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Walnut Shell for Partial Replacement of Fine Aggregate in Concrete: Modeling and Optimization

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Abstract The huge need of natural resources and the raising pollution problems from agro wastes disposal have become the top most important factors behind using agro waste in construction industry. Many agro waste materials have been recycled and reused successfully in concrete as replacement alternatives for cement, aggregate, and reinforcing materials. Kurdistan region-Iraq is the country leading producer of walnut, simultaneously; large quantities of walnut shell is disposed in landfill from agricultural, household and small scale food industries. Hence, the present study deals with using walnut shell the agro waste as partial replacement of fine aggregate in concrete for the purpose of reduction the natural resource exploitation and associated costs, minimization waste landfill, and modifying the concrete properties. A two factorial central composite design was adopted to study the effect of water/cement ratio (0.38-0.52) and walnut shell content (1.72-58.28) weight % for concrete mixes on water absorption, density and compressive strength. Control concrete samples were also investigated for comparison purpose. The experimental results were modeled and optimized using Response Surface Methodology. The response surface analysis results showed that walnut shell content has significant effect on compressive strength and density, while the quadratic effect of water/cement ratio was significant for total surface water absorption. The walnut-concrete samples seemed to have lower density, and lower initial and total surface water absorption compared to control samples. Similar findings were obtained for compressive strength. However, it was confirmed that walnut shell can be used as light replacement material instead of fine aggregate up to 30% at 0.38 water/cement ratio without adversely affecting the acceptable compressive strength for structural Portland cement concrete. The promising results indicated the potential of using walnut shell for producing structurally applicable and environmental friendly concrete.

Keywords Walnut shell, Concrete, Modeling, Optimization, Response Surface Methodology

1. Introduction

1.1. Waste Materials in Concrete

Concrete is the most widely consumed construction material around the world due to its high durability and outstanding structural properties, but concrete industry is an industry of high equipment and fuel costs, with huge usage of natural resources, also, it has negative impact on environment owing to greenhouse gases emission primarily carbon dioxide, other gases and fine particulates. Hence, elimination or minimization the negative environmental impact can enhance the promotion of the environmental sustainability of concrete industry. On the other hand, numerous predictions confirmed that using wastes in concrete components is considered as an alternative solution for preventing the excessive usage of raw materials. Studies on using wastes as partial replacement of cement and whole or partial replacement of natural aggregates are well established [1-7]. The successful use of the waste contributes to conservation of natural resources, energy saving, and minimizing the cost of construction materials, in addition, enhancing the environmental protection by minimizing the negative impact of the wastes on environment and solving its disposal problem.

Industrial wastes including coal bottom ash, fly ash, silica fume, ground granulated blast furnace slag, copper slag [8, 9] as well as recycled waste including recycled plastics [10], recycled concrete, [11, 12], and recycled waste glass [13, 14], have been widely researched and successfully used in concrete.

On other hand, the wide availability of the agriculture waste candidate those as promising alternatives to be used as aggregate in concrete [9, 15-18]. The agro-wastes can be collected from different places, then transform into

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proper aggregate using various processes.

Numerous numbers of studies had highlighted the successful use of agricultural waste in production of structural and non-structural concrete. The agriculture waste investigated include and not limited to kernel shell [19, 20], sugarcane bagasse ash [21-24], groundnut shell [25-27], oyster shell [28], sawdust [29-31], giant reed ash [32], rice husk ash [33-35], cork [36-39], tobacco waste [40], and wood ash [41].

Lot of researchers worked intensively to improve concrete properties such as decreasing the density and porosity, and increasing the workability and durability characteristics without affecting concrete strength by incorporation of agriculture waste as partial replacement of cement or aggregate. For example, sugarcane bagasse ash has been investigated by many research groups who have noted that sugarcane bagasse is suitable for partially replacement of cement [22, 42], and also for partially replacement of fine aggregate [24]. Groundnut shell has been used for cement replacement in concrete, a study in regard showed that the compressive strength of concrete mixes composed of quarry dust of 50% with 10% replacement of cement by groundnut shell found to be better than normal PCC [4].

The use of sawdust in concrete has received some interest over the past years. It was noted that, both the density and compressive strength of concrete decreased as the percentage replacement of fine aggregate by saw dust increased [29, 31]. However, another study demonstrated that using sawdust as partial replacement of fine aggregate up to 25% will contributes to reduction in sawdust waste generation without adversely affecting concrete strength [30]. Close relations were predicted by using groundnut shells for partial replacement of fine aggregate in concrete [27]. Similar trend was observed by replacement of cement by less than 10% of groundnut shell in concrete [25].

The utilization of giant reed fibres and giant reed ash in concrete has been also investigated [32]. It has been reported that the density of giant reed ash-concrete mix decreased with the increase in giant reed ash and the maximum values of compressive and flexural strengths by replacement of fine aggregate in concrete mixes obtained by an optimum ratio 7.5% of giant reed ash.

Also, partial replacement of cement by rice husk ash in concrete showed to decrease chloride penetration, the unit weight, flowability, porosity, and water absorption [34], and compressive strength [41]. More recent study showed that 15% replacement of cement by rice husk ash resulted in increase in compressive strengths, water absorption and Chloride ions penetration by about 20% [35]. While, the concrete made using cork showed better thermal resistance and improved cyclic performance compared to conventional concrete [18].

1.2. Walnut Shell in Concrete

Walnut (Juglans regia L.) is an important crop with historical account cultivation dates back to Babylon (Iraq) 2000 B.C., it is cultivated throughout the world's temperate regions for its edible nuts [43]. The walnut shell is lingocellulosic material forming the thin endocarp or husk of the walnut tree fruit. The shells may be burned or otherwise disposed in landfill.

Walnut shell has unique properties, it is very hard and takes years and years to decompose or break down. It can be crushed and could be ground into several grits from extra fine to extra course. Due to the high hardness of walnut shell, walnut shell was used as an abrasive that is applied to surface preparation on cementitious surfaces including cast-in-place concrete floors and walls, masonry walls, and shotcrete surfaces [44-46].

For the best of our knowledge, the usage of walnut shells as concrete component is rarely included in literature. A study throughout a patent demonstrated the using of walnut shell as aggregate among floor topping compositions, these compositions can be applied to new unused floors or they can be used to patch and repair old worn floors [47]. One recent research explored the use 10%, 20% and 30% walnut shell slag as partial replacement of fine aggregate. The result obtained indicated that the strength properties of concrete decreased compared to the normal concrete. The optimum 28-day compressive strength of the concrete obtained by using 20% walnut shell slag was found to be 29.3 N/mm^2 [48]. In another recent study, a type of lightweight wet-mix shotcrete was developed by adding polyethylene terephthalate (PET) fiber and walnut shell replacing natural coarse aggregates. The study showed that with increasing walnut shell content, compressive and splitting tensile strength of concrete decreased compared with plain concrete [46].

The principal objective of the recent work is to investigate the reuse of the agriculture waste walnut shell as fine aggregate in concrete. The authors think that this study is the first one deal with incorporation of walnut shell as fine aggregate in Portland cement concrete. Hence, there is a need to realize to what extent the crushed walnut shell can replace natural concrete fine aggregates. This is what this work tends to achieve throughout studying and optimizing the effect of concrete mix design on walnut shell-concrete properties including compressive strength, density and water absorption using Response Surface Methodology (RSM).

2. Experimental

2.1. Statistical Analysis Using (Statgraphics Plus for Windows Software)

RSM is a statistical tool able to investigate the interaction between several illustrative variables and one or more response variables [49]. The process of RSM includes designing of a series of experiments for sufficient and reliable measurement of the response and developing a mathematical model of the second order response surface with the best fittings. The Software portable Statgraphics centurion 15.2.11.0.exe was used to analyze the experimental data. The mathematical empirical model is defined as:

$$Y = \beta_0 + \beta_1\chi_1 + \beta_2\chi_2 + \beta_{11}\chi_1^2 + \beta_{22}\chi_2^2 + \beta_{12}\chi_1\chi_2 \quad (1)$$

Where: Y: is the response or dependent variable; χ_1 and χ_2 are the independent variables; and, β_0, β_1, β_2, β_{11}, β_{22}, β_{12} are the regression coefficients.

The extensive application of RSM is in industry when several input variables significantly influence performance measures or quality characteristics of the product or process [50]. The analyses of variance (ANOVA) are used to determine significant differences between the effects of independent variables ($p<0.05$). Pareto chart is used to identify the impact level of the independent variables on each considered response. The vertical line (significant front) in Pareto chart determines the effects that are statistically significant at 95% as confidence level. Main trends, surface response, contour plots of the response surface as well as the empirical regression model can be used to optimize the dependent parameter (responses).

2.2. Experimental Design

Table 1. Experimental Design With The Coded And Actual Levels And Quantities Of The Independent Variables For Concrete Mixes With Walnut Shells As Partial Replacement Of Fine Aggregate

Coded level	-α	-1	0	1	+α
Water / Cement	0.38	0.4	0.45	0.5	0.52
Walnut shell content (wt.%)	1.72	10	30	50	58.28

Exp. No.	W/C	Walnut shell//sand (wt.%)	water (g)	cement (g)	sand (g)	Gravel (g)	Walnut shell (g)
1	0.40	50.00	460	11500	1150	4600	526.2
2	0.45	58.28	517.5	11500	959.5	4600	613.8
2*	0.45	30.00	517.5	11500	1609.8	4600	316
5	0.40	10.00	466	11500	2069.8	4600	105.3
6	0.50	10.00	575	11500	2069.8	4600	105.3
7	0.50	50.00	575	11500	1150	4600	526.6
8	0.45	1.72	517.5	11500	2260	4600	18
9	0.38	30.00	437	11500	1609.8	4600	316
10	0.52	30.00	593	11500	1609.8	4600	316

2*: Two central points; experiments 3 and 4), α is the (axial distance) $=\sqrt[4]{2^k}$, k is the number of orthogonal design variables (in our case, k=2)

A central composite design (with 2*2=4 factorial points, 2*2 star-points and 2 repetitions of central point) was adopted to optimize and model the effect of water/cement ratio (0.38-0.52), and walnut shells content (1.72-58) wt.% for concrete mixes used walnut shell for partial replacement of fine aggregate. The analysis for each sample was replicated three times. The experimental design for the concrete mixes is presented in table 1. In the experiment, the actual variables in their natural units of measurement are used. However, when designing the experiment coded variables, are used. The coded variables will be centered on 0, and extend +1 and -1 from the center of the region of experimentation. Therefore, natural units are taken and then center and rescale to the range from -1 to +1.

2.3. Materials

The Ordinary Portland Cement used is ASTM type complied with Iraqi Specification No.5, 1984 (Iraqi Organization of Standards, IOS 5: 1984 for Portland cement). Aggregates were purchased from Soran city local market. Preparation and grading of the aggregates were complied with BS 410: 1976 standards (British Standards: BS 410: 1976. Specification for test sieves). The walnut shells were cleaned, dried and crushed into smoth rounded particles of similar grading of sand particles. Saturated-Surface-Dry test (SSD) was carried out in order to realize how much water will be absorbed by the shell. The results of the test confirmed that the shell should be placed in water before using as fine aggregate in the concrete mixes. The difference of density of natural fine aggregate and Walnut shell was taken into account when calculating the amount of walnut shell in each concrete mix.

2.4. Preparation of Concrete Mixes

Concrete mixes (1.15: 2.30: 4.60) were prepared according to the experimental design (table 1.). The cement was mixed with the aggregate; water was then added and mixed with the other constituents of the mix. The concrete slurry was compacted in three layers in steel molds which were cleaned and oiled properly. The specimens were de-molded after 24 hours and placed in the curing tank at ambient temperature for curing. Figure 1, 2, and 3 show the walnut shells, the curing of concrete cubes and the hardened cubes respectively.

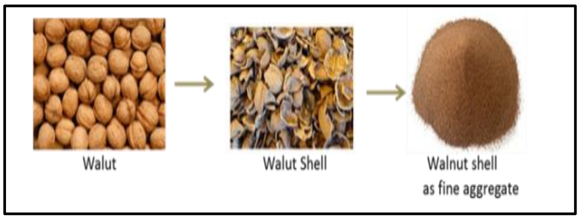


Figure 1. Walnut shells and crushed shells

Figure 2. Curing of the concrete specimens

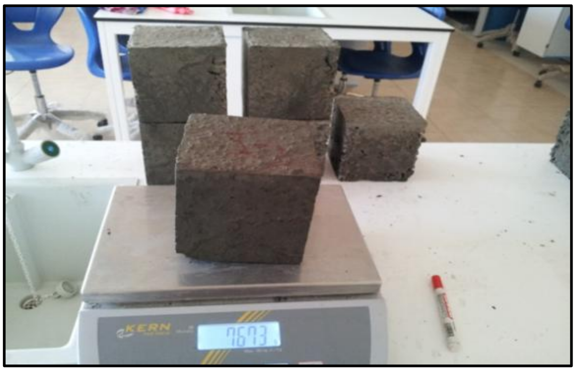


Figure 3. Hardened concrete specimens for testing

2.5. Initial and Total Surface Water Absorption

The initial and total surface water absorption test was conducted on the 28 days cured specimens by drying the specimens at 110℃ until the mass became constant, then following the change in weight of the specimens after immersion in water for (30, 60, 120) minute, and 28 days.

2.6. Concrete Density Test

The density test was carried out on the dried concrete cubes after 28 days water curing. The cubes weighted and its volume was accurately measured.

2.7. Compression Strength Test

Compression strength tests were performed according to B.S.1881: Part 116: 1983. A 150*150*150 mm cube steel molds were used. Compressive strength machine controls model 50-C23C02 with a 2000 KN load capacity was used.

3. Results and Discussion

3.1. Water Absorption Results

3.1.1. Experimental Results

The initial and total surface water absorption test was conducted on all the samples prepared according to the adopted experimental design shown in Table 1. The cured (PCC) specimens and the concrete specimens contain different content of walnut shell as partial replacement of fine aggregate (WNC) have been dried at 110℃ until the mass became constant then weighed. The weight was recorded as the dry weight (W1), then the concrete specimens were tested by immersion in water at ambient temperature for (30, 60, 120) minute, and 28 days, then the weight was noted as the wet weight (W2) of the specimen.

$$\% \text{ water absorption} = [(W2-W1)/W1] * 100 \qquad (2)$$

The experimental results of water absorption test are shown in table 2.

The data of table 2 were analyzed to study the effect of immersion time, W/C ratio, and walnut shell content on initial and total water absorption. The plots in Figures 4-8 illustrate the effect of the above parameters on water absorption % of walnut shell-concrete mixes compared to control samples.

Table 2. Experimental Design and the Experimental Data For Water Absorption Test

W/C	WNS (Wt. %)	Water absorption %							
		Immersion Period (min.)							
		30		60		120		28 days	
		PCC	WNC	PCC	WNC	PCC	WNC	PCC	WNC
0.40	50.0	0.54	0.43	0.66	0.46	0.69	0.50	3.74	1.11
0.45	58.3	0.45	0.06	0.60	0.08	0.61	0.09	0.92	0.73
0.45	30.0	0.45	0.41	0.60	0.46	0.61	0.48	0.92	0.84
0.40	10.0	0.54	0.41	0.66	0.49	0.69	0.48	3.74	1.04
0.50	10.0	0.56	0.53	0.63	0.57	0.64	0.59	1.15	1.00
0.50	50.0	0.56	0.45	0.63	0.25	0.64	0.27	1.15	0.97
0.45	1.70	0.45	0.40	0.60	0.52	0.61	0.56	0.92	0.83
0.38	30.0	0.48	0.36	0.60	0.48	0.66	0.51	1.20	1.20
0.52	30.0	0.57	0.50	0.61	0.56	0.62	0.54	1.12	1.12

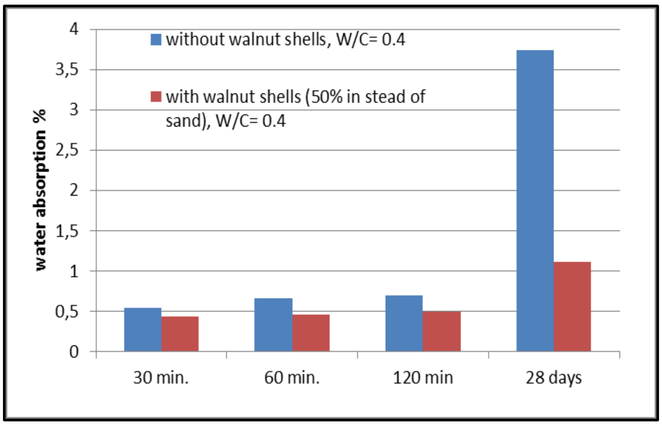


Figure 4. Effect of immersion time for control and a mix with walnut shell (50% fine aggregate), (W/C=0.4) for both mixes

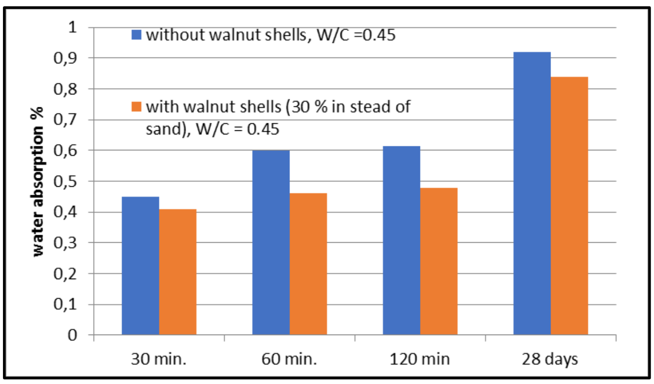


Figure 5. Effect of immersion time for control and a mix with walnut shell (30% fine aggregate), (W/C=0.45) for both mixes

The results estimated from Figures 4, 5 and 6 confirmed that immersion time and W/C ratio are crucial factors affecting water absorption. Water absorption increased with increasing immersion time for both the control mixes and the mixes with walnut shell as fine aggregate. However, the increase in water absorption seemed more remarkable for the control mixes. Also, the histograms demonstrated that % water absorption increases as the W/C ratio increases for both the control and the mixes with walnut shell (Figures

7 and 8). However, the control mixes show more water absorption in particular at W/C ratio (0.45) compared to mixes with walnut shell (Figure 8). The walnut shell-concrete samples showed lower initial water absorption at the higher W/C ratio compared to control sample as shown in Figure 7. However, the effect of W/C ratio seemed negligible on water absorption (after 28 days immersion) at higher W/C values such as there was no difference in total % water absorption between the control and the walnut shell concrete samples (Figure 8). For more highlighting, the increase in water absorption % after 28 days immersion for the control samples at different W/C ratio compared to walnut shell-concrete samples was calculated. The results are recorded in table 3.

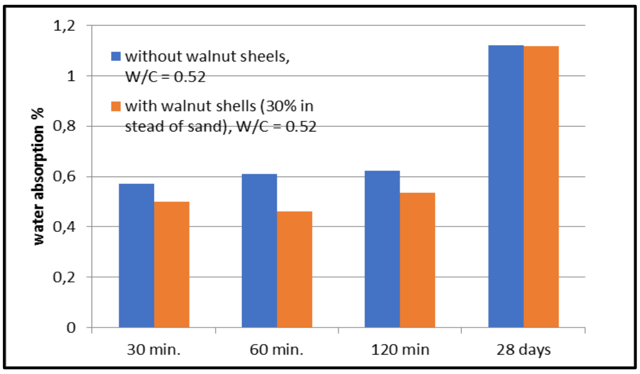


Figure 6. Effect of immersion time for control and a mix with walnut shell (30% fine aggregate), (W/C=0.52)

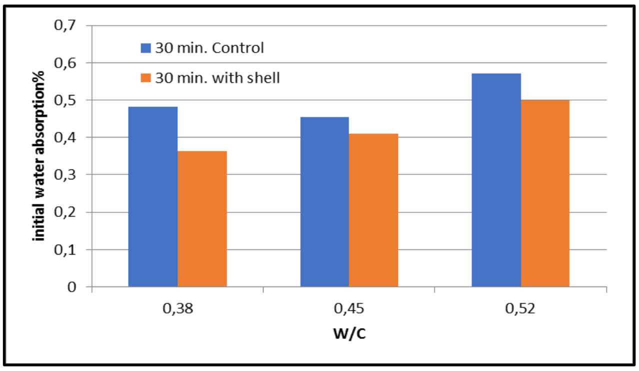


Figure 7. Effect of W/C for control and a mix with walnut shell (30% fine aggregate) at initial absorption period

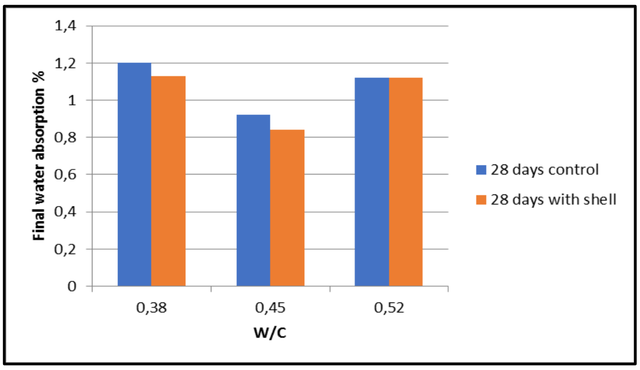


Figure 8. Effect of W/C for control and a mix with walnut shell (30% fine aggregate) after 28 days absorption period

Table 3. W/C Versus The Increase In Water Absorption % For Control Mixes

W/C	Increase in water absorption % after 28 days for PCC mixes compared to concrete mixes contain walnut shells as fine aggregate
0.40	70.27 (compared to mixes with walnut shells = 50 % as fine aggregate)
0.45	09.54 (compared to mixes with walnut shells = 30 % as fine aggregate)
0.52	0.00 (compared to mixes with walnut shells = 30 % as fine aggregate)

In general, the results indicated that with increasing walnut shell content, % water absorption decreased. The optimum decrease in % absorption was observed for mixes of W/C ratio = 0.45, and walnut shells = 30% as fine aggregate (Figure 8). Accordingly, W/C ratio = 0.45 can be considered as the optimum for manufacturing high durability concrete containing walnut shell as fine aggregate.

The phenomenon of low water absorption has essential benefits for concrete by strengthen the durability properties such as decreasing the concrete permeability and increasing its chemical resistance [51]. In general, concrete specific parameters like porosity and permeability, will determine the intensity and rate of concrete deterioration. When walnut shell is incorporated as fine aggregate in concrete, degradation of the concrete structures as a result of introducing wall nut shell is not expected due to the resistance of wall nut shell to degradation as it referred from the collected literature. The strength of wall nut shell comes from its lignin composition. Lignin is a complex cross-linked polymer. The complexity has thus far proven as resistant to detailed chemical and microbial degradation.

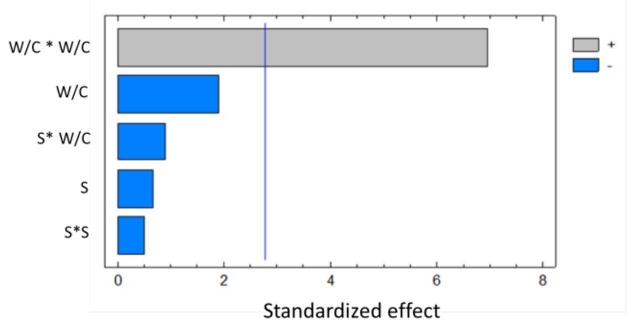
The decrease in water absorption may be attributed to the less hygroscopic constituents of the walnut shells and the probability of the particles of the shell to agglomeration which increased its ability to retain water.

Other studies on using agriculture wastes as concrete aggregates showed inverse effect, for example, using rice husks as concrete aggregate an increasing in water absorption was predicted [52]. Similar findings were reported for partial replacement of course aggregate with coconut shell and coir fibres [53].

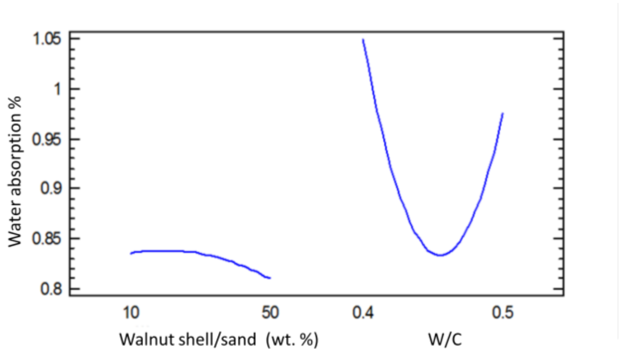
3.1.2. RSM Results for Total Surface Water Absorption

To model and optimize the effect of W/C ratio and Walnut shell content on total surface water absorption, the experimental data of the total water absorption % (after 28 days immersion) were analyzed by RSM. The response surface analysis (RSA) results are shown in Figure 9.

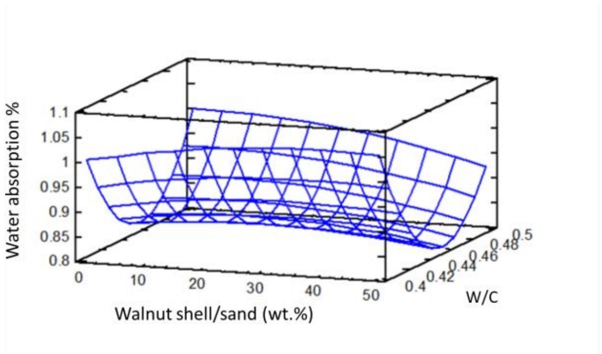
Pareto chart of Figure 9 (A) illustrated that the quadratic effect of water/ cement ratio is the significant factor affecting water absorption. The general trends plots (B), Response Surface (C), and contours plot (D) showed that as walnut shell content increases, % water absorption decreases, and there is an optimum for W/C ratio (0.45) beyond that water absorption % increases with increasing walnut shell content.



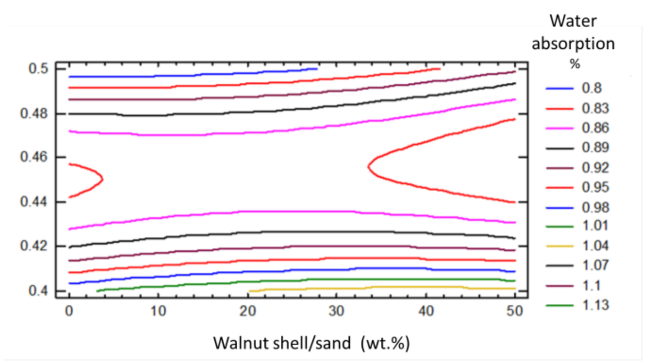
(A): Standardized Pareto chart for water absorption



(B): General trends for water absorption



(C): Estimated Response surface



(D): Contours of estimated response surface

Figure 9. Pareto chart (A), General trends (B), Response Surface (C), and contours plot (D) for water absorption of concrete mixes of different walnut shell content

The regression factor estimated from RSA (R-squared = 94.439 percent) confirmed the high capability of the adopted model to explain the experimental results.

The 2nd order empirical polynomial equation estimated from RSA is shown in equation (3):

$$\text{Water absorption \%} = 15.1956 + 0.0125*S - 63.8823*W/C - 0.00003*S^2 - 0.025*S*W/C + 70.9994*(W/C)^2 \quad (3)$$

Where, S is walnut shell content (% wt.), and W/C is Water/Cement ratio.

An optimum value of water absorption = 1.2521% was estimated from the model analysis which corresponds to a concrete mix of 0.38 Water/ Cement ratio, containing 48.14 % walnut shell as fine aggregate.

3.2. RSM Results of Compressive Strength

Performance of concrete is evaluated by mesuring its mechanical properties which include compressive strength, tensile strength, flexural strength, modulus of elasticity, shrinkage and creep. However, compressive strength is the most important and has the foremost priority. It has been often used as an index of the overall quality of concrete as concrete is designed to carry compressive loadings [54].

The shape, texture, and grading or size distribution of aggregates affect the strength properties of hardened concrete. In general, aggregates of higher surface-to-volume ratio and rough surface generate a stronger bond between the paste and the aggregate creating a higher strength. In this study wall nut shell was crushed and grinded to have similar grading of natural aggregate (sand) in order to keep the grading parameter of both fine aggregate components constant. However, more research is needed to study the effect of wall nut fine particles shape as parameter on strength properties.

Table 4. Experimental Results for Compressive Strength and Density

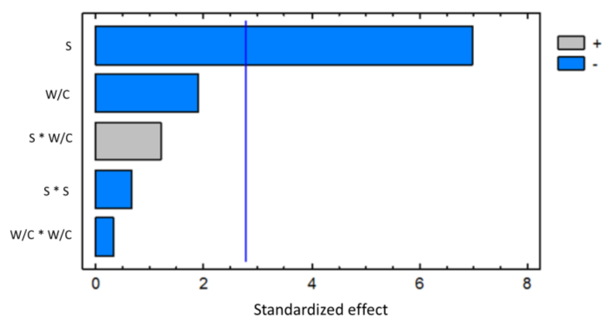
Exp. No.	W/C	(Walnut shells /sand)	Compressive strength		Density	
		wt. %	MPa		Kg/m³	
			PCC	WNC	PCC	WNC
1	0.4	50.0	42.18	16.68	2440	2210
2	0.45	58.3	44.38	15.17	2480	2200
*2	0.45	30.0	44.38	28.83	2480	2270
5	0.4	10.0	42.18	40.73	2440	2390
6	0.5	10.0	38.55	35.51	2420	2400
7	0.5	50.0	38.55	19.97	2420	2240
8	0.45	1.70	44.38	36.09	2480	2420
9	0.38	30.0	44.95	32.77	2360	2308
10	0.52	30.0	36.05	20.79	2410	2307

*2: Two central points (experiments 3 and 4).

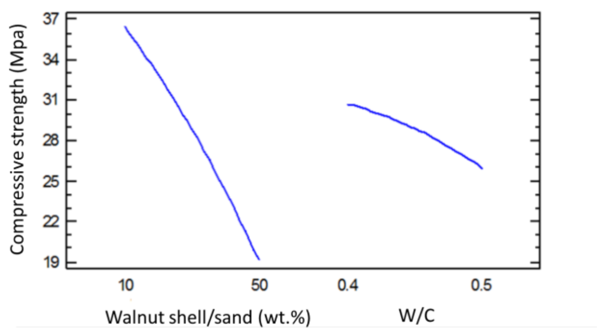
In the currentt work compressive strength test for the 28 days water cured mixes prepared through out the ten experiments (30 cubes, 3 for each experiment) was conducted using compressive strength machine Controls model 50-C23C02 with a 2000 KN load capacity. The compressive strength of the specimens was calculated by dividing the maximum load attained during the test by the cross-sectional area of the specimen. The experimental results (average values) for compressive strength of PCC (control) and walnut shell-concrete (WNC) mixes prepared according to the central composite design are shown in table 4.

According to the experimental results shown in Table 4, the highest compressive strength of 28-day hardened walnut shell-concrete samples was 40.73 MPa for a mix of 0.4 W/C and 10% wt. walnut shell, while the lowest value was 16.68 MPa for a mix of 0.4 W/C and 50% wt. walnut shell compared to 44.95 MPa for PCC sample of 0.38 W/C and 36.05 MPa of 0.52 W/C respectively.

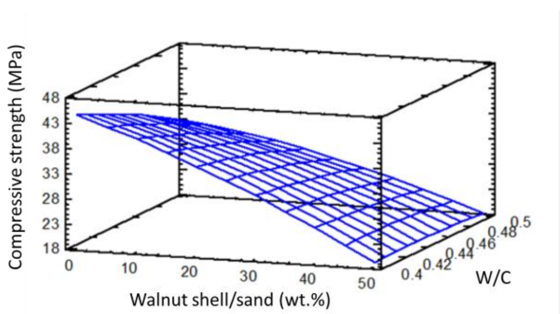
To model and optimize the effect of W/C ratio and walnut shell content on compressive strength, the experimental results for compressive strength for WNC samples listed in Table 4 were analyzed by RSM. The RSM results estimated are shown in Figure 10.



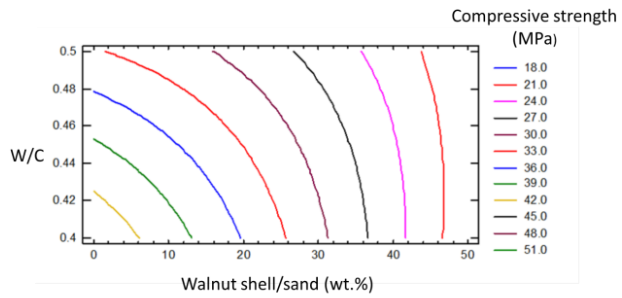
(A): Standardized Pareto chart for compressive strength



(B): General trends for compressive strength



(C): Estimeted Response surface



(D): Counters of estimated response surface

Figure 10. Pareto chart (A), General trends (B), Response Surface (D), and Contours plot (C) for compressive strength of concrete mixes of different walnut shell content

The RSM results shown in Figure 10 revealed that walnut shell content has a significant effect on compressive strength (Figure 10A), however the general trend plots demonstrated that above 10% content of walnut shell, compressive strength decreases with increasing both W/C ratio and the Walnut shell content (Figure 10B). The decrease of compressive strength with increasing the walnut shell content may be attributed to the poor fluidity which causes the void ratio to increase resulting in a lower compressive strength of the WNC mixes.

The high value of the regression factor R-squared = 93.1487 percent confirmed that the model is of high accuracy and capable to generalize between input and output parameters with reasonable good predictions. The polynomial equation showing the effect of walnut shell content and W/C ratio on compressive strength is shown in equation (4):

$$\text{Compressive Strength} = 47.0114 - 1.2267*S + 77.1005*W/C - 0.002751*S^2 + 2.1325*S*W/C - 209.252*(W/C)^2 \quad (4)$$

Where, S represent walnut shell content (% wt.), and W/C represent water/cement ratio.

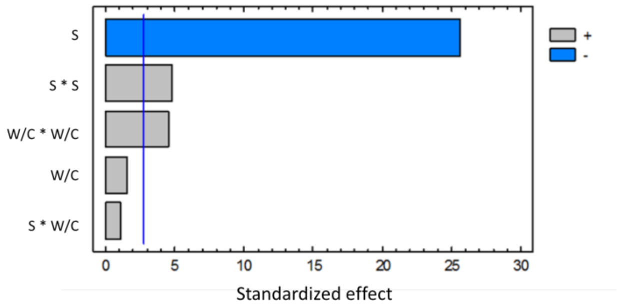
An Optimum value = 45.4267 for compressive strength was estimated from the model analysis corresponds to 1.7 wt. % content of walnut shell, and 0.38 W/C ratio. However, concrete mixes with walnut shell content up to 10% and 30% showed comparable compressive strength (40.73 and 36.05) MPa respectively to normal PCC as recorded in table 4. Hence, concrete with walnut shell up to 30% wt. could be used in casting structural concrete.

3.3. RSM Results for Density

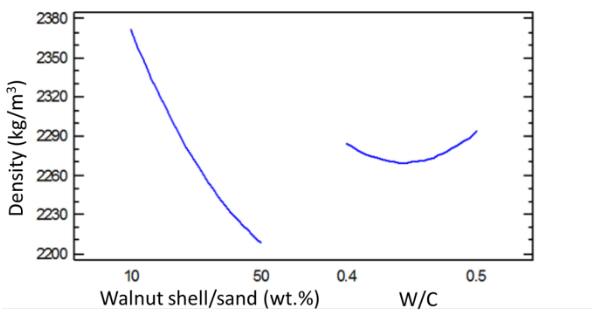
The experimental results for density test for the hardened control (PCC) and walnut shell-concrete (WNC) mixes are shown in table 4.

Based on the obtained data, density of the 28-day hardened samples seemed to decrease with increasing walnut shell content; this is owing to the specific gravity of walnut shell which is less than that for the natural aggregate. The highest density was 2480 kg/m^3 for PCC sample of 0.45 W/C, while the lowest was 2200 kg/m^3 for walnut shell-concrete sample of 0.45 W/C and 50 wt. % (walnut shell/natural fine aggregate). The results estimated in this work were in agreement with some results found for other agro waste concrete such as rice husk ash-concrete [55], and rice husk ash and coconut fibers-concrete composites [56].

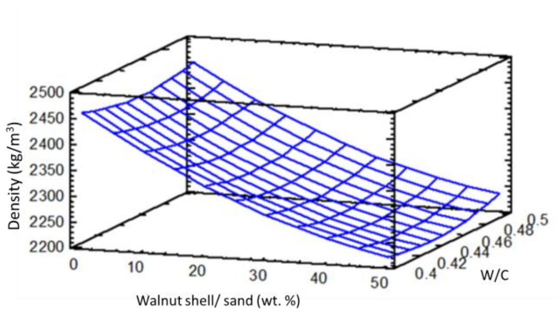
To model and optimize the impact of W/C ratio and Walnut shell content on concrete density, the experimental results recorded in Table 4 were analyzed by RSM. The RSA results are illustrated in Figure 11.



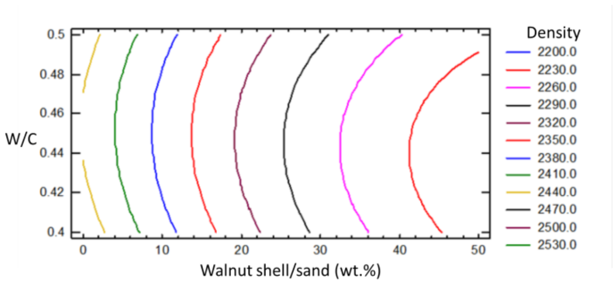
(A): Standardized Pareto chart for density



(B): General trends for density



(C): Estimated response surface for density



(D): Contours plot for density

Figure 11. Pareto chart (A), General trends (B), Response Surface (D), and Contours plot (C) for density of concrete mixes of different walnut shell content

The analysis of the experimental results by RSM predicted that walnut shell content in concrete mixes is the significant factor affects density as shown in Pareto chart (Figure 11A). However, density seemed to decrease dramatically with increasing walnut shell content. W/C ratio showed a narrow range and lower effect on density, such as the optimum density could be achieved using 0.45 W/C as shown in Figure 11(B, C and D).

The specific gravity of walnut shell is lower than that of the natural aggregate. Hence, walnut shell can be termed as lightweight aggregate as it has low specific gravity [46].

High value of the regression factor R-squared = 99.4264 percent was estimated from the model analysis which highly confirm the capability of the adopted module to explain the experimental results for bulk density.

The corresponding polynomial equation estimated from the model is represented in equation (5):

$$\text{Density} = 4005.93 - 9.36643{*}S - 6915.99{*}S{*}W/C + 0.0507814{*}S^2 + 5.0{*}S{*}W/C + 7624.95{*}(W/C)^2 \quad (5)$$

Where, S represent walnut shell content (% wt.), and W/C represent water/cement ratio.

An Optimum value = 2467.03 kg/m^3 for density was estimated from the model for the concrete mix of 0.38 W/C and 1.7 wt. % walnut shell. However, all the concrete samples contain walnut shell were of less density, the average density values ranged from 2200-2420 kg/m^3, compared to 2360-2480 kg/m^3 for PCC samples as illustrated in Table 5.

3.4. Compressive Strength-Density Relationship

It is worthy to note that in design of concrete structures the most important parameters should be taken into consideration are density and compressive strength. In general, the mechanical properties of concrete are highly influenced by its density. Higher strength concretes have low porosity and few amounts of voids such as the concrete become less permeable to water and aggressive fluids [54].

From the experimental data, relationship between density and compressive strength has been developed for walnut shell-concrete mixes of identical W/C (0.45), but different walnut shell content. A direct proportional relationship was obtained with good coefficient of determination $R^2 = 0.8612$ which indicated good confidence for the relationship (Figure 12).

$$D = 9.8199\ Cs + 2034.5 \quad (6)$$

Where D is density (kg/m^3), and Cs is compressive strength (MPa).

From this correlation, concrete density can be predicted for a particular compressive strength. However, more precise correlation is expected if more experiments are carried out. Correlations of similar trend were recorded for other agro waste-concrete composites [29, 52].

In view of the results cited in this work, walnut shell can be considered as light weight aggregate that could be applied successfully in concrete construction.

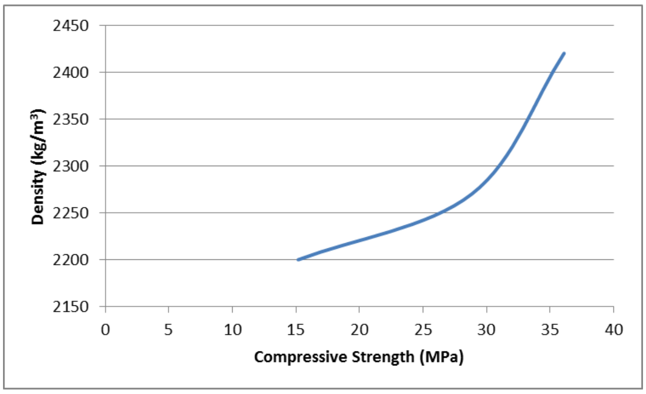


Figure 12. Compressive strength versus density relationship for walnut sell-concrete

4. Conclusions

This study contributes to development of the existing knowledge on using agro waste in concrete, as well as identification the walnut shell as a partial substituent of fine aggregate in concrete. The effect of walnut shell content and water/cement ratio on concrete properties including water absorption, compressive strength and density was studied, optimized and modeled using RSM. The RSA results confirmed the significant effect of walnut shell content on compressive strength and density, while the quadratic effect of W/C was significant for water absorption for concrete mixes contain Walnut shell as partial replacement of natural fine aggregate. The overall results confirmed that up to 30% walnut shell could replace fine aggregate in concrete resulting in a concrete with acceptable compressive strength and of lower density and water absorption compared to Portland cement concrete. The findings of the study indicated the promising potential of using walnut shell for producing structurally applicable and environmental friendly concrete.

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