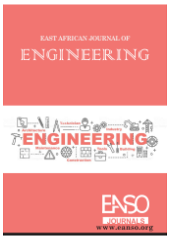

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Original Article

Effect of Cow Dung Ash and Recycled Concrete Aggregates on the Mechanical and Physical Properties of Concrete: Central Composite Design (CCD) Optimisation

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ABSTRACT

Globally, concrete constructions are dependable due to their performance under diverse conditions and the availability of concrete components. However, the potential for waste concrete is high as a result of changes in human needs. For the concrete industry's sustainable development, the ability to use recycled concrete is very important. This study aimed to investigate the effect of blending cow dung ash (CDA) with cement and waste concrete aggregates with natural coarse aggregates on concrete's mechanical and physical properties. The approach adopted involved natural coarse aggregates (NCA) substitution with recycled coarse aggregates (RAs) derived from demolished concrete fragments as well as the use of CDA as a fractional replacement for Portland cement in the production of concrete. Response surface methodology with the central composite design (CCD) option was employed in the establishment of the effect of varying the CDA and RA on the mechanical and physical properties of concrete. Results revealed that while embedding elevated amounts of CDA lowered concrete's compressive strength, a smaller percentage of less than 10% enriched the concrete strength past that of normal concrete. Furthermore, increases in the RA proportions from 20% to 30% translated to increases in the concrete compressive strength. The 5% CDA and 20% RA, 5% CDA and 30% RA and 10% CDA and 30% RA registered 0.88, 7.67 and 3.54% respectively greater than compressive strengths in the control experiment. In relation to water absorption, increases in proportions of CDA and RAs translated in 3.2% to 5.9% greater than water absorption rates in the control experiment. Therefore, optimised concrete of 8.80% CDA and 31.69% RA gives concrete with compressive strength of 36.82 MPa, 2315.4 kg/m3 bulk density, and 5.18% water absorption. However, CDA/RA concrete should not be used in areas where water accumulates and/ or structures that are in contact with water.

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INTRODUCTION

The building industry ranks high in material consumption, and it is responsible for 24% of the global material extraction and/ or depletion (Bribián et al., 2011). Universally, structures made from concrete have developed into the most dependable structures from the onset of the 20th century to date (Leopold et al., 2018). This is ascribed to both the concrete performance under different conditions and the availability of concrete components worldwide. Nonetheless, human needs change, and the potential for waste concrete is high even though designs are good (Yadhu & Devi, 2015). This is because the infrastructure changes and needs culminate in the production of construction and demolition (C&D) waste. According to Ibrahim (Ibrahim, 2019), waste generated from C&D is classified as major waste worldwide as the volumes are enormous. About 1.3 billion tonnes of solid waste worldwide are generated annually, of which building materials contribute half of the solid waste (Ramadevi & Chitra, 2017). In an address to journalists in Uganda, it was revealed that 75% of buildings within the Capital City were erected without approved plans, and plans were underway to have them demolished (Kanuniira, 2021). Despite the challenges encountered by the construction industry, the industry has the potential to substantially promote the sustainable management of resources in nature and minerals (Blankendaal et al., 2014).

In order to ensure sustainable growth in the concrete industry and the management of building waste, recycled concrete is a key component (Yehia et al., 2015). Malešev et al. (2010) study observed that recycled aggregate concrete (RAC) was satisfactorily performed, registering no significant difference from the control concrete's performance. Nonetheless, the recycled aggregate concrete test findings have been inconsistent or even in an opposite manner when compared with natural aggregate concrete with up to 50% increase in drying shrinkage 50% increase in creep (Domingo-Cabo et al., 2009), a 50% increase in water absorption (Hansen, 1992; Li, 2008), 25% decrease in compressive strength (Yang et al., 2008), 10% decrease in splitting and flexural tensile strength, 45% decrease in modulus of elasticity (Yang et al., 2008), similar to or reduced frost resistance (Zaharieva et al., 2004). In general, recycled aggregates' (RA) physical traits depend on the amount and quality of adhered mortar (Etxeberria et al., 2007). Butler et al. (2011) achieved compressive strength that was 28% higher than the natural aggregate concrete. These findings, however, conflict with trends discovered by Makul (2020), who maintained that the use of RA in place of natural aggregate results in a reduction in compressive strength. In the treatment for the enhancement of recycled aggregate, Katz (2004) observed that loose particles of cement bond covered the recycled aggregate, thereby preventing decent bonding between the recycled aggregate and the new cement matrix. This is because the old cement

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pastes, which stayed on the natural aggregate, were cracked and porous, resulting in the recycled aggregate's mechanical characteristics being weak. Hence, there is a prerequisite to enhance the recycled aggregate concrete's mechanical qualities. Furthermore, the recycled aggregate significantly absorbs more water than the natural aggregate because of the associated mortar (Malešev et al., 2010). In contrast to concrete having natural aggregate (NAC), RAC is less durable (Ibrahim, 2019). In addition it is of less weight as compared to NAC (Thakur et al., 2019). This study was also evidenced by Arezoumandi et al. (2015) who established that, the fact that recycled concrete has a relatively high porosity, increases both its water absorption rate and shrinkage in the RAC as it dries.

The undigested plant matter that passes through a cow's gut is known as cow dung, whereas cow dung ash (CDA) is produced by desiccating cow dung under the sun and then combusting it (Magudeaswaran & AS, 2018). Chemically, CDA is abundant in potassium, nitrogen, and calcium (Ojedokun et al., 2014). According to Venkatasubramanian et al. (2017), coconut fibre addition and CDA in definite proportions proves to boost the concrete strength, although the supplement of either coconut ash or CDA beyond a definite limit may lead to the strength of concrete decrease. It appears this behaviour is a result of the reduction of the strength-forming compounds (tricalcium silicate (C_3S) and tricalcium aluminates (C_3A)) in the melded cement as a result of cement being partially replaced with CDA (Samson & Moses, 2014). It is important to note that C_3S and C_3A are responsible to a great extent for early strength development (Manasseh, 2010).

Furthermore, according to Samson and Moses (2014) adding CDA to cement paste lengthens the curing time. It improves the consistency, while as the CDA grows, the compressive strength drops while curing age increases. Also, due to the huge voids in the matrix and the) weaker transition zone, compressive strength diminishes as CDA increases (Zhu et al., 2023). Increases in standard consistency could be attributed to the finer particles of CDA compared to cement, which subsequently escalates the surface area vacant for contact with water, thus the increase in the water demand of the CDA/ cement blended paste (Yilmaz, 2010). In a study conducted by Magudeaswaran and AS (2018), it was observed that a 10% increase in CDA in bricks led to a range of 6-8% water absorption. In addition, Ojedokun et al. (2014) noticed that the percentage of CDA increased with a decrease in concrete compressive strength and thus recommended that CDA concrete should be used only when 10% of CDA is added. An investigation done by Ramachandran et al. (2015) described that the rate of strength gain is relatively less during the early stage of hydration, and thus, CDA concrete mixes can be used for mass concrete applications where the the heat of hydration is a concern. All in all, during the manufacturing of concrete and mortar, CDA can be utilised as additional cementitious material. The conventional experimental optimisation can be to change one factor while maintaining the other factors constant; however, this consumes time and makes it a little complex to produce a wide range of settings for experiments (Yiga et al., 2023). However, experimental design, modelling and optimisation tools in the name of response surface methodology (RSM) have gained importance (Antonio et al., 2015).

RSM is advantageous in that it can provide optimum points in a short time and minimum efforts of computations in the analysis of experiments in which the desired responses are affected by a number of independent (Hong & Shi, 2020). The response surface plots are used in the range of points for optimum operation (Taieb et al., 2019). RSM is used to establish the important terms in the model and to generate response plots that are of importance in predicting the response (Umar et al., 2020). Consequently, RSM offers the finest approach to surmounting the difficulty and complexity of developing CDA-RCA concrete with the required mechanical and physical properties. The main designs of experiments used in RSM include the Box-

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Behnken design (BBD) (Umar et al., 2020), Central Composite Design (CCD) and Doehlert design. The designs are different from one another due to the series of experimental runs, levels of every factor and centre point (Vahdati & Rasouli, 2016). The CCD approach is the most popularly applied RSM design because it has centre, axial and factorial design points (Kumar et al., 2019; Sarafrazi et al., 2019). CCD takes on three forms: face-centred, inscribed, and circumscribed.

Nonetheless, the latter (circumscribed CCD) is the fundamental CCD, which does the test at five-factor levels and hence provides high excellence estimations over the whole design space. RSM-CCD generates three-dimensional (3D) surface response and contour (2D) plots (Bhatti et al., 2012), which explain the indirect or direct interactions of any two among the significant factors and their respective combined effect on the target response. This is appraised by way of expressions of polynomial form using minimal experimental runs (Bahrani et al., 2018; Sharma et al., 2017; Singh et al., 2018). Quite different statistical software has been employed to carry out RSM modelling including Matlab (Xiao et al., 2018), statistics (Antonio et al., 2015), Minitab (Rahimi et al., 2021), Design Expert (Kumar et al., 2019; Syuhadah et al., 2019) and Stratigraphic Centurion (Umar et al., 2020). The central composite design approach under RSM is conducted by using Minitab, Design Expert, Matlab and R-software packages (Asghar et al., 2014). However, a Design expert provides a simple, effective way to input and manipulate the statistical data and then executes effective solutions to address the target problem under study; thus, it provides the quickest modelling methodology (Nazir et al., 2017).

As a result, this research focussed on investigating the effect of blending cow dung ash with cement and waste concrete aggregates with coarse natural aggregates on the physical and mechanical concrete properties with a view to the possibility of using the waste concrete aggregates and cow dung ash as partial replacements of natural coarse aggregates and cement respectively in the generation of concrete. This would go a long way in reducing the amount of waste concrete aggregates and cement whose production negatively impacts the environment. Design of experiments and optimisation were performed using the central composite option of RSM, response surface methodology.

Study Objectives

The main objective of this study was to investigate the effect of blending cow dung ash with cement and waste concrete aggregates with natural coarse aggregates on concrete's mechanical and physical properties.

MATERIALS AND METHODS

Materials

Demolished concrete was obtained from the Nyagak III Hydro Power Project in the West Nile region of Uganda. The demolished concrete samples were crushed to a maximum nominal particle size of 20 mm for coarse aggregates and a minimum of 2 mm for the fine aggregates using a sledgehammer. The samples were screened and sieved to remove any impurities from the crashed concrete and thus termed RA. This RA was utilised as a partial substitute for natural coarse aggregates (NCA) in concrete. The NCA was obtained from the Maracha stone quarry site in the West Nile region of Uganda, and it is where the NCA for construction of the Nyagak III Hydro Power Project was obtained. Busitema village farms located in Eastern Uganda were the main source of Cow dung. The cow dung was dried in the sun, milled, and calcined under controlled conditions at temperatures between 400 and 500 ^{o}C. The resultant ash, after cooling, was ground by means of a mortar and pestle into finer particles and finally sifted using a sieve of 212 µm. Ordinary Portland cement (O.P.C. – CEM 1 42.5N) from Tororo Cement was employed for this study, whereas the river sand used in the study was derived from River Nyagak. Sieve analysis was conducted on the sand as per BS 812-103.1 (1985) in order to ascertain the particle size distribution. No tests were conducted on the Potable water that was used.

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Methodology

In this section, an overview of the steps undertaken in this study is described.

Experiment Design

Experimental Factors

True experimental research design was employed and used in this very study to establish the effect of CDA (A) and RA (B) on compressive strength, bulk density, and water absorption properties of concrete. The actual and coded factors at their respective coded and actual levels are given in *Table 1*.

Table 1: Experimental factors

Factors	Coded factors	Levels with coded and actual values				
		-α	-1	0	1	-α
CDA (%)	A	5	6	10	14	15
RA (%)	B	20	23	30	37	40

Design of Experiments and Model Fitting

RSM-CCD was used to examine the correlation between the paper properties and process conditions. In the design of the sets of experiments, two levels were sought, which included low (-1) and high (+1), as illustrated in *Table 1*. The star (axial) levels are placed at alpha (α) (alpha) from the centre level, and this renders the experimental design circumscribed and rotatable. The number of experiments is generated using Equation 1 (Bayuo et al., 2020; Sadhukhan et al., 2016).

$$N = 2^n + 2n + n_c \quad (1)$$

Where N is the overall total of experimental runs, n is a number of factors, and n_c represents the central number of experiments. This implies that a total of 13 runs for two factors (CDA and RCA additions) are generated with 4-star points, 4 factorial points and 5 centre points. The central experiments are simply replicated to reduce the experimental error and also establish how reproducible the data could be. The design of experiments was executed by State Ease Design Expert 13 statistical software.

Response surface and perturbation plots were generated to give a better view of the main factors' interaction effects on the responses. The 3D response surface plots advocate that all the terms, including the linear interaction terms as well as the square terms, elucidate just about all the response's variability. Therefore, a quadratic (square) term in each factor is crucial as influenced by the fold in the response surface plots on a 2-factor combination.

In order to develop a regression equation that portrayed the relationship between factors and responses, the numerical terms obtained were statistically fitted. The centre experiments were conducted to reduce the error in the experiments and to establish whether the data could be reproduced. In a bid to establish the finest fit for every concrete property (response), the particular sequential sum of square values for the model was considered. From each case, the polynomial with the uppermost order, where the model is not aliased and the additional terms are significant, was chosen, as reported by Yiga et al. (2021). With reference to this research, a non-linear quadratic regression model, which includes main, two-way interaction and square effects of the concrete additions, was assessed. Response surface plots were produced with the use of the model given by Equation 2 (Bayuo et al., 2020).

$$Y = \beta_o + \sum_{i=1}^{k} \beta_i x_i + \sum_{i=1}^{k} \beta_{ii} x_i^2 + \sum_{i=1}^{k-1} \sum_{j=i+1}^{k} \beta_{ij} x_i x_j \quad (2)$$

Where Y is the predicted response, x_i and x_j Are the coded factors, β_o, β_i, β_{ii}, and β_{ij} are constant (intercept on the response axis), linear, quadratic and interaction coefficients, respectively, and k is the number of factors. To examine the significance of each factor's individual effects and their interactions with the responses, an ANOVA based on a 5% significance level (alpha-value) was done. This statistical significance criterion

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provided a platform for model reduction. If the significance is less than 0.05 (P-value < 0.05), which lies in the area of the hypothesis rejection, the effect of the parameter considered was significant and remained in the model. Conversely, when the significance is greater than 0.05 (P-value > 0.05), the effect of the parameter considered is not significant; therefore, it is excluded from the model. Diagnostic plots for the scattering of the residuals, such as normal probability plots of the residual, actual versus predicted and plots of residuals versus fits and order, were applied.

Grading of Aggregates

Grading, of course, and fine aggregates (RA and NCA) were carried out with the objective of determining the distribution of particle size of the aggregates to be used in this very study since they influence the quality of concrete to be produced. Therefore, sieve analysis on both fine and coarse aggregates was conducted in agreement with BS 812-103.1(1985).

Determining Moisture Content of Fine and Coarse Aggregates

Moisture content affects the water-to-cement ratio used, hence affecting the durability and strength of concrete. This test aimed to determine the amount of water present in the fine and coarse aggregates evaluated as a percentage of the dry sample mass. The moisture content test was done in agreement with BS EN 1097-5 (1999).

Concrete Mix Design

Concrete mix design was done to finalise the fractions of concrete mix constituents (i.e., fine aggregates, cement, water, and coarse aggregates) and to produce concrete of desired properties. The target concrete class in this study was C25 because it can be used in all construction areas, and the concrete mix design was conducted in agreement with BS 5328-2 (1997). The quantities of materials required for 1 m3 of concrete and scaled down to 0.03 m^3 for this study are shown in *Table 2,* whereas the quantity of materials required for this study based on the experiment design is shown in *Table 3*.

Table 2 Material quantities required for concrete

Quantity(kg)	Cement	Fine aggregates (sand)	Coarse aggregates	Water	Total
Per m^3	422	750	986	205	2363
Per 0.03 m^3	12.66	22.50	29.58	6.15	70.89

Table 3 Material quantities required for concrete based on the experiment design.

	Quantity of materials in 0.03 m^3 of concrete (kg)									
Test no.	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
Cement	12.66	12.027	12.027	12.027	11.394	11.394	11.394	10.761	10.761	10.761
CDA	0.000	0.633	0.633	0.633	1.266	1.266	1.266	1.899	1.899	1.899
Fine aggregate	22.50	22.50	22.50	22.50	22.50	22.50	22.50	22.50	22.50	22.50
NCA	29.58	23.664	20.706	17.748	23.664	20.706	17.748	23.664	20.706	17.748
RA	0.000	5.916	8.874	11.832	5.916	8.874	11.832	5.916	8.874	11.832
Water	6.15	6.15	6.15	6.15	7.15	7.15	7.15	8.20	8.20	8.20

Concrete Slump Test

In order to establish the workability of the freshly mixed concrete, slump tests were conducted in accordance with BS EN 12390-2. (2000). Slump tests, thus, are an indirect measurement of fresh concrete consistency or stiffness.

Compressive Strength Test

The test on compressive strength was done in accordance with BS EN 12390-2 (BS EN 12390-2, 2000) so as to determine the concrete mix strength at seven days and 28 days. Three cubes of concrete, each measuring 150×150×150 mm were prepared for each test making it a total of 120 cubes with 60 crashed at 7 days and the remaining

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60 crashed at 28 days. Upon crashing, averages were taken for each test, and the results were analysed.

Water Absorption Test

The test on water absorption was done in accordance with BS 1881-122 (1983) so as to determine the pore volume of the concrete.

RESULTS AND DISCUSSION

The results and discussion of the investigations conducted in this study are presented in the underlying section.

Sieve Analysis

Plots for particle size distribution for fine aggregates, particle size distribution for NCA and particle size distribution for RA are shown in *Figure 1*, *Figure 2*, and, respectively. The sieve analysis plots show that the fine aggregates, the NCA and the RA fall within the limits specified by BS 812-103.1 (1985); thus, they are suitable for use in concrete.

Figure 1: Particle size distribution for fine aggregates

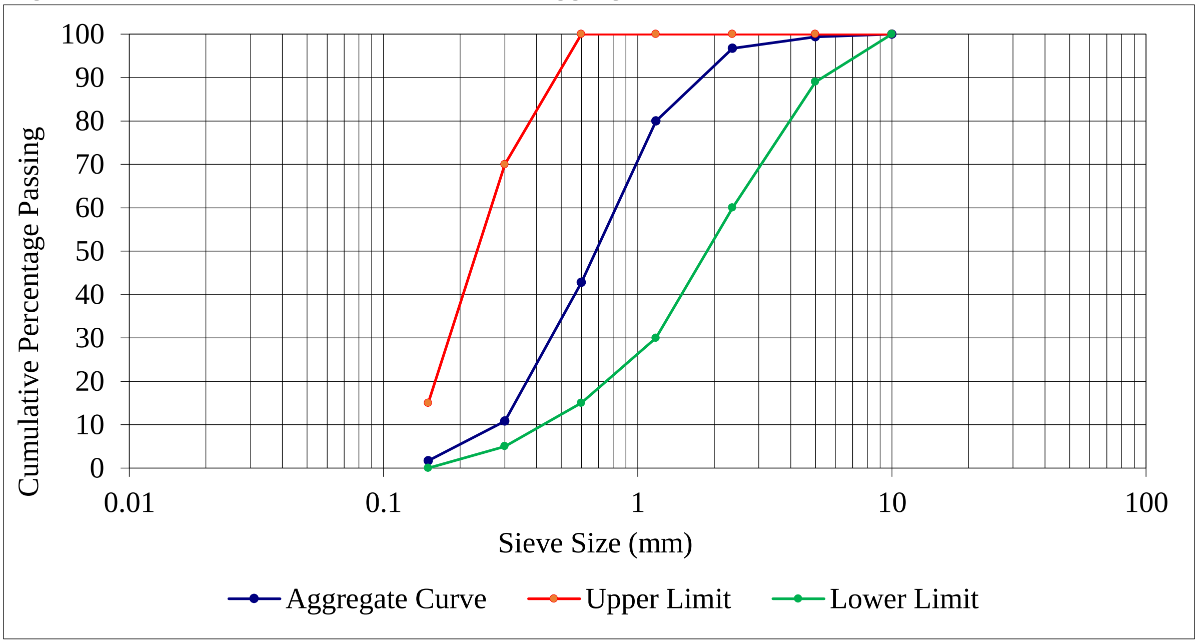

Figure 2: Particle size distribution for NCA

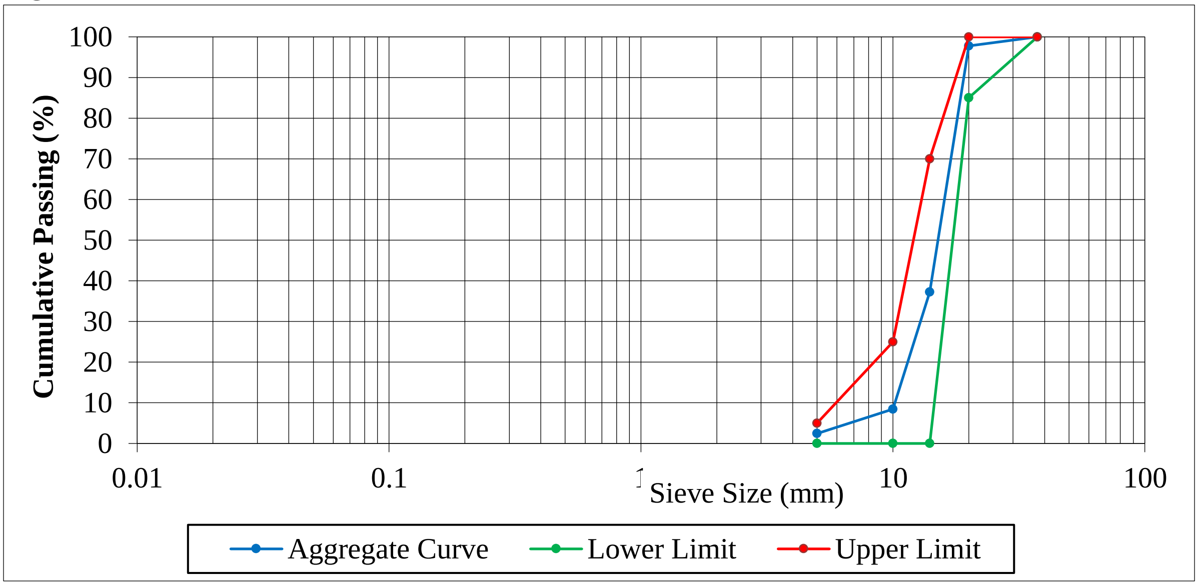

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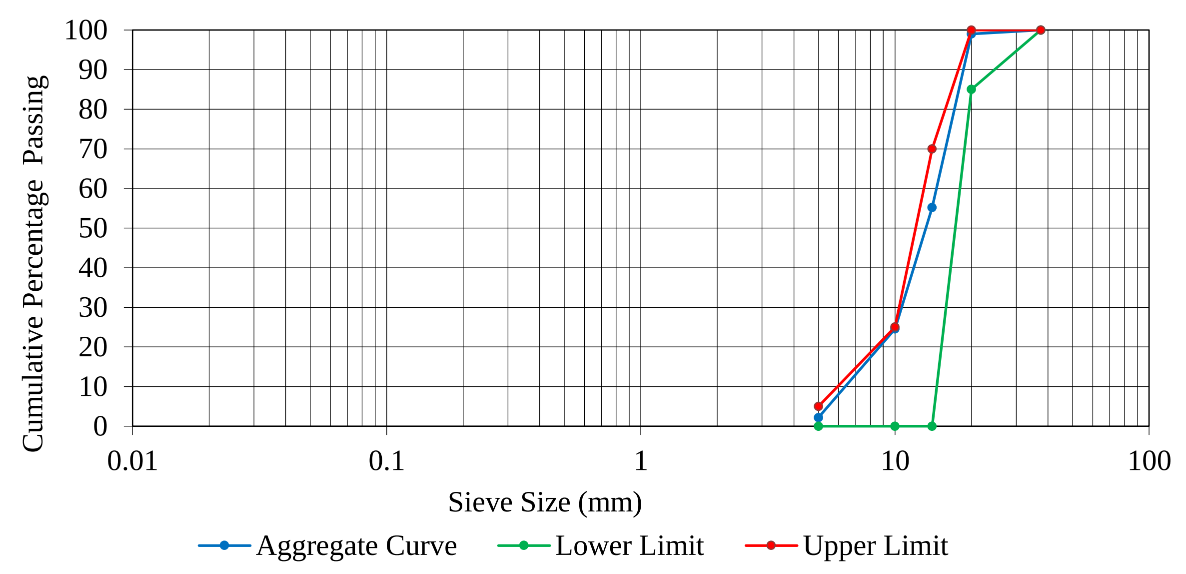
Figure 3: Particle size distribution for RA



Moisture Content

The moisture content results for the fine aggregates, NCA and RA are shown in *Table 4*. From the results, the fine aggregates had the highest moisture content, followed by RA and NCA, which did not have any moisture content. The highest moisture content in the fine aggregates is attributed to the fact that the sand was obtained from River Nyagak. Conversely, the water contained in the RA is attributed to the old porous cement paste that was retained on the aggregate, thus creating voids for moisture. This is consistent with observations made by Katz (2004).

Table 4 Moisture content for the aggregates

Aggregates	Fine aggregates	NCA	RA
Weight of the wet sample W_t (g)	492.0	415.5	443.0
Weight of the oven-dried sample W_d (g)	465.0	415.5	442.5
Moisture content (%) = $(W_t-W_d)/(W_d)$	6.59	0.00	0.11

Concrete Slump

Results of the concrete slump are shown in *Table 5*, and it is evident that they are within the limits of the desired slump of 60 – 180 mm as specified by BS EN 12390-2 (BS EN 12390-2, 2000). However, there was a decrease in workability and an increase in consistency with increases in CDA and increases in RA. The decreases in workability and increases in consistency with increases in RA are attributed to the old porous cement on the RA surface, which led to increased absorption of water by the RA, and this is consistent with observations made by Katz (2004). On the other hand, the decreases in workability and increases in consistency with increases in CDA could be attributed to the finer particles of CDA compared to cement that subsequently increases the surface area available for contact with water, thus increasing the water requirement of the CDA/ cement blended paste as observed by Yilmaz (2010).

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Table 5 Concrete slump results

Mix type	Slump (mm)
Control experiment (normal mix)	101
Trial mix 1 (5% CDA and 20% RA)	100
Trial mix 2 (5% CDA and 30% RA)	99
Trial mix 3 (5% CDA and 40% RA)	98
Trial mix 4 (10% CDA and 20% RA)	97
Trial mix 5 (10% CDA and 30% RA)	98
Trial mix 6 (10% CDA and 40% RA)	97
Trial mix 7 (15% CDA and 20% RA)	95
Trial mix 8 (15% CDA and 30% RA)	95
Trial mix 9 (15% CDA and 40% RA)	94

Experimental Design Results

The levels of the well-thought-out factors of CDA (A) and RA (B) with their corresponding results for the selected concrete properties at the age of 28 days, which included bulk density, compressive strength and water absorption, are presented in *Table 6*. The age of 28 days yielded better results and thus were recorded in *Table 6*.

Table 6: Experimental design matrix with responses

Runs	Factors		Responses		
	CDA	RA	Bulk density	Compressive strength	Water absorption
	%	%	Kg/m^3	MPa	%
1	10	30	2312	35.1	5.0
2	6	37	2358	32.3	5.7
3	10	30	2317	36.4	5.2
4	10	20	2386	22.1	5.0
5	14	37	2309	28.6	6.8
6	5	30	2321	37.8	5.0
7	14	23	2368	24.5	6.7
8	10	30	2313	35.5	5.1
9	10	30	2302	34.7	5.2
10	10	30	2318	36.2	6.1
11	10	40	2368	32.3	5.6
12	6	23	2401	25.6	5.6
13	15	30	2304	23.4	7.7

The CDA and RA effect on the concrete properties was derived from the central composite design of experiments. The model for each response was generated and evaluated, with results and discussions presented in the underlying sections. The effect of CDA and RCA on three responses, which included bulk density, compressive strength and water absorption, were discussed with reference to results in *Table 6*.

Bulk Density

The results obtained reveal that the inclusion of CDA and RA has a significant decrease in the concrete density, as illustrated in the perturbation plot (*Figure 4b*). With the addition of CDA, the density reduces gradually along the design level values (5 – 15 % CDA). However, for RCA, the density reduced up to the middle level (20 – 30 % RA), which is in agreement with Rahman et al. (2022), who registered a significant decrease, and thereafter, it gradually increased. As the percentage contents of Cow Dung Ash and Recycled Concrete Aggregates grow, the Cubes' Density falls. The weight of the concrete being light discloses the existence of CDA and RA, and the greater the percentages of CDA, the lighter the concrete. This is because the produced recycled concrete has a moderately high porosity, resulting in an increase in the RAC shrinkage when it is dry, as well as its rate of water absorption

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(Arezoumandi et al., 2015). Additionally, investigations comparing the effectiveness of natural or high-performance concrete with and without the application of RA show that conventional concrete has comparably higher values for the same attributes (Makul, 2020). The recycled concrete performs well with a limited percentage of < 10 % CDA and < 31 % RA. The gains of CDA/RA concrete proffers lightness of weight and low thermal conductivity, making it a valuable construction material (Thakur et al., 2019). As expected, the mixes' hardened density decreases with the incorporation of RA particles as it has less density than the natural aggregates. Furthermore, the angularity of the RA can reduce compacting capacity, resulting in a lower hardened density of the recycled concrete. RA's specific gravity is subordinate to the natural aggregates (Makul, 2020). Therefore, an increase in the concentration of RA has a substantial influence on the reduction of concrete density, as illustrated in *Figure 4b*. The interaction of the CDA and RA on bulk density has been illustrated in *Figure 4a* with an optimum density of 2315.14.

The model is thus adequate with R^2 of 0.89 and Adjusted R^2 of 0.80. Making predictions about the response for particular levels of each factor can be done using the equation in terms of coded factors. By comparing the factor coefficients, equation 3 can be used to establish the relative impact of the factors.

$$\text{Bulk density} = 2311.73 + 12.81\,A - 15.96\,B - 212.53\,C - 35.79\,B^2 \quad (3)$$

Table 7: ANOVA for bulk density

Source	Sum of Squares	df	Mean Square	F-value	p-value	Remark
Model	12556.54	5	2511.31	10.86	0.0034	Significant
A-CDA	1496.22	1	1496.22	6.47	0.0384	Significant
B-RA	2018.27	1	2018.27	8.73	0.0213	Significant
AB	64.00	1	64.00	0.2768	0.6150	Not significant
A^2	164.50	1	164.50	0.7116	0.4268	Not significant
B^2	8940.73	1	8940.73	38.68	0.0004	Significant
Residual	1618.23	7	231.18			
Lack of Fit	1457.03	3	485.68	5.85	0.0680	Not significant
Pure Error	161.20	4	40.30			
Cor Total	14174.77	12				

In the model, A and B are linear terms, AB is an interaction term and A^2 and B^2 are square terms. The model expressions show the model term's synergistic influence toward the response as a positive sign before the coefficient and its antagonistic effect as a negative sign. According to ANOVA (*Table 7*), the linear effects of CDA and RA and the square effect of RA were significant with a p-value < 0.05. The interaction effect and square effect of CDA were not significant since the p-value was> 0.05.

Diagnostic plots for the dispersion of the residuals, including plots of the residual's normal probability versus fits and order, were applied. The conjecture of independence, normality and randomness of the residuals matched, satisfied and were suitable (*Figure 4c* and *d*). Consequently, the lack of fit of the models was inconsequential. The regularity assumptions were also gratified as the normal probability plots approximated along a straight line. The non-significant lack of fit and p-model p-value < 0.05 (*Table 8*) supports these diagnostics.

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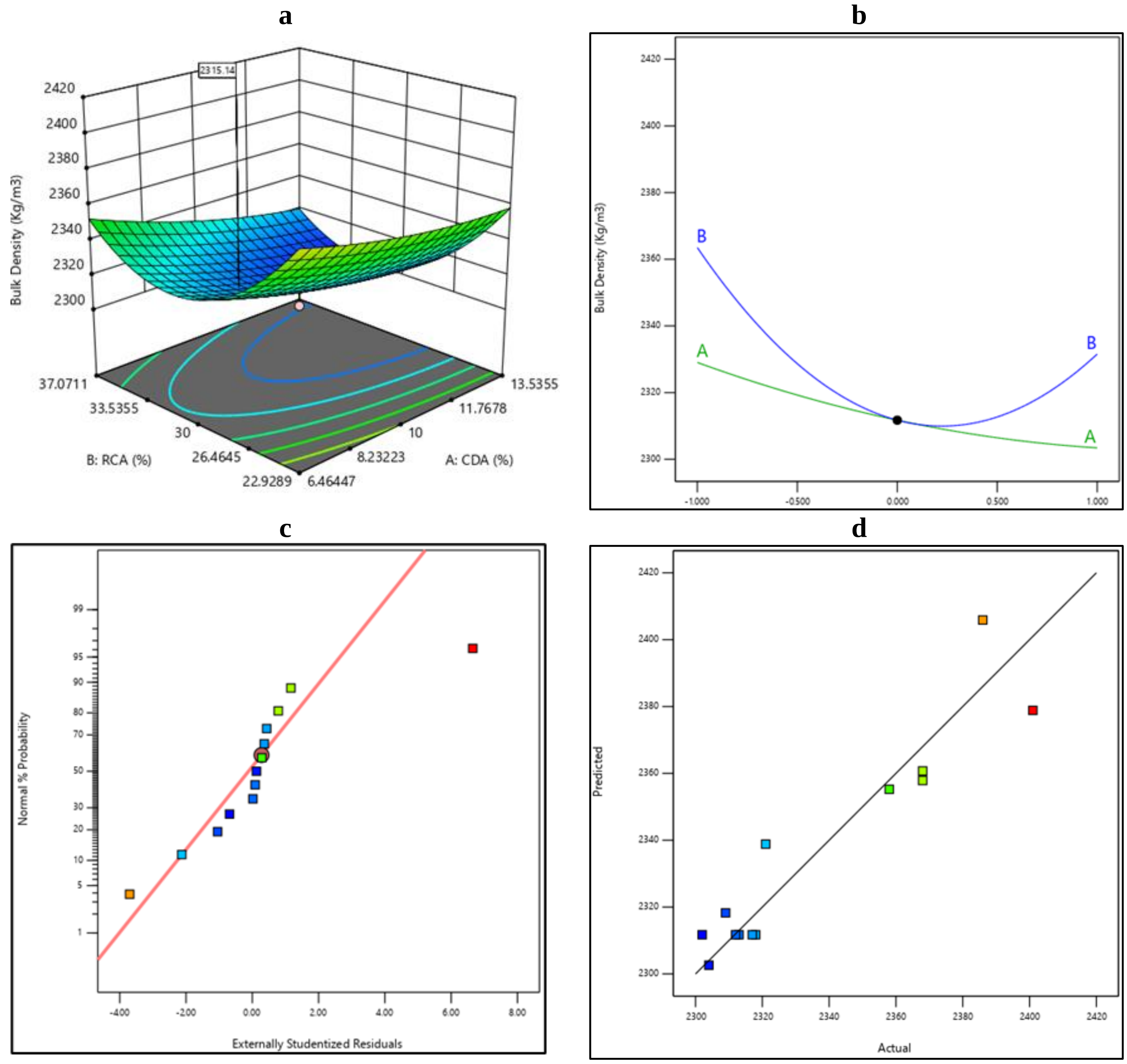
Figure 4: (a) Response surface (b) perturbation plot (c) Normal probability-residual (d) predicted-actual values for bulk density of concrete.



Compressive Strength

Compressive strength slightly decreased with an increase in CDA up to 10 %, and beyond this, it decreased exponentially with CDA inclusion. The compressive strength increased exponentially with an increase in RA up to 30 %, beyond which further increase led to almost a constant strength.

The main effects of CDA and RA are illustrated by the perturbation plot (*Figure 5b*). The average compressive strength slightly decreased with an increase in CDA up to 10 %, and beyond this, it decreased exponentially with CDA inclusion. Whereas the average compressive strength increased with increases in RA proportions up to 30%, after which it decreased. The decreases in the average compressive strength with increases in CDA proportions could be attributed to the reduction of C_3S and C_3A, which are strength-forming compounds in the blended cement as a result of partial alternative of cement with CDA as noted by Samson and Moses (2014) Furthermore, literature declares that CDA comprises of cementitious materials enriched with silica which is a pozzolanic material (Ramachandran et al., 2018). When nano-silica reacts with calcium hydroxide generated from the primary hydration of cement, it is converted into additional C-S-H, which is the supporting constituent for strength and density in the hardened cementitious system. The uneven distribution of CDA in the cement matrix is

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another factor that contributes to the decline in compressive strength, resulting in a large number of voids or pores in the cement matrix and a weaker transition zone at the interface (Zhu et al., 2023). Since the rate of strength gain is relatively less during the early stage of hydration, CDA concrete mixes can be used for mass concrete applications where the heat of hydration is a concern (Ramachandran et al., 2015).

The equation in terms of coded factors can be made use of to make forecasts about the compressive strength for given levels of each factor. The coded equation (4) is beneficial for identifying the relative impact of the factors by comparing the factor coefficients. The model is thus adequate with R^2 of 0.89 and Adjusted R^2 of 0.8

$$\text{Compressive strength} = 35.6 - 2.83\,A + 3.17\,B - 2.65\,A^2 - 14.32\,B \qquad (4)$$

Table 8: ANOVA for Compressive Strength

Source	Sum of Squares	df	Mean Square	F-value	p-value	Remark
Model	329.96	5	65.99	11.38	0.0030	Significant
A-CDA	72.96	1	72.96	12.59	0.0094	Significant
B-RA	79.65	1	79.65	13.74	0.0076	Significant
AB	1.69	1	1.69	0.2916	0.6060	Not significant
A^2	57.01	1	57.01	9.83	0.0165	Significant
B^2	130.02	1	130.02	22.43	0.0021	Significant
Residual	40.58	7	5.80			
Lack of Fit	38.51	3	12.84	1.83	0.0848	Not significant
Pure Error	2.07	4	0.5170			
Cor Total	370.54	12				

The model F-value of 11.38 infers that the model is significant. An F-value this large could only happen due to noise with a 0.30% probability**.** Model terms are significant for a p-value less than 0.0500. From the ANOVA (*Table 8*), the significant model terms are A, B, A^2, and B^2. The lack of fit P-value of 0.0848 implies the Lack of Fit is not significant. A large lack of fit F-value could occur due to noise, with a mere 8.48% likelihood. A significant lack of fit is good.

The observations with respect to CDA fractions are in unison with Ojedokun et al. (2014), who noted that concrete compressive strength decreases with increases in the CDA percentage and thus recommended that CDA concrete should be used only when CDA does not exceed 10%.

Conversely, increases in the average concrete compressive strength with increases in the RA proportions up to 30% and then decreasing when the proportion of the RA was increased to 40% could be attributed to differences in the amount of loose particles of cement paste that cover the RA thus interfering with the bonding between the recycled aggregate and the new cement matrix as evidenced by Katz (2004). This observation is harmonious with the results of Malešev et al. (2010), who noted that concrete from recycled aggregates performs satisfactorily with no significant difference from the performance of control concrete. The fact that compressive strength declines with greater RA concentration (> 30%) increment clearly indicates that RA significantly increases the amount or number of voids in the concrete mixtures. Additionally, the strength is decreased because the cohesion force between the cement and the RA surface is weaker than that between the cement matrix and NCA (Rahman et al., 2022). In addition, the decrease could be ascribed to differences in the amount of loose particles of cement paste that cover the RA, thus interfering with the bonding between the recycled aggregate and the new cement matrix, as evidenced by Katz (2004).

However, the interaction of CDA/RA (*Figure 5a*) gives an improvement of compressive strength from 28.1 MPa (natural concrete) to 36.8 MPa with 8.79 % CDA and 31.69 % RA, giving an overall increase in compressive strength by 31.03

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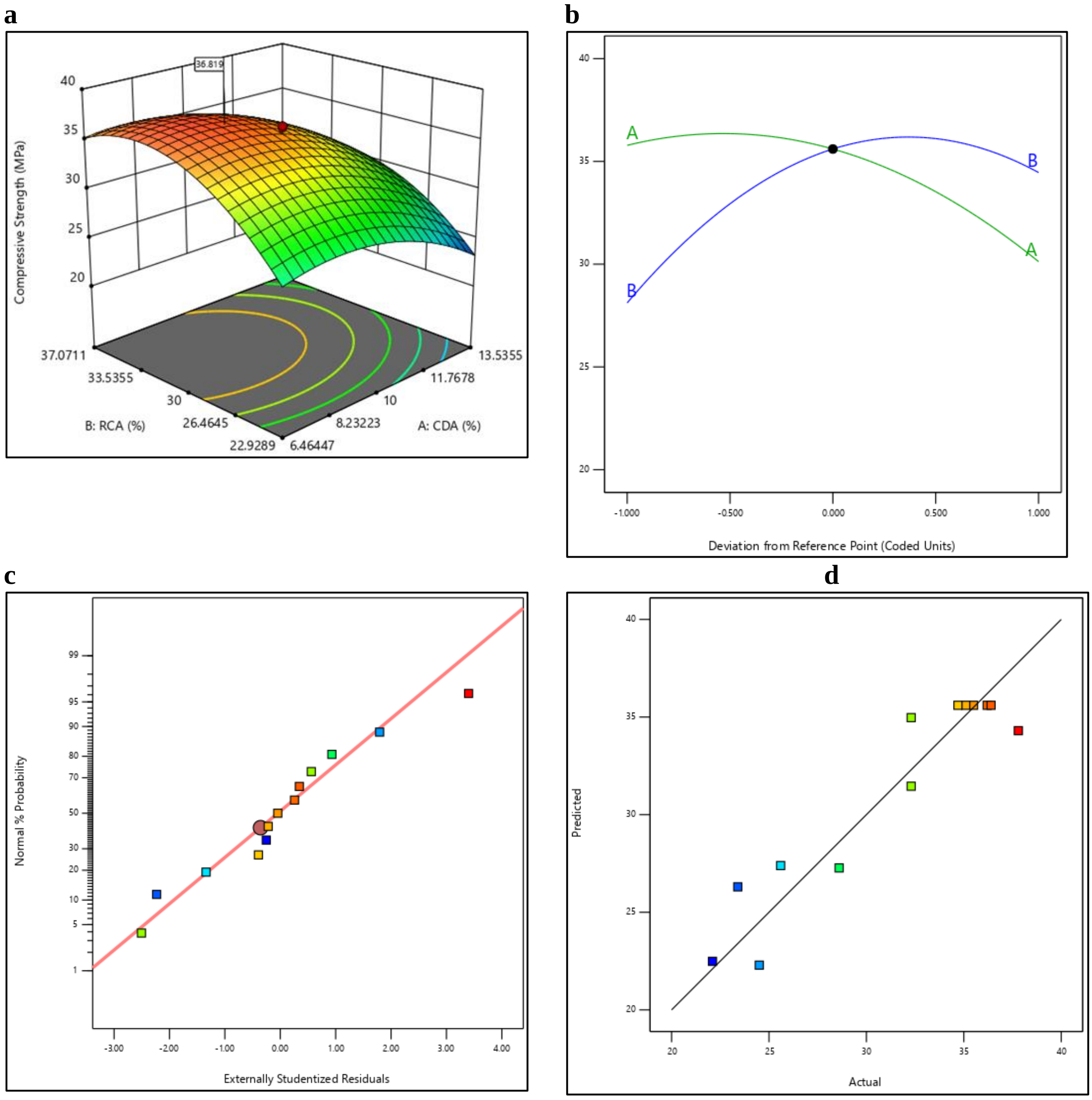
%. This is in close agreement with Butler et al. (2011), who achieved compressive strength that was 28% higher than the natural aggregate concrete. However, these values are in divergence from trends discovered in the literature that have given an account of a diminution in compressive strength when natural aggregate is substituted with RA (Makul, 2020). Failure planes around the aggregate show that the mortar-aggregate interface, also known as the interfacial transition zone (ITZ), is the limiting strength component or factor. When taking into account the recycled concrete, which comprises the adhered mortar and the original natural aggregates, this proposes that either the new or the old ITZ is the restraining strength factor. Failure planes that arise through the coarse aggregate suggest that the limiting strength factor is the strength of the coarse aggregate itself (Rahman et al., 2022).

Figure 5: Response surface (a) and perturbation plot (b) for bulk density (c) Normal probability-residual (d) predicted-actual values of concrete compressive strength.



The assumptions of randomness, independence and normality of the residuals were suitable, matched and satisfied, as shown in diagnostics (*Figure 5c* and *d*); therefore, the lack of fit of the models was insignificant. The normality assumptions were as well satisfied as the normal probability plots approximated along a straight line. The non-significant lack of fit and p-model p-value < 0.05 (*Table 8*) supports these diagnostics.

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Water Absorption

water absorption Outcomes for CDA/RA-modified concrete are presented in *Figures 6a* and *b*. From the results, it is clear that increases in both CDA and RA proportions translate to increases in water absorption of the trial mixes when compared with the control experiment. Nevertheless, RA registered a slight increase. This is attributed to both the fines within the CDA and the attached mortar on the recycled aggregate, which significantly absorb water, and this observation is consistent with studies conducted by Magudeaswaran and AS (2018) and Yilmaz (2010). The relationship of the control mix with CDA/RA mixes has portrayed that the mixes, prepared with the incorporation of the CDA, have higher water absorption up to the optimal level of substitutions (8.76 % CDA and 31.69 % RA). The gain in the volume of voids leads to an increase in water absorption capacity. It is observed till about 10% CDA and 30 % RA replacement.

Predictions regarding the water absorption for specific levels of each factor can be made using the equation in terms of coded factors. The coded equation (5) helps determine the relative impact of the factors by comparing the factor coefficients. The model is thus adequate with R^2 of 0.51 and Adjusted R^2 of 0.42.

$$\text{Water Absorption} = 397.23 - 56.64\,A + 56.78\,B + 38.07\,C \quad (5)$$

Table 9: ANOVA for water absorption

Source	Sum of Squares	df	Mean Square	F-value	p-value	Remarks
Model	7.27	5	1.45	7.14	0.0113	Significant
A-CDA	4.36	1	4.36	21.44	0.0024	Significant
B-RA	0.1383	1	0.1383	0.6795	0.4369	Not significant
AB	8.882E-16	1	8.882E-16	4.365E-15	1.0000	Not significant
A^2	2.77	1	2.77	13.60	0.0078	Significant
B^2	0.0135	1	0.0135	0.0665	0.8039	Not significant
Residual	1.42	7	0.2035			
Lack of Fit	0.6365	3	0.2122	1.08	0.4535	Not significant
Pure Error	0.7880	4	0.1970			
Cor Total	8.69	12				

As indicated by the model's F-value of 7.14, it is significant. An F-value this large could only occur owing to noise with a 1.13% probability. Model terms are considered significant when the P-value is less than 0.0500. The significant model terms from ANOVA (*Table 9*) are A and A^2. The Lack of Fit P-value of 0.4535 infers the Lack of Fit is not significant relative to the pure error. A Lack of Fit F-value this large could be caused by noise with a probability of 45.35%.

Similarly, the conjectures of randomness, normality and independence of the residuals were suitable, matched and satisfied, as shown in diagnostics (*Figure 6c* and *d*); therefore, the lack of fit of the models was insignificant. The normality assumptions were also fulfilled as the normal probability plots approximated along a straight line. The non-significant lack of fit and p-model p-value < 0.05 (*Table 9*) supports these diagnostics.

Optimal points of the predictor were established at the respective maximum points of the responses. The second-order polynomial models (equations (3), (4), and (5) developed in this analysis were made use of for the responses in demand to obtain specific optimum input factors. The response optimisation exercise was performed at a composite desirability of 0.913 in Design Expert 13. The optimum process conditions were 8.80 % CDA and 31.70 % RA. At these optimum conditions, the concrete properties are 2315.4 kg/m^3 bulk density, 36.82 MPa and 5.18 % water absorption, thus adequate for the better performance of the concrete in building applications. The bulk density is in close agreement with Butler et al. (2013), who obtained recycled concrete of 2400 kg/m^3 with a 35 %

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addition of RCA. The compressive strength is in close agreement with Fakitsas et al. (2012), who obtained 37.5 MPa with 30 % addition of RCA. As well, the water absorption is in line with Mbereyaho et al. (2020) and Venkatasubramanian et al. (2017), who obtained 6.8 % water absorption with 5 % CDA addition.

Figure 6: Response surface (a) and perturbation plot (b) for bulk density (c) Normal probability-residual (d) predicted-actual values for the water absorption of concrete.

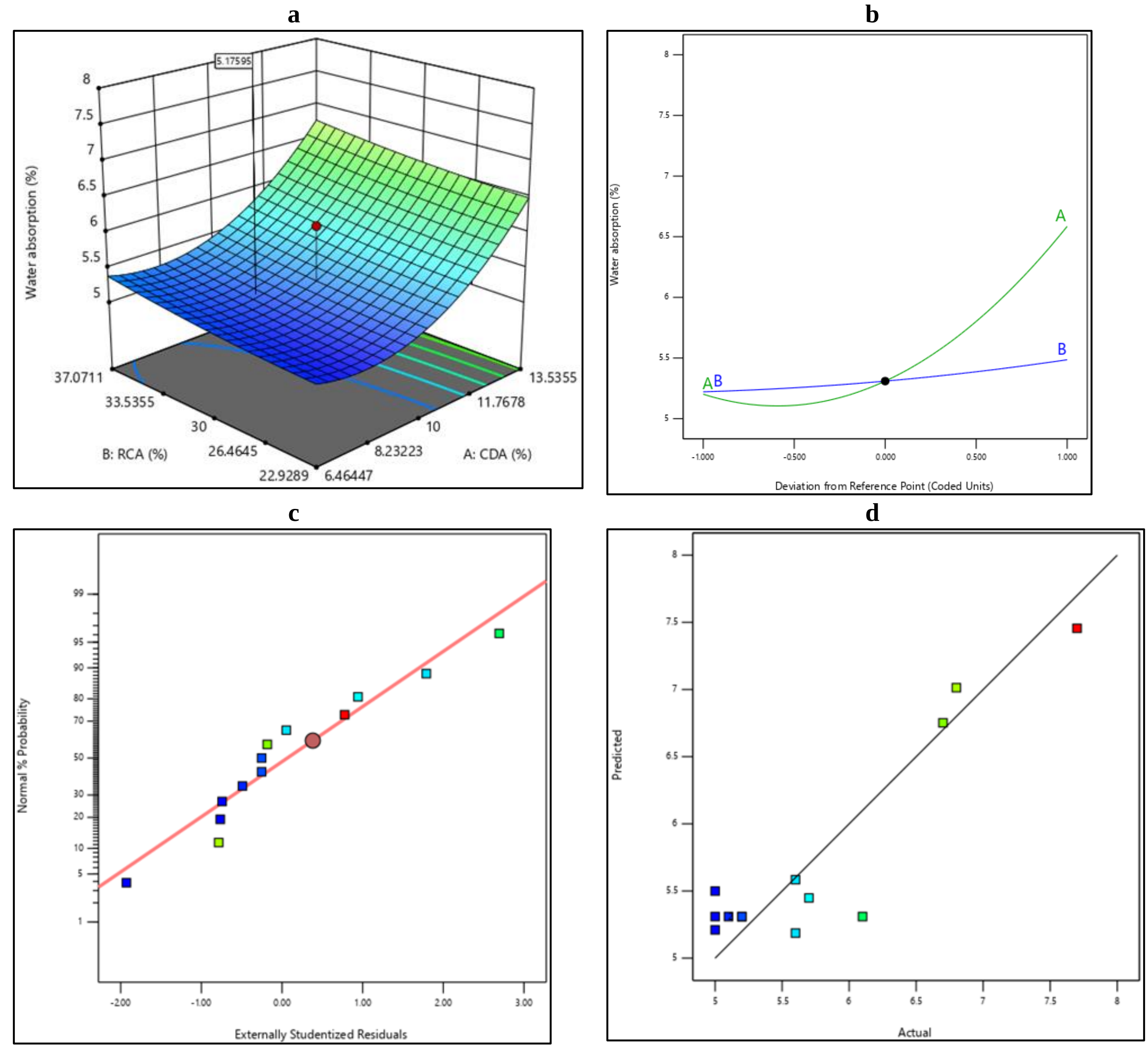

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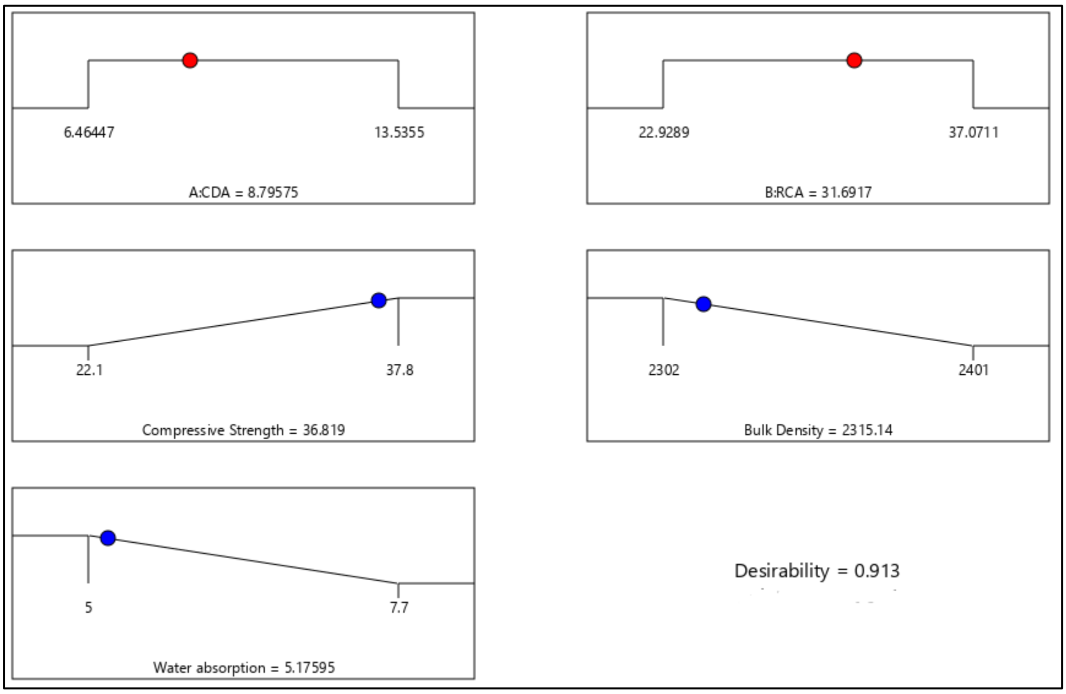
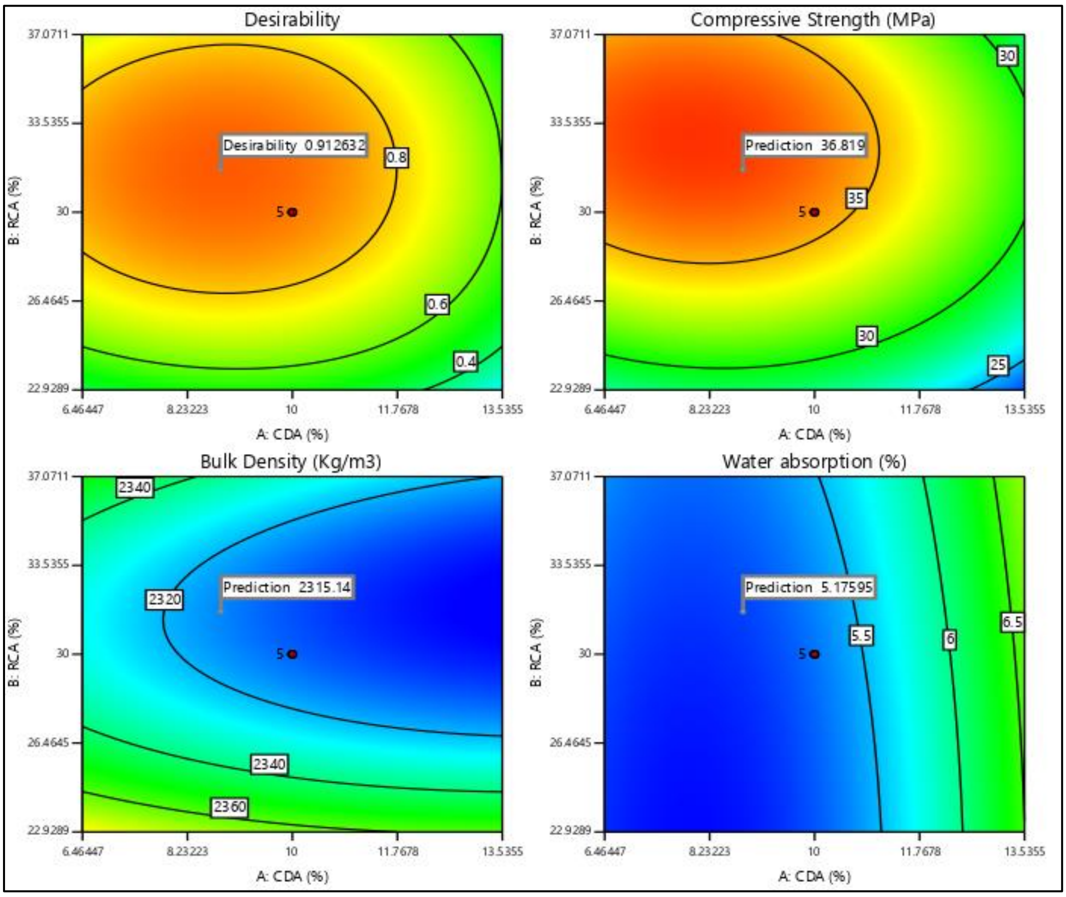
Figure 7: Desirability ramps for the responses



The normal concrete had a density of 2407 kg/m3, a water absorption capacity of 1.8 % and a compressive strength of 28.1 MPa. The inclusion of CDA and RA in the normal concrete thus gives a percentage reduction of density by 3.8%, an increase in water absorption by 187.8 % and an increase in compressive strength by 31.03 %.

Figure 8: optimisation of CDA and RA



CONCLUSIONS

In general, the slump of concrete blended with the several proportions of CDA and RA were within limits of the desired slump of 60 – 180 mm as specified by BS EN 12390-2 (BS EN 12390-2, 2000). Response surface methodology (RSM) with central composite design was employed to explore the effect of CDA and RCA on bulk density, water absorption and compressive strength of concrete. It has been reflected that an increase in proportions of CDA from 5% through 10% to 15% translated to decreases in concrete compressive strength, while increases in the RA proportions from 20% to 30% translated to increases in the concrete compressive strength. However, concrete with proportions of 40% RA resulted in decreases in the compressive strength. The optimum process conditions were 8.80 % CDA and 31.70 % RA. At these optimum conditions, the concrete properties are 2315.4 kg/m^3 bulk density, 36.819 MPa and 5.18 % water absorption, thus adequate for the better performance of the concrete in building applications. With regards to water absorption, concrete with proportions of CDA and RA had water absorption rates varying from the control experiment in the range of 3.2% to 5.9%. Therefore, for improved concrete compressive strength, concrete with proportions of 8.80 % (5 – 10%) CDA and 31.70 % (30 – 35%) RA should be adopted. However, concrete blended with CDA and RA should not be used in areas where water accumulates and/ or structures that are in contact with water.

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