Optimization of Mix Composition of Cement-less Wastepaper-based Lightweight Block (CWLB)

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Abstract: - The development of cement-less wastepaper-based lightweight block (CWLB) is another important step towards the production of eco-friendly building materials from wastepaper. This block which was designed to be used for non-load bearing/non-structural application was developed without the use of hydraulic cement. This study was conducted to optimize the mix composition of CWLB for the purpose of maximizing its compressive strength. This aim was achieved by employing the Taguchi statistical optimization technique in conjunction with laboratory experimentation. The result indicated that water/binder ratio had the most significant effect on the compressive strength of CWLB. The analysis of result establishes the CWLB specimen with optimal parameter to be that which was made from; 2.5 WPA/Sand ratio, 0.75 Water/binder ratio, and 3.5 Metric ton (i.e. 13.7MPa) compacting force. Also, the optimal CWLB displayed; an average compressive strength of 2.71MPa which indicated an increase of 402% compared to the 0.50MPa displayed by the worst parameter combination and an average density of 901.5kg/m^3. The compressive strength and the density of the optimal CWLB was found to maximally satisfy the requirements for non-load bearing lightweight blocks. Considering the high amount (typically, 75%) of waste content in the composition of CWLB, it was reckoned as a viable eco-friendly lightweight block suitable for non-load bearing application. Future work will investigate other relevant properties of CWLB which include; Elastic modulus, water absorption, thermal conductivity, and reaction to fire.

Key-Words: - Taguchi method, compressive strength, non -loadbearing, block, Wastepaper, Mix composition, Optimization.

1 Introduction

The environmental impacts associated with the activities of the construction industry and the unsustainable waste generation resulting from increased civilization and proliferating standard of living coexists among the global environmental issues confronting this present generation. Critical analysis of the Municipal Solid Waste (MSW) generation upturn from 0.64kg/day in 2002 to 1.2kg/day in 2012 [1] suggests that the world experienced an estimated 88% increase in per capital MSW generation within a ten years period. The construction industry on the other hand is reported to be responsible for 60% raw material consumption at the global level [2]. A typical evidence of this impact is the fact that; the building industry requires about six to seven more tonnes of sand and gravel, for each single tonne of cement used in construction [3] aside from the excessive raw materials being exhausted in cement production [4].

Following the continuous suggestion and consideration for the use of environmental friendly materials, minimization of raw material consumption [5], practice of industrial ecology [5], and the attempts of researchers to achieve sustainability in the construction industry through recycled use of waste in the production of construction materials[6], building materials such as: fibre cement board [7], lightweight block [8]; [9]; [10], low density board [11], papercrete [10]; [8], plastering mortar [12], have been produced from wastepaper. However, extensive literature review showed that, building material produced from waste paper suffers high water absorption [8; 13; 12] thickness swelling and low strength with increasing wastepaper fibre content [8]; [14]; [15]; [16], This drawback of strength reduction arises due to the corresponding water content increment that occurs in the mix with increasing waste paper content [17].This implies that contradiction exists between the hygroscopic properties of paper fibre and the moderate water requirement for cement hydration and it means that the high water cement ratio resulting from increasing paper content lowers the strength of the building material concerned. Aside this, the utilization of considerable quantity of cement in the composition of wastepaper based building materials as a means of strength properties improvement is believed to be undermining their environmental friendliness.

Thus, the development of cement-less wastepaper-based lightweight block (CWLB) is another important step towards the production of eco-friendly building materials from wastepaper. This block which was designed to be used for non-load bearing/non-structural application was developed without the use of hydraulic cement. Its constituents are majorly waste materials, which includes; wastepaper aggregate (WPA), waste additive (obtained as industrial waste by-product), and lesser quantities of sand, water and natural admixture. CWLB was specifically developed to address the low compressive strength which usually occurs with increasing waste paper content in wastepaper based blocks produced with cement as binding medium. The findings from the exploratory study conducted to develop its mixture proportioning process and the study of the factors that influence its compressive strength were reported and published [18];[19].

Based on the findings from the study of factor effects [19], the processing parameters which includes; Water/ binder ratio, WA/sand ratio, and compacting force were found to have the crucial effects on the compressive strength of CWLB. Therefore, for the purpose of maximizing the compressive strength of CWLB to satisfy the strength requirements for non-structural/non-load bearing blocks, this optimization study was conducted to determine the optimum mixture composition for CWLB. This aim was achieved by employing the Taguchi statistical optimization technique in conjunction with laboratory experimentation.

2.1 Taguchi Method

The Taguchi method is a statistical optimization process technique developed by Genichi Taguchi around the 1950s [20].It is a Design of Experiment DOE [21] approach that is grounded on quality philosophy which seeks to develop product and processes that are robust to environmental factors and other sources of variation. Robustness can be described as the extent of the product or processes capabilities to perform efficiently and consistently with minimal effect from the uncontrollable noise factors due to operation or manufacturing [21].

The use of Taguchi approach in product development offers design engineer a proficient and an organised means of determining a near optimum design parameters for quality performance. The concept of Signal-to-noise-ratio encompassed within the Taguchi method enables the measurement of variability of performance response relative to the desired value under different noise conditions. Taguchi method recognises that in product development, some factors that cause variability can be controlled while there are also factors that are uncontrollable. The uncontrollable factors are known as noise factors. The identification of controllable factors is important in Taguchi DOE, because in the course of experimentation, noise factors are controlled to force variability to occur thereby leading to the determination of optimal control factors settings that make the processor product robust or resistant to variation form the noise factors. The noise factors are regarded as the cause of variability in performance as well as product failure. The S/N ratio helps to evaluate the stability of performance of an output characteristic [22].

Having previously performed a series of trial experimentation and salient parameter studies [19] which addresses the step 1-4 of the procedure for Taguchi design methodology (Fig. 1).This study employs Taguchi method to determine the best combination of processing parameters/control factors required to obtain the optimum mixture composition for CWLB with maximal compressive strength. The compressive strength of the block was solely studied as the quality response in this optimization process because of its intrinsic importance in structural design. The Taguchi approach was chosen over the other types of DOE (including; full factorial, screening experiments, response surface and mixture experiment) as it is capable of analysing more factors with fewer experimental runs while also enabling the analysis of effects on response.

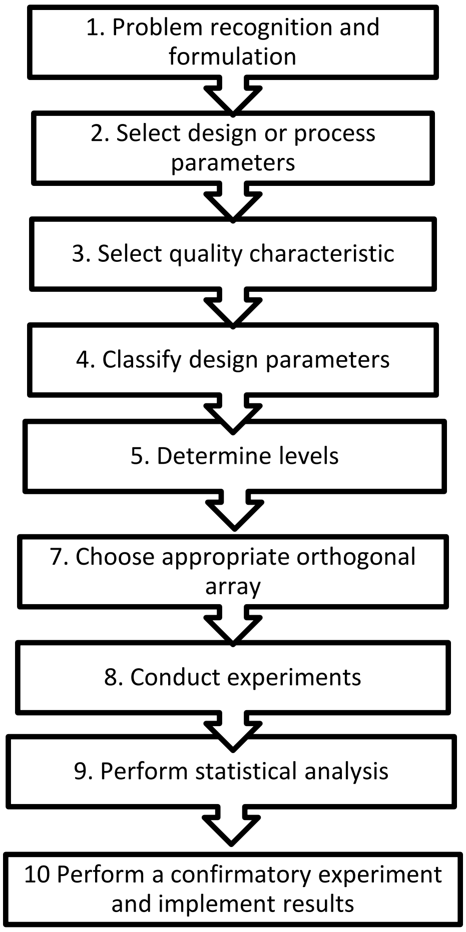

Fig. 1: Procedure for Taguchi design methodology [22]

2 Experimental Procedure

In this study, CWLB was produced from constituent materials which includes; wastepaper aggregate (WPA), sand, waste additives (binder), natural admixture (stoneware clay) and water. Given the variation in the physical properties of the constituent materials (Table 2), batching was carried out by weight in order to achieve accurate proportioning of materials for the CWLB mixes. Several mixes were prepared from varied combinations of WPA/Sand ratios, WPA/binder ratios, and water/binder ratios. CWLB specimens of sizes 50mmx50mm x50mm were molded using a 10 ton manual hydraulic press containing a preinstalled pressure gauge (Fig. 2). The experiment was conducted with three controllable three-level processing parameters namely; WPA/Sand ratios, water/binder ratios and compacting forces. Other processing parameters which includes; WPA particle size (passing 3.35mm BS sieve), specimen curing duration (28days), mixing time (27 min), admixture quantity (5% by weight of WPA), were kept constant. The selected processing parameters and their levels are shown in table 3.

Table 2: Physical properties of CWLB constituent materials

Physical Properties	Materials			
	Wastepaper Aggregate (WPA)	Sand	Waste Additive (binder)	Natural admixture (clay)
Specific gravity	0.661	2.63	1.04	0.895
Loose Bulk density (kg/l)	0.096	1.428		0.911
Particle sizes range (mm)	(3 - 0.125)	(4 - 0.063)	-	-
% Solid content	-	-	23%	-

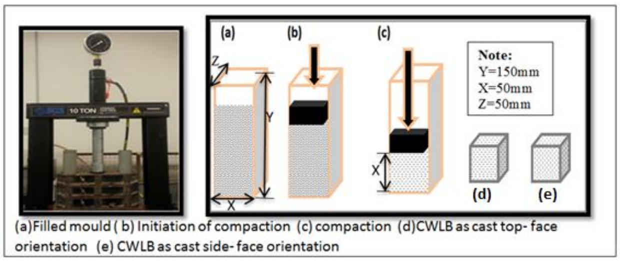

Fig. 2: 10 ton manual hydraulic press containing a preinstalled pressure gauge and CWLB Molding process

With three factors, each with three levels, the full factorial design would require $3^3=27$ possible combinations of trials. Carrying out a large number of experiments for all the combinations will amount to excessive resources and time consumption. The Taguchi method designs an orthogonal array (OA) to simplify the large number of experiments, and allocates them into a smaller number of trials to run the experiment. Orthogonal array is an arrangement of numbers in columns and rows in a manner that each column represent a factor while the rows stand for levels of the factors [23]. Only three processing parameters, each with three levels, were considered in this study, nine trials of CWLB specimen with varied compositions were produced using the L_9 (3^3) OA, as presented in Table 4a and 4b.

Table 3: CWLB processing parameters and levels

Designations	Control Factors	Units	Level 1	Level 2	Level 3
A	WPA/sand ratio	-	2.08	2.27	2.5
B	Water/binder ratio	-	0.75	2.25	3.75
C	Compacting force	Metric ton	3	3.25	3.5

Table 4a: Table of Taguchi Orthogonal Array L_9 (source: Ref. [24])

Experiment Number	Factors and level			Parameter setting
	A	B	C	
1	1	1	1	A1B1C1
2	1	2	2	A1B2C2
3	1	3	3	A1B3C3
4	2	1	2	A2B1C2
5	2	2	3	A2B2C3
6	2	3	1	A2B3C1
7	3	1	3	A3B1C3
8	3	2	1	A3B2C1
9	3	3	2	A3B3C2

Table 4b: Table of Taguchi Orthogonal Array $L_9(3^3)$ showing details of CWLB parameter combinations

Experiment Number	Factors and level			Parameter setting
	A	B	C	
1	1(2.08)	1(0.75)	1(3)	A1B1C1
2	1(2.08)	2(2.25)	2(3.25)	A1B2C2
3	1(2.08)	3(3.75)	3(3.5)	A1B3C3
4	2(2.27)	1(0.75)	2(3.25)	A2B1C2
5	2(2.27)	2(2.25)	3(3.5)	A2B2C3
6	2(2.27)	3(3.75)	1(3)	A2B3C1
7	3(2.5)	1(0.75)	3(3.5)	A3B1C3
8	3(2.5)	2(2.25)	1(3)	A3B2C1
9	3(2.5)	3(3.75)	2(3.25)	A3B3C2

The 50mmx50mmx50mm CWLB specimen (Fig. 3) produced from the experimental run in table 4b were subjected to curing in ambient laboratory air for 28days. The density of the specimen at 28days curing age were determined in accordance with BS EN 772-13:2000 [25] specification. Compressive strength test was conducted on the specimen in accordance to BS EN 772-1:2011 [26] specification. The result of compressive strength obtained was analysed by adopting the (the bigger the better) signal-to-noise (S/N) ratio and by analysis of variance (ANOVA) in order to determine the optimal processing parameter required to produce CWLB with satisfactory compressive strength and to establish the impacts of each processing parameter on the compressive strength of CWLB.

Fig. 3: 50mmx50mmx50mm CWLB specimen

2.1 Analysis Method

In analysing the results, the (S/N) ratio introduced by Taguchi for determining product quality characteristics was adopted. In Taguchi method, a high S/N ratio implies that the signal is much higher than the random effect of the noise factors. The part or process operation consistent with the highest S/N ratios always yields optimal quality characteristics with minimum variance. Also, quality characteristics in the Taguchi method can be categorized into; 'the smaller the better' (indicating minimization), 'the nominal the better' (indicating Nominalization) and 'the bigger the better' (indicating Maximization) [22]. In the study of the mechanical properties especially compressive strength of blocks, higher strength is usually desired. Therefore, since the focus of this study was to maximize the compressive strength of CWLB, the S/N ratio which corresponds to 'the bigger the better' quality characteristic was utilized in the analysis, and it was calculated using Eqn. (1)[22]:

$$S/N_L = -10log\left(\frac{1}{n}\sum_{i=1}^{n}\frac{1}{y_i^2}\right) \ldots\ldots\ldots\ldots\ldots\ldots(1)$$

Where:

y_i is the value of the compressive strength for the ith trials, n is the numbers of samples, and S/N_L is the symbol representing 'the bigger the better' signal-to-noise-ratio.

In this analysis, the level of the factor with the larger S/N ratio denotes that this level can result in a larger compressive strength. By selecting the level with a larger S/N ratio for each factor, the estimation of the set of optimal levels of the processing parameters for CWLB was actualized. A confirmation test/selection of optimum parameter setting according to the identified optimal factor levels was carried out as applicable. The experimental results as well as the computed S/N_L ratios for each parameter settings are presented in table 5.

2.1.1 Determination of Mean of S/N_L ratio, Main effect of control Factors and the rank of Effect.

The averaged effect response for S/N_L ratio of each factor was investigated to determine the contributions of WPA/Sand ratio, Water/binder ratio, and Compacting force to the magnitude of the compressive strength. Minitab 17 statistical software was used to carry out analysis of variance (ANOVA) on the experimental results and the corresponding computed S/N_L ratio and was also use to obtain the main effect plot for S/N_L ratio. The mean of S/N_L ratio $\bar{\text{j}}_i$ (which represented the factor average effect at each level) was obtained by applying the expression for determining average of S/N ratio for each factor [24] as shown in Eqn. (2). The effect of each factor E_j (which is simply the observed range of S/N ratio at different factor levels) was obtained by using the expression [24] shown in Eqn. (3). The rank was estimated based on the magnitude of the effect of each factor.

$$\bar{\mathbf{j}}_i = \frac{1}{n}\sum_{j_i=1}^{n} j_i \,|_{\forall j,i} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(2)$$

Where:

j represents any of the factors A,B or C (at any instance), i stands for any of the levels 1,2 or 3 (at any instance), $\bar{\text{j}}_i$ is the mean of S/N ratio, n is the number of levels in the experiment. The sign $|_{\forall j,i}$ signifies that Eqn.(2) was evaluated at j and i values.

$$E_j = F_{jmax} - F_{jmin}|_{\forall i} \ldots\ldots\ldots\ldots\ldots\ldots(3)$$

Where:

E_j is the effect of factor j, F_{jmax} and F_{jmin} are maximum and minimum value of factor j respectively. The sign $|_{\forall i}$ indicates that Eqn. (3) was evaluated across the level.

3 Results and discussions

The plot of compressive strength test result for each experimental run is presented in figure 4. It was observed that experiment number 7 displayed the highest compressive strength compared to all other experimental runs. Also, the CWLB produced from experiment number 6 displayed the lowest compressive strength compared to others, which indicates that parameter combination in experiment number 6 is the worst parameter setting compared to others.

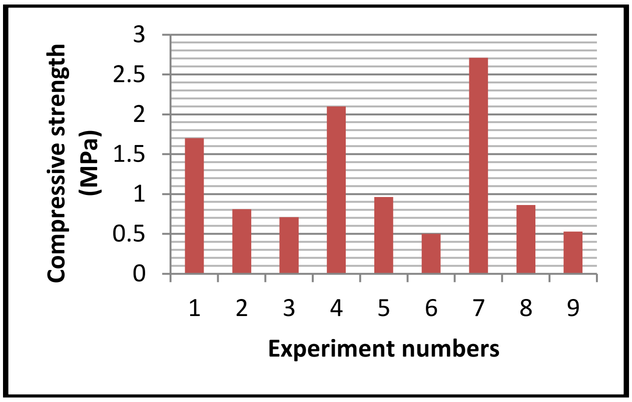

Fig. 4: Plot of compressive strength test result for each CWLB experimental run

3.1 Main effect of processing parameter/control factors

In this study, the compressive strength result of CWLB produced from each experimental run was statistically analysed using S/N_L ratio which correspond to the "bigger the better" quality characteristics and were computed based on equation 1, since the higher compressive strength is desired. The computed S/N_L ratios for each parameter combinations are presented in table 5.

Figure 5 present the graph of main effect plot for S/N_L ratio which was plotted to find the optimum levels of WPA/Sand ratio, Water/binder ratio and compacting force required to produce CWLB with maximal compressive strength. It was found that an increment in WPA/sand ratio lead to an increase in compressive strength of the block, while a decrease in WPA/Sand ratio resulted in a decrease in compressive strength. However an insignificant effect variation was observed within the range investigated. Low water/binder ratio resulted in higher compressive strength while high water/binder ratio lead to lower compressive strength and the effect variation was significant within the range tested. Also, the compressive strength of CWLB increases with increasing compacting force and decreases at lower compacting forces.

Table 5: Experimental Results and Computed S/N_L ratio

Experiment Number	Factors and levels			Response	S/N_L ratio
	A	B	C	Compressive strength (MPa)	
1	1	1	1	1.7	4.609
2	1	2	2	0.81	-1.830
3	1	3	3	0.71	-2.975
4	2	1	2	2.10	6.444
5	2	2	3	0.96	-0.356
6	2	3	1	0.50	-6.021
7	**3**	**1**	**3**	**2.71**	**8.659**
8	3	2	1	0.86	-1.310
9	3	3	2	0.53	-5.514

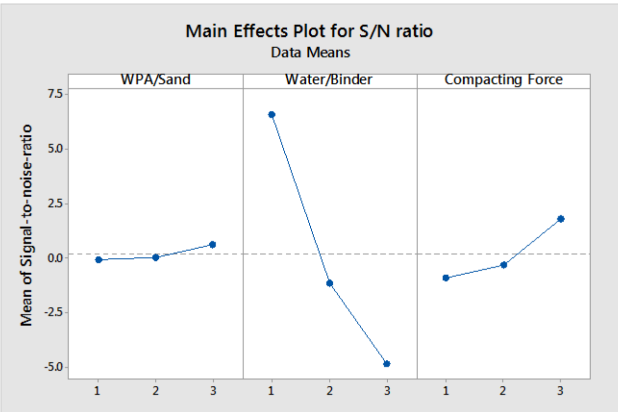

Fig.5: Main effect plot for WPA/ sand ratio, Water/Binder ratio, and Compacting force.

3.2 Optimum Mixture composition of CWLB

Judging from both figure 5 and the data presented in table 6, the most significant processing parameters for CWLB is factor B (Water/Binder ratio) as it displayed the largest effect and ranked 1st. Factor A (WPA/Sand ratio) is the least significant as it exhibited the least effect, hence ranked 3rd. Factor C (Compacting Force) has the second largest effect as it ranked 2nd. Furthermore from table 6, the optimal parameter setting based on maximum values was deduced to be A3B1C3 which revealed that the CWLB should be produced from a combination of 2.5 WPA/Sand ratio, 0.75 Water/Binder ratio and 3.5 Metric ton Compacting force. This optimal parameter setting is equivalent to a mix ratio of 1:0.4:0.2 of WPA, Sand, and Binder ratio. It is also equivalent to 62.5% WPA, 25% Sand and 12.5% binder when estimated based on aggregate and binder only (i.e. excluding water content and natural admixture).

Table 6: Mean of S/N Response, Effects of Factors and Rank of Effects

Description		Factors and levels		
		A	B	C
$\bar{j}_i$ (see Eqn. 2)	Level 1	-0.06	6.57	-0.91
	Level 2	0.02	-0.3	-0.3
	Level 3	0.61	-4.84	1.78
Ej (see Eqn. 3)	Effect	0.67	11.41	2.69
Rank of effect	Rank	3	1	2

3.3 Confirmation Test and Review of CWLB Properties.

Incidentally, the identified optimal parameter setting of CWLB coincided with the parameter setting on experiment number 7(see table 5).Therefore the result of compressive strength for experiment number 7 was compared with the result obtained from the worst parameter setting (i.e. experiment number 6). From table 7, it was established that the optimum parameter setting increases the compressive strength of CWLB by 442% compared to that of the worst parameter setting. Likewise from Table 7, the optimal CWLB exhibited average compressive strength of 2.71MPa and average density of 901.5kg/m^3. In contrast with standard recommended mechanical and physical property requirement for non- load bearing blocks; the 2.71MPa average compressive strength of CWLB is maximally higher than the 1.5MPa minimum compressive strength recommended by BS EN 771-4:2011[27] for non-load bearing lightweight block (see Fig. 6) and the 901.5kg/m^3 average density of CWLB falls within the range of 300-1000kg/m^3 (BS EN 771-4:2011) [27] and 625kg/m^3-1500kg/m^3 (BS EN 2028 1975)[28] specified for lightweight non-load bearing blocks.

In contrast with cement based wastepaper blocks (e.g. papercrete) (Fig. 6), the 2.71MPa compressive strength displayed by CWLB is higher than the 1.84MPa [9] reported for papercrete block containing 40% by volume paper pulp, and the ≈1.4MPa [8] reported for papercrete block containing 35.7% cement 35.7 sand and 28.6% wastepaper (i.e. mix ratio 1: 1:0.8)

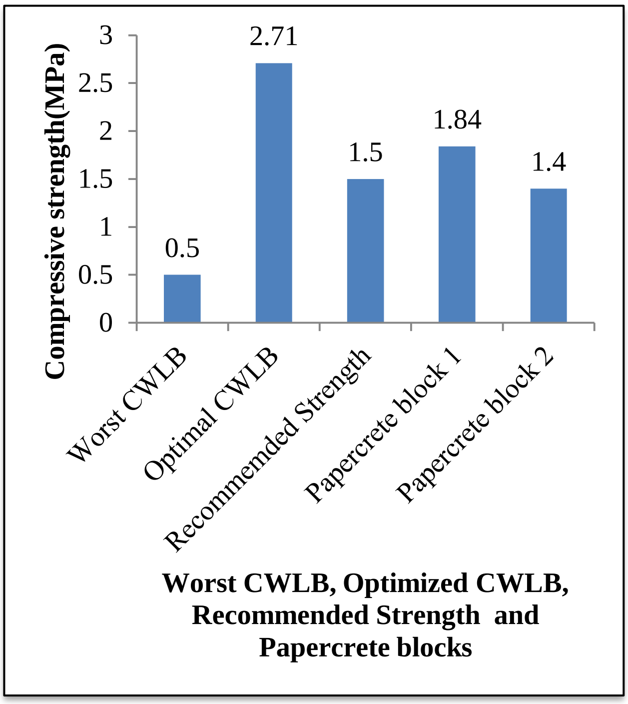

Fig. 6: Comparison of the compressive strength Optimized CWLB with Worst CWLB, Standard Non- load bearing block and Papercrete blocks

Table 7: Confirmation test, Properties and Optimal parameter combination for CWLB

	Factors and levels			Compressive strength (MPA)	S/N_L ratio
	A	B	C		
Worst composition	1	3	1	0.50	-5.352
Optimal composition	3	1	3	2.71	8.659
Percentage increase				**442%**	-

Properties and Optimal parameter combination for CWLB

Optimal Parameter Combination			Properties	
WPA/Sand ratio	Water/Binder ratio	Compacting force(Metric ton)	Compressive strength (MPa)	Density (kg/m^3)
2.5	0.75	3.5	2.71	901.5

4.0 Conclusions

The details of the optimization of the mixture composition of CWLB using Taguchi approach is presented in this paper. CWLB specimens of sizes 50mmx50mm x50mm were molded from mixture of WPA, sand, waste additive (binder), natural admixture and water. The control parameters which include; WPA/Sand ratio, Water/Binder ratio and Compacting force were investigated with the aim of maximizing the 28days compressive strength of CWLB. The outcome of the investigation showed that the compressive strength of CWLB depends on the processing parameters. Comparison of the main effect of WPA/Sand ratio, Water/Binder ratio and Compacting Force indicated that Water/Binder ratio has the most significant effect on the compressive strength of CWLB. The identified optimal parameter setting of 2.5 WPA/Sand ratio, 0.75 Water/Binder ratio, and 3.5 Metric ton Compacting force produced CWLB specimen with properties suitable for non-load bearing application (viz: 2.71MPa average compressive strength and 901.5kg/m^3 average density). The optimum mix composition of CWLB which contains 62.5% WPA, 25% Sand and 12.5% waste additive (binder) makes a highly eco-friendly block as it amounts to the presence of 75% waste content.

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