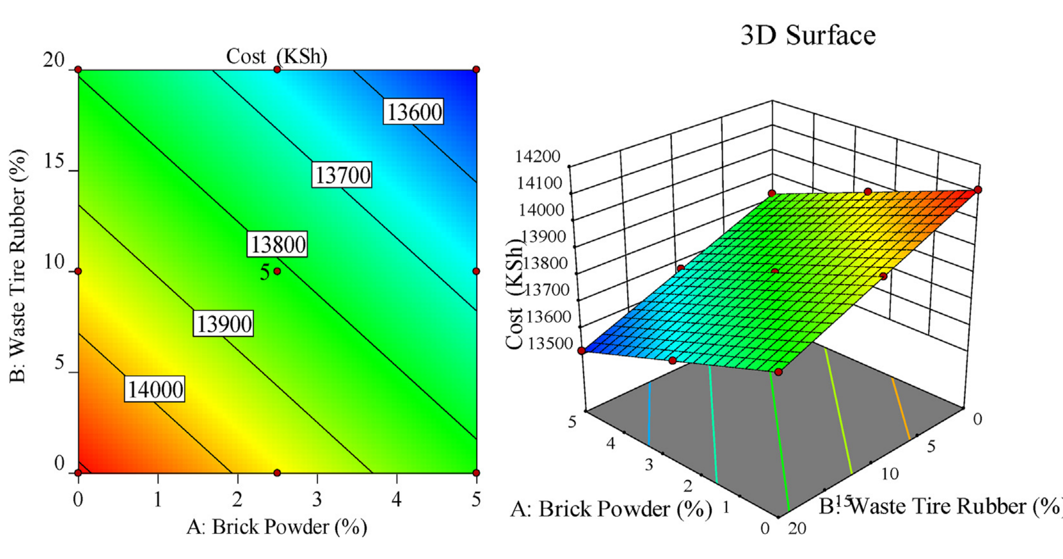


Figure 2. Contour plot and corresponding response surface of cost.

Table 7. Diagnostic case statistics report for cost response.

Run order	Actual value	Predicted value	Residual	Leverage	Internally studentised residuals	Externally studentised residuals	Cook's distance	Influence on Fitted Value DFFITS	Standard order
1	13810.71	13810.71	0.0000	0.172	0.000	0.000	0.000	0.000	11
2	13512.12	13512.12	0.0000	0.790	0.000	0.000	0.000	0.000	4
3	13810.71	13810.71	0.0000	0.172	0.000	0.000	0.000	0.000	10
4	13810.71	13810.71	0.0000	0.172	0.000	0.000	0.000	0.000	12
5	13952.12	13952.12	0.0000	0.494	0.000	0.000	0.000	0.000	5
6	13669.30	13669.30	0.0000	0.494	0.000	0.000	0.000	0.000	6
7	13826.49	13826.49	0.0000	0.790	0.000	0.000	0.000	0.000	2
8	13810.71	13810.71	0.0000	0.172	0.000	0.000	0.000	0.000	13
9	13794.93	13794.93	0.0000	0.790	0.000	0.000	0.000	0.000	3
10	14109.31	14109.31	0.0000	0.790	0.000	0.000	0.000	0.000	1
11	13810.71	13810.71	0.0000	0.172	0.000	0.000	0.000	0.000	9
12	13653.53	13653.53	0.0000	0.494	0.000	0.000	0.000	0.000	8
13	13967.90	13967.90	0.0000	0.494	0.000	0.000	0.000	0.000	7

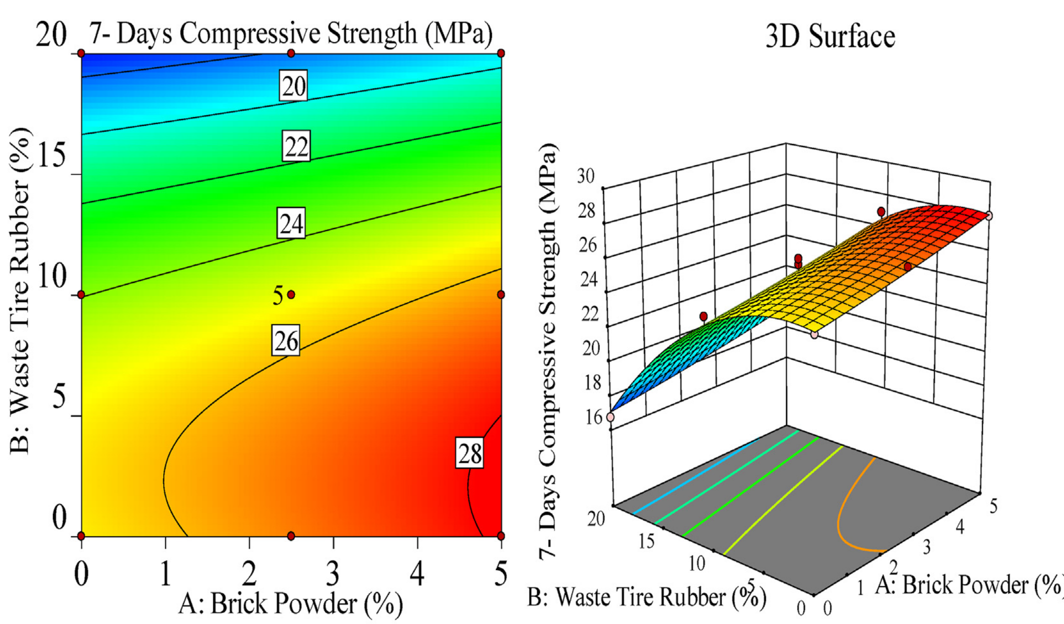
Table 8. ANOVA for 7-days compressive strength (MPa) response surface quadratic model.

Source	Sum of squares	df	Mean square	F-value	p-value	
Model	141.13	5	28.23	64.47	<0.0001	Significant
A-Brick Powder	9.74	1	9.74	22.24	0.0022	
B-Waste Tire Rubber	108.16	1	108.16	247.04	<0.0001	
AB	0.0414	1	0.0414	0.0945	0.7674	
A^2	0.0364	1	0.0364	0.0831	0.7815	
B^2	20.44	1	20.44	46.70	0.0002	
Residual	3.06	7	0.4378			
Lack of Fit	1.32	3	0.4409	1.01	0.4748	Not significant
Pure Error	1.74	4	0.4355			
Total	144.19	12				

the design space. The formation of horizontal band in residuals vs predicted plot (Figure 4b) suggests that the variances of the error terms are equal. Also, ideal residual plot in this figure is an indication that there is no outlier in the model.

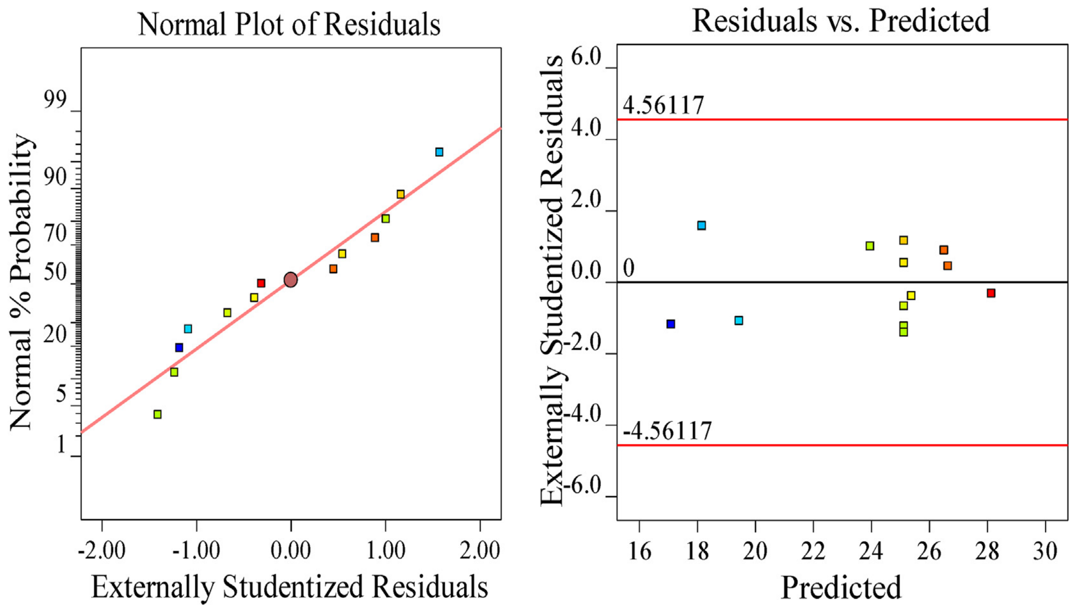
3.3.3. 28-Days compressive strength

Table 10 establishes quadratic model of 28-days compressive strength by ANOVA. The interaction influence of BCBP and WTR on 28-days compressive strength is exhibited in Figure 5. The 3-D surface graph has curvilinear shape in conformance with the fitted quadratic model. The normal probability against externally studentised residuals and residuals versus predicted plots are depicted in Figures 6a and 6b respectively. From Table 11, the diagnostic case statistics report for 28-days compressive strength response is shown. From Table 11, the model is generally deemed adequate despite a minor discrepancy existing for two Cook's Distance values and three DFFITS values. The discrepancy may be attributed to a possible data error.



(a) Contour plot (b) 3-D response surface plot

Figure 3. Contour plot and corresponding response surface of 7-days compressive strength.



(a) Normal probability plot (b) Residuals vs predicted (Fits) plot

Figure 4. Diagnostic plots for 7-days compressive strength response.

Table 9. Diagnostic case statistics report for 7-days compressive strength response.

Run order	Actual value	Predicted value	Residual	Leverage	Internally studentised residuals	Externally studentised residuals	Cook's distance	Influence on Fitted Value DFFITS	Standard order
1	24.33	25.13	-0.7929	0.172	-1.317	-1.406	0.060	-0.642	11
2	19.12	19.45	-0.3247	0.790	-1.072	-1.085	0.721	-2.106 (1)	4
3	25.47	25.13	0.3465	0.172	0.576	0.546	0.012	0.249	10
4	25.81	25.13	0.6832	0.172	1.135	1.163	0.045	0.531	12
5	24.44	23.97	0.4727	0.494	1.004	1.005	0.164	0.994	5
6	26.94	26.51	0.4260	0.494	0.905	0.892	0.134	0.882	6
7	28.04	28.14	-0.1013	0.790	-0.334	-0.312	0.070	-0.606	2
8	24.71	25.13	-0.4202	0.172	-0.698	-0.670	0.017	-0.306	13
9	16.75	17.10	-0.3481	0.790	-1.148	-1.180	0.828	-2.291 (1)	3
10	25.27	25.39	-0.1246	0.790	-0.411	-0.385	0.106	-0.748	1
11	24.41	25.13	-0.7154	0.172	-1.188	-1.232	0.049	-0.562	9
12	18.83	18.16	0.6728	0.494	1.430	1.573	0.333	1.555	8
13	26.88	26.65	0.2259	0.494	0.480	0.452	0.038	0.447	7

(1) Exceeds limits.

Table 10. ANOVA for 28-days compressive strength (MPa) response surface quadratic model.

Source	Sum of squares	df	Mean square	F-value	p-value	
Model	273.79	5	54.76	18.10	0.0007	Significant
A-Brick Powder	0.1604	1	0.1604	0.0530	0.8244	
B-Waste Tire Rubber	255.68	1	255.68	84.52	<0.0001	
AB	0.0054	1	0.0054	0.0018	0.9675	
A^2	4.39	1	4.39	1.45	0.2674	
B^2	6.79	1	6.79	2.24	0.1778	
Residual	21.17	7	3.02			
Lack of Fit	14.87	3	4.96	3.14	0.1487	Not significant
Pure Error	6.31	4	1.58			
Total	294.96	12				

The adequacy of the constructed model was statistically checked using ANOVA. R^2 and R^2_{adj} values of 0.9282 and 0.8769 obviously demonstrate strong relativity of experimental findings with the fitted regression model. The lack of fit is also insignificant and this is desirable since a model that fits is needed [57]. The ANOVA value of F-ratio 18.10 is significant and there is a 0.07% probability that this F-value could materialise as a consequence of noise. The usage of F-ratio elucidates on the effect of the empirical variables on the responses [58]. The signal to noise ratio of 12.29 explicitly indicates adequate signal. The signal to noise ratio exceeding 4 is an indication that the quadratic model can be used to navigate the design space [59]. From Figure 6a, the absence of departures from the regression line is an indication of goodness of fit in the model. The distribution of points that is consistent with the regression line illustrates enhanced adequacy of the applied regression model [60]. Also, random bouncing of residuals in Figure 6b demonstrates that the assumed relationship is reasonable.

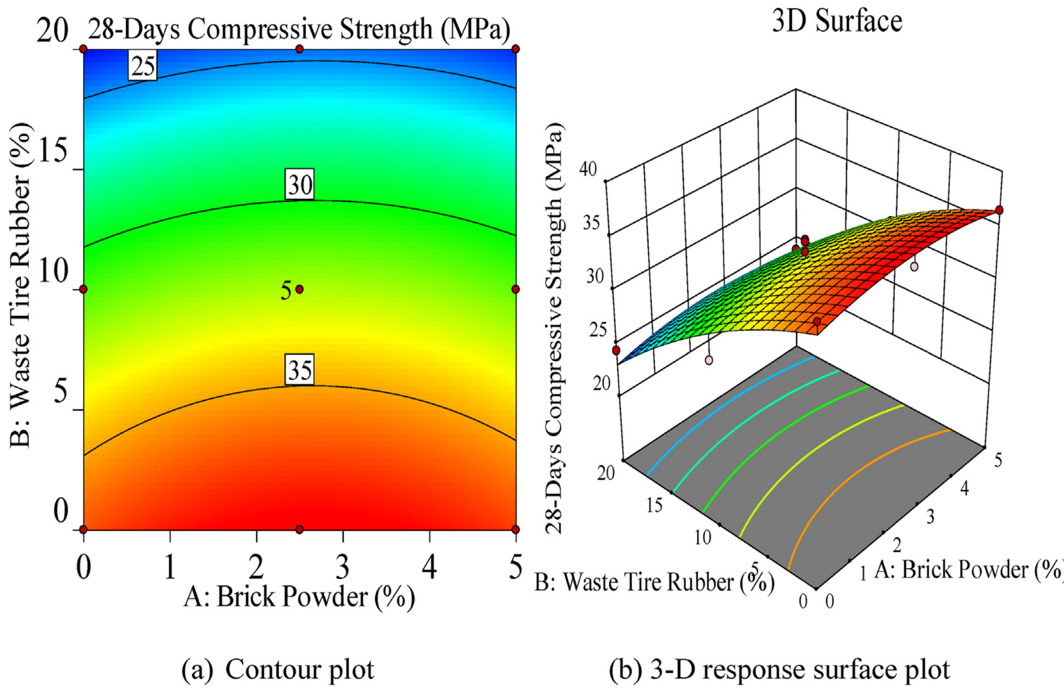


Figure 5. Contour plot and corresponding response surface of 28-days compressive strength.

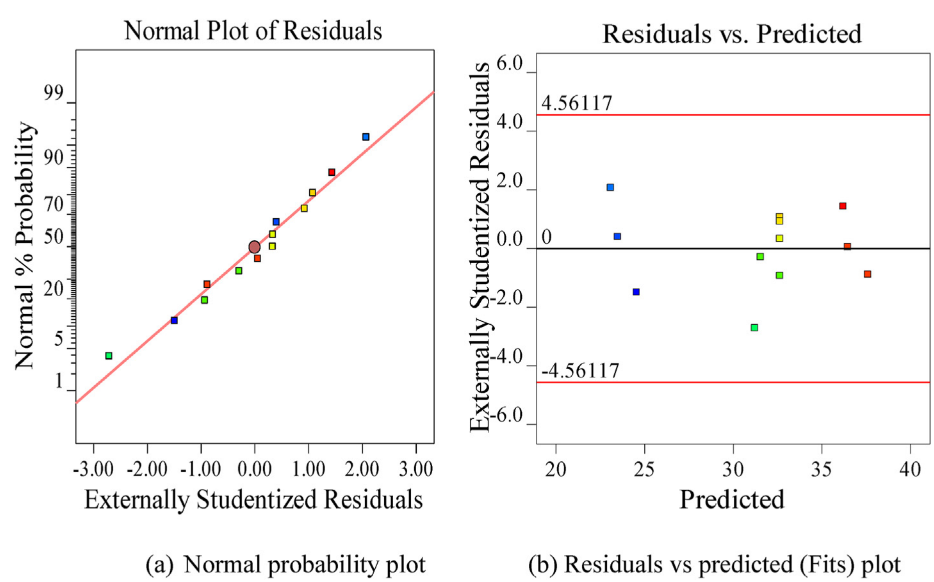


Figure 6. Diagnostic plots for 28-days compressive strength response.

3.4. Optimisation and model verification

The contour plots in Figures 7a and 7b illustrate the optimised conditions using desirability analysis of Design Expert 12. Desirability analysis is a crucial step towards establishing optimised preparation conditions showing best compromise amongst numerous responses [41].

From the contour plots (Figure 7a), 5% BCBP and 6.875% WTR are established as values that pronounce superior strength performance at lower cost. At these conditions, cost and 7-days compressive strength are KSh 13 718.43 and 27.607 MPa respectively. The overall desirability is 0.783. Checking these optimum values resulted in cost of KSh 13 718.42 and compressive strength of 27.65 (±0.46) MPa. The optimised cost showed excellent agreement with the cost computed using optimised independent variables. In addition, compressive strength from desirability analysis also agrees considerably with experimental findings after testing 6 cubes. It was confirmed that compressive strength improvement and cost reduction can be explained by the models.

Optimisation procedure of cost and 28-days compressive strength from desirability analysis gave 5% BCBP and 5.844% WTR as optimum values. The corresponding predicted cost and 28-days compressive strength values are KSh 13 734.64 and 33.970 MPa. A desirability of 0.705 (Figure 7b) illustrates the response closeness to its ideal parameter. Checking the cost response gave a value of KSh 13 734.63. The experimental optimum value of 33.92 (±0.43) MPa was also determined for 28-days compressive strength after testing 6 cube specimens. From these findings, one can note that the predicted optimal values are in reasonable agreement with the verified values.

Table 11. Diagnostic case statistics report for 28-days compressive strength response.

Run order	Actual value	Predicted value	Residual	Leverage	Internally studentised residuals	Externally studentised residuals	Cook's distance	Influence on Fitted Value DFFITS	Standard order
1	34.12	32.64	1.48	0.172	0.935	0.926	0.030	0.423	11
2	23.83	23.48	0.3414	0.790	0.429	0.402	0.115	0.780	4
3	34.33	32.64	1.69	0.172	1.068	1.081	0.040	0.493	10
4	31.16	32.64	-1.49	0.172	-0.939	-0.929	0.031	-0.424	12
5	28.79	31.22	-2.43	0.494	-1.962	-2.709	0.627	-2.678(1)	5
6	31.16	31.54	-0.3877	0.494	-0.313	-0.292	0.016	-0.289	6
7	36.51	36.47	0.0463	0.790	0.058	0.054	0.002	0.104	2
8	33.20	32.64	0.5600	0.172	0.354	0.331	0.004	0.151	13
9	24.44	23.08	1.36	0.790	1.709	2.072	1.833(1)	4.022(1)	3
10	37.28	36.21	1.07	0.790	1.338	1.436	1.124(1)	2.788(1)	1
11	33.21	32.64	0.5700	0.172	0.360	0.337	0.005	0.154	9
12	22.84	24.54	-1.70	0.494	-1.376	-1.492	0.309	-1.475	8
13	36.49	37.60	-1.11	0.494	-0.899	-0.885	0.132	-0.875	7

(1) Exceeds limits.

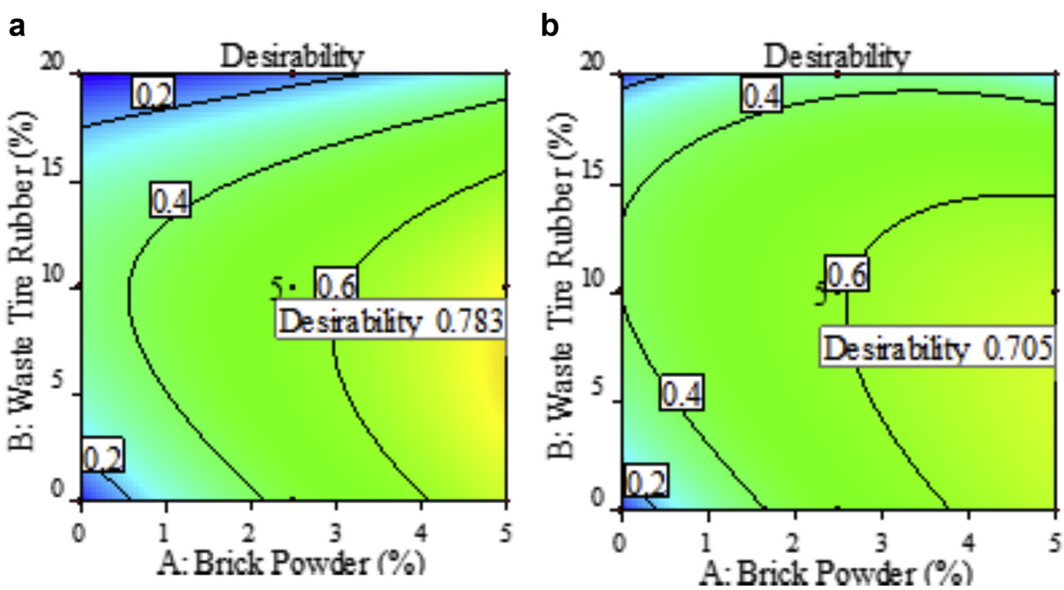


Figure 7. Optimisation of BCBP and WTR using desirability analysis.

4. Conclusion

The following conclusions were established from this research.

i. The production cost of rubberised concrete incorporated with BCBP and WTR is identified to be lower than that of normal concrete. From the findings, it is reasonable to appraise such sustainable construction.
ii. The findings from the linear and quadratic polynomial models used herein illustrate that the models were adequate in predicting the cost and compressive strength responses.
iii. It was found that 5% BCBP and 6.875% WTR improved the 7-days compressive strength at a lower production cost. In addition, 5% BCBP and 5.844% WTR were noticed to yield maximum 28-days compressive strength at lower cost.
iv. The developed optimised values provide attractive solution towards sustainable construction and waste management. RSM was found to give significant amount of information within short period and with lowest number of experiments.

Declarations

Author contribution statement

David Sinkhonde: Conceived and designed the experiments; Performed the experiments; Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data; Wrote the paper.

Richard Ocharo Onchiri, Walter Odhiambo Oyawa & John Nyiro Mwero: Conceived and designed the experiments; Analyzed and interpreted the data; Wrote the paper.

Funding statement

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

Data availability statement

Data will be made available on request.

Declaration of interests statement

The authors declare no conflict of interest.

Additional information

No additional information is available for this paper.

Acknowledgements

The authors would like to express their profound thanks to Jomo Kenyatta University of Agriculture and Technology for provision of laboratory equipment.

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