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Original Research Article

Modeling and Optimization of Concrete Compressive Strength Produced by Replacing Natural Aggregate with Recycled Coarse and Recycled Asphalt Pavement Aggregates

Adamu Lawan[1*], Aliyu Abubakar Abbas[2], Joshua Ochepo[3]

[1]Department of Civil Engineering, Ahmadu Bello University, Zaria, Nigeria (PhD)
[2]Student, Department of Civil Engineering, Ahmadu Bello University, Zaria, Nigeria
[3]Department of Civil Engineering, Ahmadu Bello University, Zaria, Nigeria (PhD)

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***Corresponding author:** Adamu Lawan
Department of Civil Engineering, Ahmadu Bello University, Zaria, Nigeria

Abstract

The modeling and optimization of concrete compressive strength produced by replacing natural aggregate (NA) with recycled coarse aggregate (RCA) and recycled asphalt pavement (RAP) aggregates was investigated. The materials used were cement, water, fine aggregate, and coarse aggregate (NA, RCA, and RAP). The RCA and RAP replaced NA at 20, 40, 60, 80, and 100% separately, and in combination, with a total of two hundred and forty (240) cubes cast, while the concrete compressive strength was determined after curing by complete immersion in water at 3, 7, 14, 21, and 28 days. The modeling and optimization was done with the aid of design expert (version 13) software, while the Analysis of Variance (ANOVA) was done using SPSS (Statistical Package for Social Sciences) version 23 and adopting the Least Square Difference (LSD) method. Results from the findings showed that the optimum 28 days concrete compressive strength are concrete produced with 20%RAP, 40%(20%RAP +20%RCA), 60%(30%RAP + 30%RCA), and 80%(40%RAP + 40%RCA) replacements which are not significantly different from the control concrete, however, 40%(20%RAP +20%RCA) and 80%(40%RAP + 40%RCA) concrete had compressive strength higher than the control concrete. Also, the 3, 7, 21, and 28 days compressive strength can be predicted with quadratic model, while the 14 days strength can be predicted with 2-Factor Interaction (2FI) model. The optimization result showed that by replacing natural aggregate with 10.0% RAP and 50.0% RCA, the 28 days compressive strength of the concrete was 33.74N/mm^2.

Keywords: Cement, Concrete, Compressive-strength, Aggregates, Modeling, Optimization.

1.0 INTRODUCTION

Concrete is amongst the most commonly utilized construction materials in use now adays. The concrete comprises of not less than 75% by volume of aggregate materials which are usually found locally, in some areas, it is economical to substitute natural aggregates (NA) with more abundantly available materials in the production of concrete. Several research over the years have dealt with the issue of aggregate supplies and demands and the probable use of waste materials as aggregates for concrete (Okafor, 2010). Effort have been made to introduce a replacement of natural aggregates in conventional concrete with locally available materials like sintered domestic refuse (Wainwright & Boni, 1983) palm kernel shell (Okafor, 1988) palletized blast furnace slag (Mayfield & Louati, 1990) and several recycled concrete (Evangelista & de Brito, 2007; Sri Ravindrarajah *et al.*, 1987). Yet, shortage of NA for production of concrete in some parts within Nigeria call for an alternative that will produce almost the same required strength. Also, the need for improved methods of solid waste disposal and energy conservation has contributed to the increased attention in this development.

Reclaimed Asphalt Pavement (RAP) materials are usually dumped in the open areas, creating environmental nuisance to the community. Recycling industries in many parts of the world convert low-value waste into secondary construction materials such as a variety of aggregates and other construction components. These materials are often used for road construction materials, backfill for retaining walls, low-grade concrete production, drainage and brick-work of block work for low-cost housing (Rashwan & AbouRizk, 1997).

Recycled Coarse Aggregate (RCA) replacement of NA in concrete have a very positive effect on the environment because it reduces the production of non-renewable natural resource such as Natural aggregate. Also, contribute positively by reducing the landfill areas which will lead to decrease in air and water pollutions. Many studies were conducted to examine the influence of using RCA in concrete toward yielding a developmental usage of recycled materials in concrete for construction purpose that will be economical and safe (Bui *et al*., 2017; Choi & Yun, 2012; Dimitriou *et al*., 2018; Guo *et al*., 2018; McGinnis *et al*., 2017; Omary *et al*., 2016; Pedro *et al*., 2017; Seo & Choi, 2014; Shi *et al*., 2016; Verian *et al*., 2018; Wijayasundara *et al*., 2018; Yildirim *et al*., 2015; Zhou & Chen, 2017)

Recycling construction materials has two main environmental importance i.e., it saves energy and decreases landfill waste, recycling saves large quantities of energy, and in general it reduces the consumption of natural resources in producing new materials and also decreases greenhouse emissions, which aid to tackle climate change by averting pollution which eliminates the need to collect new raw materials. Construction materials are ever more judged by their ecological features. Concrete reutilizing (both RAP/RCA) gains relevance since it protects natural resources and eradicates the necessity for disposal by using the available concrete as an aggregate source for new concrete or other applications.

To help in realizing higher infrastructure sustainability, is these developments of alternative usage of recycle material and use of new materials, purposely designed with sustainability as a principal goal, in terms of enhanced social wellbeing, growing economic prosperity in construction, and reduced environmental effect (Mukherjee & Vesmawala, 2013). Producing concrete containing RAP/RCA as aggregate would help in resolving the challenge of both the industrial and construction waste and also decrease the cost for concrete materials.

2.0 MATERIALS AND METHODS

2.1 Materials

2.1.1 Cement

Cement was obtained from the open market at Zaria and used for the experiment.

2.1.2 Water

Water in Civil Engineering Laboratory of ABU Zaria was used in producing the concrete mixture for this study.

2.1.3 Fine Aggregate

The fine aggregate used was sieved through a BS 4.75mm sieve to remove some of the contained coarse aggregates.

2.1.4 Coarse Aggregates

2.1.4.1 Natural aggregate

Crushed granite was used in this research. It was obtained from a local dealer within Zaria city.

2.1.4.2 Reclaimed Asphalt Pavement

Crushed RAP (Reclaimed Asphalt Pavement) of maximum nominal particle size of 25mm was used in this research work as coarse aggregates. The coarse aggregate was obtained from nearby location along Kaduna- Zaria-Kano expressway in Nigeria. The RAP aggregate was used as obtained from source i.e. removal of bitumen coating from the RAP was not done. Hence, the RAP used for this study contained some bitumen coating.

2.1.4.3 Recycled Coarse Aggregate

The RCA of maximum nominal aggregate size of 25mm was used in this study and was obtained by crushing specimens of old structural components. The RCA was sourced from discarded crushed concrete cubes from the department of Civil Engineering, ABU Zaria.

2.2 METHODS

2.2.1 Tests on Cement

2.2.1.1 Consistency of Cement

This test was conducted in accordance to BS-EN-196-3 (2016). The test was conducted in the concrete laboratory of Ahmadu Bello University Zaria.

2.2.1.2 Setting Time of Cement

The test was conducted as described in BS-EN-196-3 (2016).

2.2.1.4 Soundness of Cement

The test was conducted on cement using the Le Chaterlie's mould as described in BS-EN-196-3 (2016). The specimens were prepared using the water-cement ratio as determined from the consistency test. The expansion of each of the specimen was measured.

2.2.1.5 Specific Gravity of Cement

This test was carried out according to BS-EN-196-3 (2016).

2.2.2 Tests on Aggregate

2.2.2.1 Sieve Analysis of Fine and Coarse Aggregates

Sieve analysis was conducted on fine and coarse aggregate (NA, RAP, and RCA) using various sieve sizes in accordance with BS-882:2 (1992).

2.2.2.2 Water Absorption Tests of Aggregates

The test was conducted in accordance with BS-812:2 (1995).

2.2.2.3 Specific Gravity of Aggregates

The specific gravity tests for coarse and fine aggregates were conducted in accordance with BS-812:2 (1995).

2.2.2.4 Bulk density of aggregate

The bulk density was performed to determine the weight that would fill a unit volume and was conducted in accordance with BS-812:2 (1995).

2.2.2.5 Aggregate Impact Value Test

The test was conducted in accordance to British standard BS-812-110 (1990) which specified maximum value of 25 percent when the aggregate is to be used in heavy duty floors, 30 percent when the aggregate is to be used in concrete for wearing surfaces and 45 percent when it is to be used in the other concrete.

2.2.2.6 Aggregate Crushing Value

Aggregate crushing value gives a relative measure of the resistance of an aggregate sample to crushing under gradually applied compressive load. This test was performed with a single size aggregate passing 12.7mm sieve and retained in 9.52mm sieve. The aggregate crushing value test was carried out in accordance with BS-812-110 (1990).

2.2.3 Compressive Strength Test

The compressive strength test of the hardened concrete was determined using the compressive testing machine at the concrete laboratory of Department of Civil Engineering, Ahmadu Bello University Zaria.

2.3 Mix Design

Trial mix design of the concrete was conducted to obtain target strength of 25 N/mm^2 at 28 days with a workability of 25–75 mm and a w/c ratio of 0.5.

2.4 Design of Experiment

Design Expert v13 was used to design the experiment of concrete produced by adding RCA-RAP as a replacement of Natural Aggregate (NA) as shown in Table 1. The concrete cubes were cured for 3, 7, 14, 21, and 28 days before crushing.

Table 1: Materials Schedule

S/No	Specimen Detail	NA (%)	RCA (%)	RAP (%)	Concrete Cubes
1	Control (100% NA)	100	0	0	18
2	20% RCA	80	20	0	18
3	40% RCA	60	40	0	18
4	60% RCA	40	60	0	18
5	80% RCA	20	80	0	18
6	100% RCA	0	100	0	18
7	20% RAP	80	0	20	18
8	40% RAP	60	0	40	18
9	60% RAP	40	0	60	18
10	80% RAP	20	0	80	18
11	100% RAP	0	0	100	18
12	20% RAP + RCA	80	10	10	18
13	40% RAP + RCA	60	20	20	18
14	60% RAP + RCA	40	30	30	18
15	80% RAP + RCA	20	40	40	18
16	100% RAP + RCA	0	50	50	18
Total					**240 cubes**

The design of experiment from Table 1 shows that there is a total of 16 experiments runs at different percentage replacements of RAP ad RCA aggregate. However, since, the concrete cubes are cast in triplicates and crushed at 3, 7, 14, 21, and 28 days, the total number of cubes per experiment is Fifteen (15). Hence, a total of concrete cubes cast is two hundred and forty (240).

2.5 Model and Optimization of RAP-RCA Concrete

Regression models were formulated to predict the 3, 7, 14, 21, and 28 days compressive strength of RAP and RCA concrete, while Optimization of the 28 days compressive strength of RAP and RCA concrete was done using the Response Surface Analysis Method (RSM) to with the aid of design expert (version 13) software. Also, Analysis of Variance (ANOVA) on the concrete compressive strength was done using SPSS (Statistical Package for Social Sciences) version 23 and adopting the Least Square Difference (LSD) method of ANOVA. In the analysis of the data, a 95% confidence level was adopted and values less than 0.05 were considered to be statistically significant while values that are greater than 0.05 were considered not statistically significant.

3.0 RESULTS AND DISCUSSION

3.1 RESULTS

3.1.1 Preliminary Test on Materials

Preliminary tests were conducted on the materials used in this study to determine its conformity to relevant codes, tests were conducted on cement, fine and coarse aggregate, RCA aggregate, and RAP aggregate, with the results presented in Table 2.

Table 2: Preliminary Tests Result

Description of Test	**Results**	**Standard**	**Code**
Cement			
Consistency (%)	30.0	26-33%	BS-EN-196-3 (2016)
Initial setting time (mins)	133	≥45	BS-EN-196-3 (2016)
Final setting time (mins)	189	≤ 600	BS-EN-196-3 (2016)
Soundness (mm)	2.0	≤ 10mm	BS-EN-196-3 (2016)
Specific gravity	3.15	3.1 – 3.16	BS-EN-196-3 (2016)
Aggregates			
Bulk density	**(kg/m^3)**		
Fine aggregate	1360	<1520	BS-812:2 (1995)
Coarse aggregate	1405	<1520	
RAP	1745	<1520	
RCA	1165	<1520	
Specific Gravity			
Fine aggregate	2.50	2.5 – 2.8	BS-812:2 (1995)
Coarse aggregate	2.60		
RAP	2.50		
RCA	2.56		
Aggregate Crushing Value	(%)		
Coarse aggregate	26.02	25 – 30%	BS-812-110 (1990)
RAP	23.3	< 25%	
RCA	36.1	30% - 45%	
Aggregate Impact Value	(%)		
Coarse aggregate	25.9	25 – 30%	BS-812-110 (1990)
RAP	18.99	< 25%	
RCA	31.19	30% - 45%	
Water Absorption	(%)		
Coarse aggregate	0.67	< 3%	BS-812:2 (1995)
RAP	1.16		
RCA	4.84		

The results from Table 2 shows that the cement used in this study is adequate for concrete production since the consistency (30%), initial setting time (133 minutes), final setting time (189 minutes), soundness (2mm), and specific gravity (3.15) all met code requirements.

Also, from the table, the fine and coarse aggregate used in this study were found to be adequate for concrete production since the specific gravity, bulk density, aggregate crushing value, and aggregate impact value all met code requirements. However, the properties of the RAP aggregate from the table shows that the bulk density of RAP aggregate (1745kg/m^3) is higher than that of RCA (1165kg/m^3) and natural coarse aggregate (1405kg/m^3) due to the presence of bitumen coating in the RAP aggregate as a result of environmental exposure, oxidation and weathering process, which causes the asphalt cement covering the RAP aggregates to become a lot harder (Thakur *et al*., 2010).

The specific gravity of the RAP (2.50) and RCA (2.56) is lower than that of the natural aggregate (2.60) which can be attributed to bitumen coating of the RAP (Al-Mufti & Fried, 2018) and due to the presence of old cement paste/ mortar on RCA aggregate particles that makes it less dense than NCA because of greater porosity (Anderson *et al*., 2009).

More also, the RCA crushing value (36.1%) is greater than that of RAP aggregate (23.3%) and natural aggregate (26.02%). It has been found that the ACV of RCA is considerably higher than that of NCA due to relatively weak cement paste and mortar attached to RCA particles (Malešev *et al*., 2010).

Furthermore, the RCA aggregate impact value (31.19%), is also greater than that of RAP aggregate (18.99%) and natural aggregate (25.9%). It has also been found from previous studies that the AIV of RCA is greater than that of NCA due to attached mortar and cement paste that makes RCA less strong, and therefore result in a greater AIV for RCA *(Malešev et al.,* 2010).

Finally, from the table, the water absorption value of the RCA (4.84%) is higher than that of the natural aggregate (0.67%) and RAP (1.16%). This is attributed to certain amount of cement paste/ mortar from the original concrete that remains attached to RCA particles after crushing (Yang *et al*., 2008).

3.1.2 Gradation of Fine Aggregate

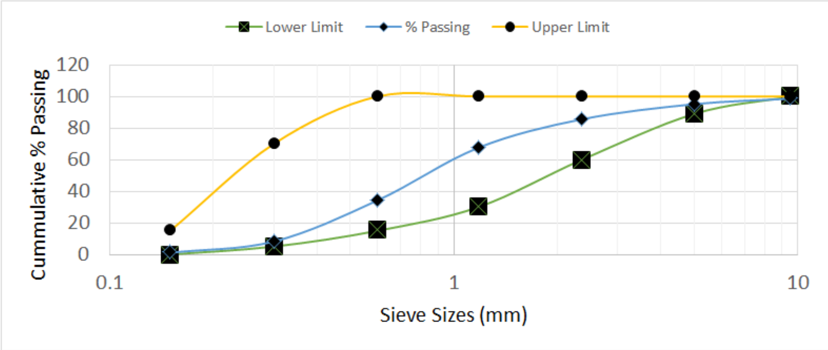

Figure 1: Particle Size Analysis of Fine aggregate

Figure 1 shows the particle size results of the fine aggregate used in this research. BS-882:2 (1992) was used to grade the fine aggregate which showed that the fine aggregates were of grading zone 2 (25% finer than 600µm and 75% coarser than 600µm). This shows that the fine aggregate is suitable for use.

3.1.3 Gradation of Coarse Aggregate

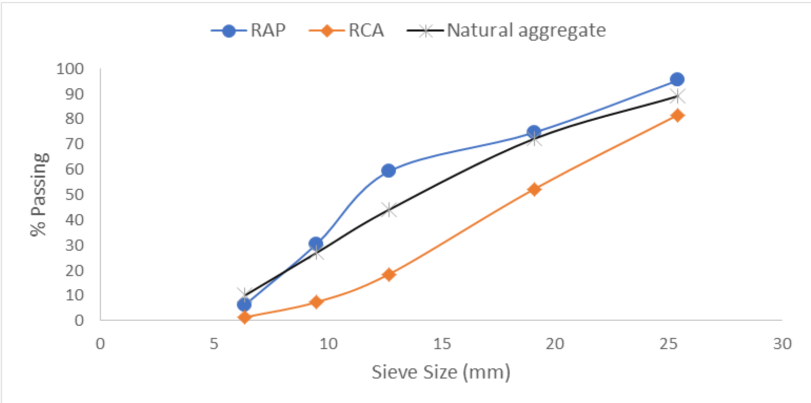

Figure 2: Gradation of Coarse Aggregate

Figure 2 shows the particle size results of the coarse aggregate used in this research and from the graph, aggregates are uniformly distributed and fell within the limits specified in BS-882:2 (1992). Hence, the coarse aggregate is suitable for use with a nominal size of 25.4mm.

3.2 Compressive Strength

The compressive strength of RAP, RCA, and combination of RAP + RCA was determined at days 3, 7, 14, 21, and 28 days which was compared to the control, and the results are presented below.

3.2.1 Concrete Compressive Strength

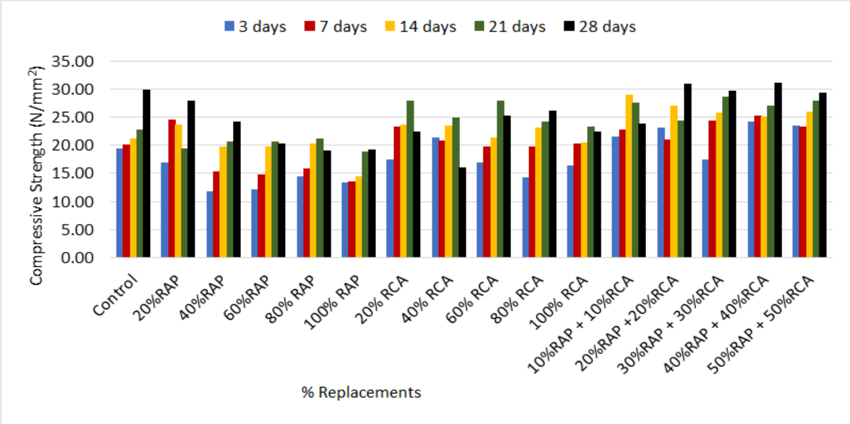

Figure 3: Compressive Strength of RAP and RCA Concrete

The result from Figure 3 shows that aggregate replacement of 40%RAP + 40%RCA have the optimum compressive strength at day 3, aggregate replacement of 40%RAP + 40%RCA have the optimum compressive strength at day 7, aggregate replacement of 10%RAP + 10%RCA have the optimum compressive strength at day 14, aggregate replacement of 30%RAP + 30%RCA have the optimum compressive strength at day 21, and aggregate replacement of 40%RAP + 40%RCA have the optimum compressive strength at day 28.

The outcome of the 28 days compressive strength shows that RAP replacements from 20-100% had a compressive strength lower than the control concrete, with reduction in strength as RAP replacement increases, which is in agreement with the works of *(Hossiney et al.*, 2008; Tia *et al.*, 2012). However, the low strength can be attributed weak bond between the aggregate and the cement paste in the presence of the asphalt film on the surface of the aggregate. The soft asphalt film would cause stress concentration which may ultimately results in micro cracks around the aggregate, this results in strength reduction in concrete containing RAP as aggregates (Huang *et al.*, 2006; Huang *et al.*, 2005).

Also, the 28 days compressive strength shows that RCA replacements from 20-100% had a compressive strength lower than the control concrete which is in agreement with the works of (Anderson *et al.*, 2009; Choi & Yun, 2012; Gutiérrez, 2004; Pedro *et al.*, 2017; Rahal, 2007). The low 28 days compressive strength of RCA concrete can be attributed to voids formed in concrete (Anderson *et al.*, 2009) or if the RCA have a lower water absorption capacity since it is presumed that the compressive strength increase is due to a higher amount of internal curing water and the larger pores (Dimitriou *et al.*, 2018).

However, the combination of RAP and RCA at 20%RAP +20%RCA, 30%RAP + 30%RCA, and 40%RAP + 40%RCA replacement have compressive strength equal or higher than the control concrete. This is attributed to the synergy in matrix of RAP and RCA combination and an indication that the RAP used exhibit less cracks at failure when tested under compressive loading which is a behavior exhibited mainly due to asphalt motor coating around the aggregate by reducing the elastic modulus of the concrete containing RAP and enhancing the specimens to absorb more loads (Singh *et al.*, 2019; Solanki & Dasha, 2016), and the RCA used either is of high-strength old concrete (Afroughsabet *et al.*, 2017; Anderson *et al.*, 2009; Gutiérrez, 2004; Malešev *et al.*, 2010; Rahal, 2007), or the RCA have a high-water absorption capacity (Dimitriou *et al.*, 2018), which can all lead to increased compressive strength.

Table 3: ANOVA of 28 days Compressive Strength

(I) exp	(J) exp	Mean (N/mm^2)	Mean Difference (I-J)	Sig.
Control (Mean = 29.87N/mm^2)	20%RAP	27.85	2.01333	**.245**
	40%RAP	24.29	5.57333*	.003
	60%RAP	20.37	9.49667*	.000
	80% RAP	19.11	10.75667*	.000
	100% RAP	19.19	10.68000*	.000
	20% RCA	22.52	7.35000*	.000
	40% RCA	16.00	13.86667*	.000
	60% RCA	25.34	4.53167*	.008
	80% RCA	26.08	3.79000*	.033

	100% RCA	22.52	7.35000*	.000
	10%RAP + 10%RCA	23.85	6.01667*	.001
	20%RAP +20%RCA	30.96	-1.09667	**.523**
	30%RAP + 30%RCA	29.63	.23667	**.890**
	40%RAP + 40%RCA	31.11	-1.24333	**.470**
	50%RAP + 50%RCA	28.15	1.72000	**.325**

*. The mean difference is significant at the 0.05 level.

The Analysis of Variance (ANOVA) result from Table 3 shows that the 28 days compressive strength of the control concrete is not significantly different from concrete produced with replacements of 20%RAP, 20%RAP +20%RCA, 30%RAP + 30%RCA, 40%RAP + 40%RCA, and 50%RAP + 50%RCA with mean compressive strength difference of 2.10N/mm^2, 1.10N/mm^2, 0.24N/mm^2, 1.24N/mm^2, and 1.72N/mm^2 respectively. Hence, there is no significant difference between concrete produced with natural aggregate and some concrete produced with RAP, and RCA+RAP aggregate i.e. 20%RAP, 30%RAP + 30%RCA, 20%RAP + 20%RCA, 40%RAP + 40%RCA, and 50%RAP + 50%RCA coarse aggregate replacement

The outcome of this findings shows that although concrete produced with coarse aggregate replacement of 20%RAP +20%RCA, and 40%RAP + 40%RCA are higher than the control concrete, the variation might be by chance (i.e. good compaction, shape of aggregate, etc.). Hence, 20%RAP, 30%RAP + 30%RCA, 20%RAP +20%RCA, 40%RAP + 40%RCA, and 50%RAP + 50%RCA coarse aggregate replacement can be used to produce concrete with compressive strength close to the control i.e. 25-30N/mm^2.

3.3 Regression Model of RAP and RCA Concrete

The regression analysis was conducted in order to predict the 3, 7, 14, 21, and 28 days compressive strength of RAP and RCA concrete as shown in Table 4.

Table 4: Model for Compressive Strength of RAP and RCA Concrete

Days	**Model**	**R^2 Value**	**Adjusted R^2**	**Predicted R^2**
3 days	$22.64511 - 0.381095A - 0.081075B + 0.007694AB + 0.002956A^2 + 5.52E\text{-}6B^2$	0.5531	0.4958	0.4298
7 days	$27.55644 - 0.397784A - 0.172759B + 0.007491AB + 0.002621A^2 + 0.000939B^2$	0.5022	0.4384	0.3641
14 days	$26.87719 - 0.112209A - 0.065227B + 0.003465AB$	0.6059	0.5771	0.5259
21 days	$23.70533 - 0.077713A + 0.172419B + 0.001398AB + 0.000374A^2 - 0.001838B^2$	0.5258	0.4650	0.3916
28 days	$22.640 + 0.142648A + 0.057243B + 0.018441AB – 0.00202A^2 – 0.00048B^2$	0.7539	0.6992	0.6382

Note: A = %RAP; and B = %RCA;

The result from Table 4 shows that the 3, 7, and 21 days RCA and RAP concrete compressive strength significantly fits a quadratic model, the 14 days strength fits a 2-Factor Interaction (2FI) model, and the 28 days strength also fits a quadratic model i.e. predicted R^2 values are in reasonable agreement with the Adjusted R^2 values with a difference less than 0.2. However, the R^2 value of the 28 days compressive strength is the highest (0.7539) compared to the 3, 7, 14, and 21 days compressive strength. Hence, the quadratic model can significantly predict the 28 days compressive strength of RAP and RCA concrete as shown in Figure 4.

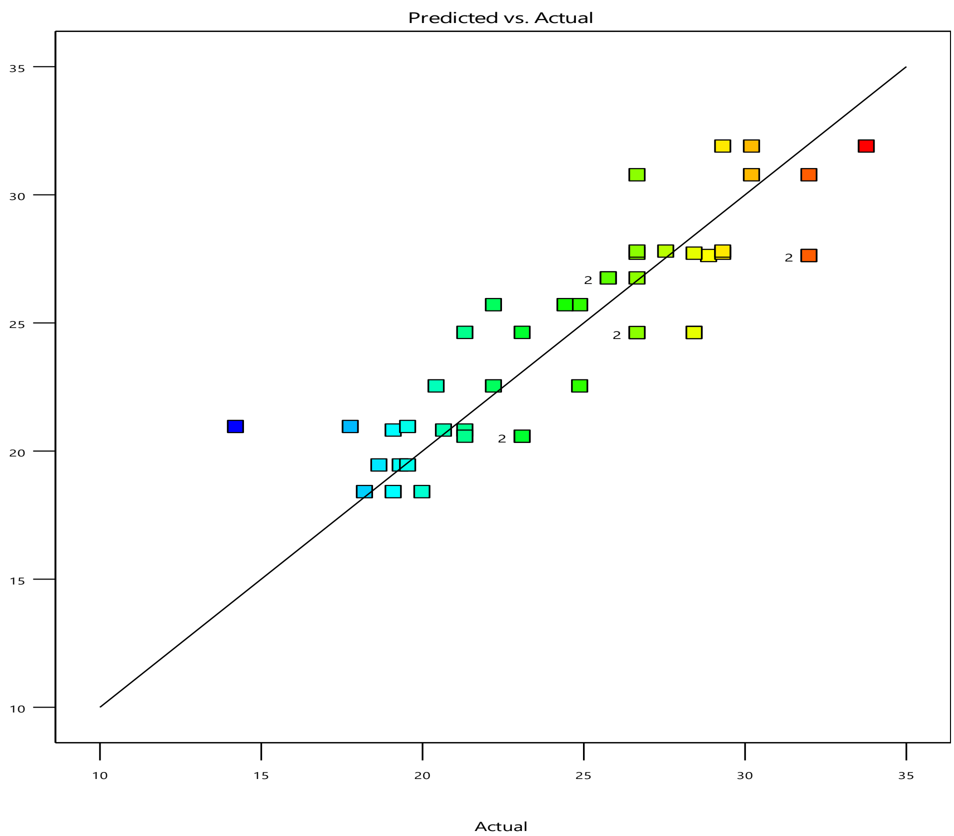

Figure 4: Actual and Predicted Value of 28 Days Compressive Strength

3.4 Optimization of RAP and RCA Concrete

Optimization was also done such that the dependent variable (28 days compressive strength) was maximized, and the independent variables (%RAP and %RCA were set at default i.e. in range of actual values), and the result is presented in Figure 5.

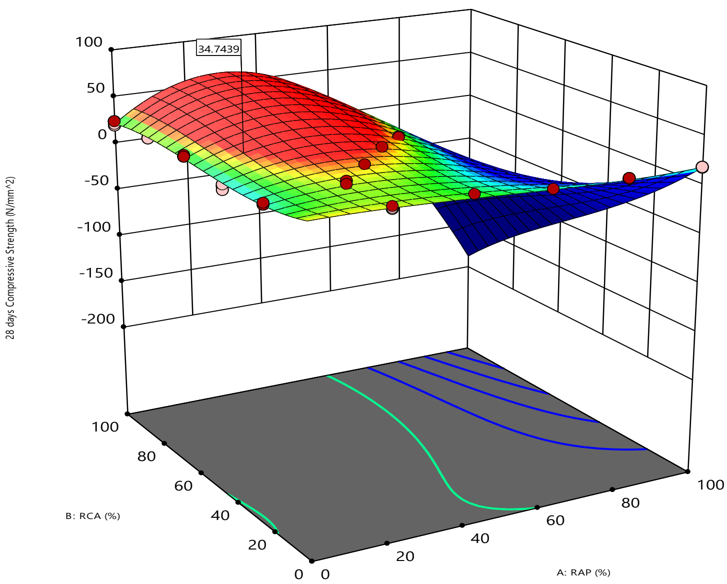

Figure 5: Optimized 28 Days Compressive Strength

In the optimization, 5 runs were analyzed out of the 50 number of design points, while the optimized parameters with a desirability value of 0.927 was selected among the 5 runs since its closest to 1. However, the result from Figure 5 shows that the Optimized compressive strength is approximately 33.74N/mm2 when concrete is produced by replacing natural aggregate with approximately 10.0% RAP and 50.0% RCA.

To validate the optimized result, the percentage replacement of RAP (10%) and RAC (50.0%) was substituted in the 28 days predictive model of concrete compressive strength given in Table 4 given as;

$$22.640 + 0.142648A + 0.057243B + 0.018441AB - 0.00202A^2 - 0.00048B^2$$

Where A = RAP = 10%
B = RCA = 50%

Hence;

$$22.64 + (0.142648 * 10) + (0.057243 * 50) + (0.018441 * 10 * 50) - (0.00202 * 10^2) - (0.00048 * 50^2) = 34.745N/mm^2.$$

Hence, the value of the optimized ($34.744N/mm^2$) 28 days compressive strength is close to the predictive model ($34.745N/mm^2$) concrete 28 day's compressive strength.

4.0 CONCLUSION

This study investigated the compressive strength of concrete produced by replacing natural aggregate with RAP and RCA at various percentages. At the end of the investigation, it was concluded that the optimum 28 days concrete compressive strength of the modified concrete are concrete produced with 20%RAP +20%RCA, 30%RAP + 30%RCA, and 40%RAP + 40%RCA which are either equal or greater than the control concrete. The ANOVA result showed that there is no significant difference between the control concrete and concrete produced with 20%RAP, 20%RAP +20%RCA, 30%RAP + 30%RCA, 40%RAP + 40%RCA, and 50%RAP + 50%RCA aggregate replacements. Also, the 3, 7, 21, and 28 days compressive strength of RAP and RCA concrete can be significantly predicted with the quadratic model, while the 14 days strength can be significantly predicted with the 2-Factor Interaction (2FI) model. Finally from the investigation, it was revealed that the optimized 28 days compressive strength of RAP and RCA concrete is $33.74N/mm^2$ which will be achieved by replacing natural aggregate with approximately 10.0% RAP and 50.0% RCA, this was also validated with the model of 28 days concrete compressive strength.

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