Strength and Stiffness Properties of the Optimum Mix Composition of Cement-less Wastepaper-based Lightweight Block (CWLB)

OKEYINKA ORIYOMI M, OLOKE DAVID A, KHATIB JAMAL M
School of Architecture and the Built Environment
Faculty of Science and Engineering
University of Wolverhampton, City Campus,
Wolverhampton, West Midlands WV1 1SB,
UNITED KINGDOM
O.M.Okeyinka@wlv.ac.uk

Abstract: - The cement-less wastepaper-based lightweight block (CWLB) is a newly developed eco-friendly non-load bearing block manufactured from majorly cellulosic wastes without the use of cement. The main constituents of CWLB includes; wastepaper aggregate (WPA) produced from post-consumer wastepaper, waste additive and sand. This study was conducted to determine its optimum mix composition and the corresponding strength and stiffness properties. The experimentations carried out covered; the optimization of the mix composition of CWLB using the Taguchi statistical optimization technique (TSOT) and the determination of the compressive strength, density, elastic modulus and the ultrasonic pulse velocity (UPV) of the optimal CWLB specimen. The findings from the TSOT ascertains that the optimum mix composition of CWLB comprises of processing parameters including; 2.5 WPA/sand ratio, 0.75 water/binder ratio, and 3.5 Metric ton (i.e. 13.7 MPa) compacting force. Also, it was found that the optimal CWLB exhibited; an average compressive strength of 2.71 MPa, an average density of 901.5 kg/m^3, an average UPV of 989.9 m/s and an estimated elastic modulus of 883.4 MPa. The comparison of these properties with the applicable standard requirements indicates the suitability of CWLB for non-load bearing application. In addition, the presence of 75% waste content in the mix composition of CWLB indicates its eco-friendliness and its potential to contribute to the sustainability in the construction industry through reduction in natural resources consumption. The innovation presented in this study includes; the development of a suitable optimum mix composition of constituent materials for the novel CWLB, the identification of factors that affects it strength properties and the determination of its engineering properties. Future work will investigate other relevant properties of CWLB which include; capillary water absorption, thermal conductivity, and the reaction to fire.

Key-Words: - Taguchi method, compressive strength, non -loadbearing, block, Wastepaper, Mix composition, Optimization, Density, Ultrasonic pulse velocity (UPV), Elastic modulus.

1 Introduction

The various notable environmental impacts associated with the creation of the built environment and the unsustainable waste generation resulting from increased civilization and proliferating standard of living represents major issues of global environmental concerns. Critical analysis of the Municipal Solid Waste (MSW) generation growth from 0.64 kg/day in 2002 to 1.2 kg/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 wastepaper 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. Having developed the mixture proportioning process [18] and identified the; Water/binder ratio, WPA/sand ratio, and compacting force as the crucial factors that affects the compressive strength of CWLB [19], this study was conducted to determine the optimum mix composition of CWLB (using the Taguchi statistical optimization technique) and also determine the strength and stiffness properties of the specimen produced from same. The essence is to obtain the maximized compressive strength of CWLB and assess its suitability for use in wall construction with reference to the standard requirements for non-loadbearing blocks. The corresponding UPV and the elastic modulus of the optimal CWLB specimen were also determined to assess its quality and stiffness.

1.1 Structure of the Study

The studies presented in this paper are divided into two major categories. The first study category dealt with the optimization of the mix composition of CWLB using the Taguchi statistical optimization technique. The experimental and the analytical details for the optimization study are presented in section 2.1 to s.1.2 of this paper. The second study category dealt with the determination of the strength and stiffness properties (including: compressive strength, density, UPV and elastic modulus) of the resulting optimal CWLB, the experimental details are presented in 2.2 of this paper. The findings from the optimization study are presented in section 3.1 to 3.3.1 and the findings from the investigated properties are presented in section 3.3.2 to 3.3.4. The conclusion of the studies and the future work in progress are presented in section 4 of this paper.

1.2 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, during experimentation, noise factors are controlled to force variability to occur thereby leading to the determination of optimal control factors setting that make the process or product robust or resistant to variation from 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].

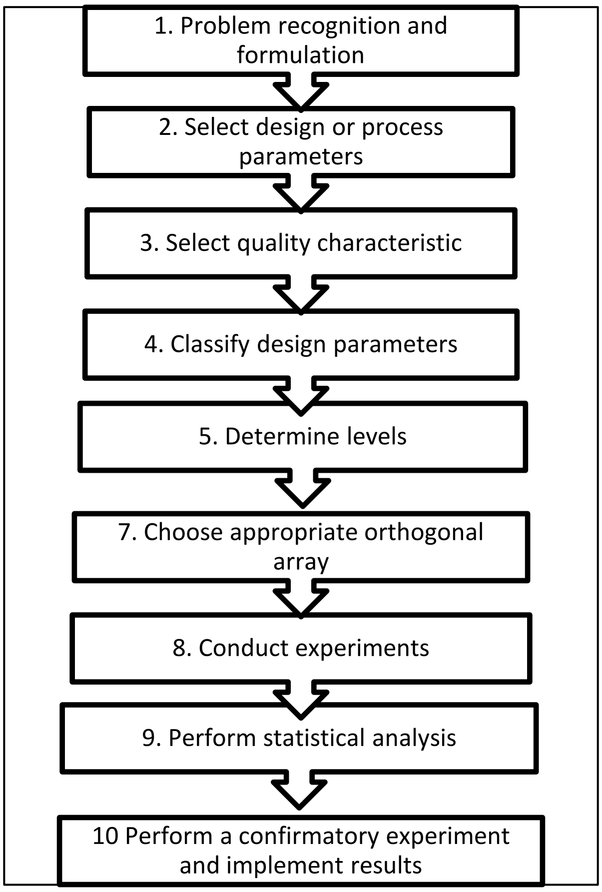

Fig. 1: Procedure for Taguchi design methodology [22]

2 Materials and Methods

In this study, CWLB was produced from constituent materials which includes; wastepaper aggregate (WPA), sand, waste additives (binder), natural admixture (stoneware clay) and water. The WPA utilized as major aggregate filler was systematically produced from post-consumer wastepaper (old newsprint), the detail procedure is reported in [19]. The waste additive used as binder was obtained as a byproduct of food processing industry, its elemental composition is presented in Table (1). The sand utilized as minor additional filler and the stoneware clay utilized as admixture were obtained from local suppliers in Wolverhampton, United Kingdom.

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 50mm x 50mm x50mm were molded using a 10 ton manual hydraulic press containing a preinstalled pressure gauge (Fig. 2).

Table 1: Elemental Composition of the Waste Additive Utilised as Binder

Elements	**Waste additive**	
	Solid part	**Liquid part**
	ppm	**ppm**
Al	0.03	0.01
Ca	5.42	6.09
Fe	0.08	0.02
K	6.60	28.87
Mg	0.40	3.06
S	0.78	2.15
Si	65.71	27.20

Table 2: Physical Properties of Constituent Materials of CWLB

Physical Properties	**Materials**			
	Wastepaper Aggregate (WPA)	**Sand**	**Waste Additive (binder)**	**Natural admixture (Stoneware 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)	Not applicable	< 0.063
Percentage Solid content (%)	100	100	23	100

The CWLB specimens produced from all laboratory experimentation in this study were cured in ambient laboratory air for 28 days duration prior to testing. The first part of this study dealt with the optimisation of CWLB while the second part determines the strength and stiffness properties of the optimal CWLB specimen. Each of the tests were conducted on three samples of CWLB cubic specimens.

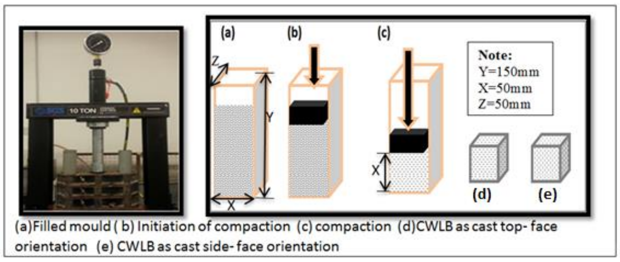

Fig. 2: 10 ton manual hydraulic press containing a preinstalled pressure gauge and CWLB Molding process

2.1 Experimental Details for the Optimisation of Mix Composition of CWLB

This study employs Taguchi method to determine the best combination of processing parameters/control factors required to obtain the optimum mix composition for CWLB. The previously performed series of trial experimentations and salient parameter studies [19] have addressed the step 1-4 of the procedure for Taguchi design methodology (Fig. 1). Thus, the compressive strength of the block was solely studied as the quality response in this optimisation process because of its intrinsic importance in the design of masonry structures. 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.

The optimisation experiment was designed based on three controllable three-level processing parameters namely; WPA/sand ratios, water/binder ratios and compacting forces. Other processing parameters of CWLB which includes; WPA particle size (passing 3.35 mm BS sieve size), specimen curing duration (28 days), 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.

With three factors, each with three levels, the full factorial design would have required 3^3=27 possible combinations of trials. Meanwhile, carrying out a large number of experiments for all the combinations would have amounted to excessive resources and time consumption.

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

However, the Taguchi method employed in this study utilizes an ‘orthogonal array (OA)’ (which 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]) to simplify the large number of experiments, and allocates them into a smaller number of trials to run the experiment. This explains the reason why only three processing parameters, each with three levels, were considered in this study. Thus, nine trials of CWLB specimen with varied compositions were produced using the L_9 (3^3) OA, as presented in Table 4a and 4b.

The 50mm x 50mm x 50mm CWLB specimen (Fig. 3) produced from the experimental runs in Table 4b were tested for density (based on BS EN 772-13:2011 [25]) and compressive strength (based on BS EN 772-1:2011 [26]) after curing. Being the focused quality response, 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.

Table 4a: Table of Taguchi Orthogonal Array L₉ (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


Fig. 3: 50mmx50mmx50mm CWLB specimen

2.1.1 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]:

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

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.

2.1.2 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. The 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 $\bar{j}_i$ (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.

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

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), $\bar{j}_i$ 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.

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

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.

2.2 Experimental Details for Determination of the Strength and Stiffness Properties of CWLB

The tests conducted on CWLB's optimum mix composition (i.e. optimal CWLB specimen) to determine its strength and stiffness properties includes; compressive strength test (in accordance with the BS EN 772-1:2011) [26], ultrasonic pulse velocity (UPV) (in accordance with BS EN 12504-4:2004 recommended procedure) [27] and elastic modulus (estimated using Eqn. (4) which was derived based on the principle of ultrasonic pulse velocity testing described by BS 1881-203:1986 [28] and BS 12504-4:2004 in conjunction with the Newton-Laplace acoustic theory).

$$\boldsymbol{E = \rho V^2} \qquad (4)$$

Where; E is the elastic modulus in (MPa), ρ is the density in (kg) and V is the UPV of the CWLB specimen in (m/s).

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.

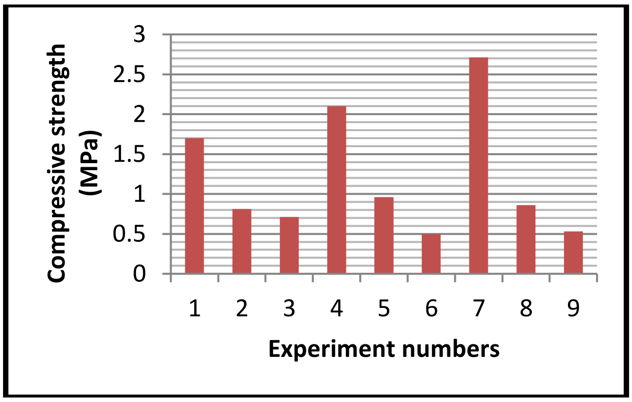

Fig. 4: Plot of compressive strength test result for each CWLB experimental run

3.1 Main Effect of Processing Parameter/Control Factors

In this study, the average compressive strength result of CWLB samples (*n=3*) 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

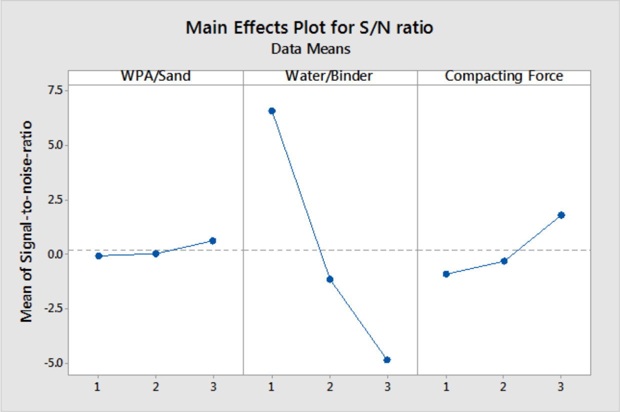

Fig. 5: Main effect plot for WPA/ sand ratio, Water/Binder ratio, and Compacting force.

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.

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

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).

3.3 Properties and Optimal Parameter Combination for CWLB

This section evaluates the effectiveness of the Taguchi DOE technique in optimizing the mix composition of CWLB and discusses the compressive strength, UPV and the elastic modulus of the resulting optimal CWLB. Table 7 shows the comparison of the worst and the optimal composition of CWLB. Table 8 presents the properties of the resulting optimal CWLB.

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%**	-

3.3.1 Confirmation Test and Review of Effectiveness of Taguchi DOE on Optimization of CWLB.

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. This finding indicate the suitability of the Taguchi Method in optimizing the mix composition of CWLB.

Table 8: Properties and Optimal parameter combination for CWLB

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)**	**UPV (m/s)**	**Elastic Modulus (MPa)**
2.5	0.75	3.5	2.71	901.5	989.9	883.4

3.3.2 Compressive strength and Density of of the Optimal CWLB Specimen.

As shown Table 7, the optimal CWLB exhibited an average compressive strength of 2.71 MPa and average density of 901.5 kg/m^3. In contrast with standard recommended mechanical and physical property requirement for non-load bearing blocks; the 2.71 MPa average compressive strength of CWLB is maximally higher than the 1.5MPa minimum compressive strength recommended by BS EN 771-4:2011 [29] for non-load bearing lightweight block (see Fig. 6) and the 901.5 kg/m^3 average density of CWLB falls within the range of 300-1000kg/m^3 (BS EN 771-4:2011) [29] and 625kg/m^3-1500kg/m^3 (BS EN 2028 1975) [30] specified for lightweight non-load bearing blocks. This finding thus indicates the suitability of CWLB for non-load bearing application in wall construction.

In contrast with the existing cement based wastepaper blocks (e.g. papercrete) (Fig. 6), the 2.71 MPa compressive strength displayed by CWLB is higher than the 1.84 MPa [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).

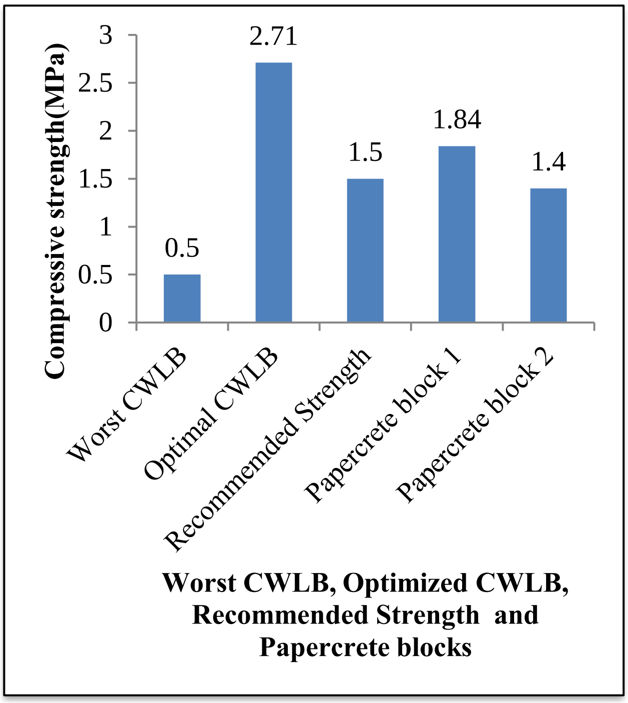

Fig. 6: Comparison of the compressive strength Optimized CWLB with Worst CWLB, Standard Non- load bearing block and Papercrete blocks

3.3.3 Ultrasonic pulse velocity of the Optimal CWLB

The UPV of CWLB was determined using a Pundit Ultrasonic testing equipment which consisted of; an electronic circuit that generate pulses, a 50kHz transducer that transforms electronic pulse into mechanical pulse and a pulse reception circuit which receives the signal. The UPV was calculated from the path length (0.05m for CWLB specimen) divided by the transit time. At optimum mix composition, CWLB displayed an average ultrasonic pulse velocity of 989.9m/s. The UPV of a building material indicates its quality in terms of strength and porosity. It should however be noted that, there are no existing classification of UPV values for neither wastepaper based building materials nor masonry blocks. Evaluating the quality of CWLB with reference to the UPV concrete classification, the 989.9 m/s average UPV value displayed by CWLB is comparatively less than the 2000 m/s UPV value specified for weak concrete. This finding thus indicates the high porosity of CWLB microstructure and its low strength property compared to concrete. The low UPV value displayed by CWLB is expected, because; it is a lightweight block and not a concrete, and it is made from combination of cellulosic waste, sand and non- hydraulic binder. Therefore, the implementation of CWLB in building construction is recommended to be limited to application as non-load bearing lightweight blocks.

3.3.4 Elastic Modulus of the Optimal CWLB

The Modulus of elasticity of a building material is an indication for its stiffness against deformation. For a masonry structure design to adequately comply with serviceability specification, the knowledge of elastic modulus of the masonry unit is required for determination of elastic deformation due to first application of load and for estimating creep arising from sustained load [31].

As shown in Table 8, the elastic modulus for the optimal CWLB specimens was estimated to be 883.4 MPa. In contrast with the existing cement-based wastepaper block, the 883.4MPa estimated elastic modulus for CWLB is maximally higher than the; 800 psi (5.52 MPa), 700psi (4.83 MPa), 590 psi (4.07 MPa) reported by [10] and [32] for papercrete produced from paper-cement-sand of; 1:1:5 gal, 1:1:10 gal and 1:1:15 gal respectively. This finding indicates the high stiffness characteristics of CWLB and its suitability for use as non-load bearing blocks.

4 Conclusions

The details of the optimization of the mixture composition of CWLB using Taguchi approach and the investigation of the strength and stiffness properties of the resulting optimal CWLB is presented in this paper. CWLB specimens of sizes 50mm x 50mm x 50mm 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 28 days 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 the Water/Binder ratio has the most significant effect on the compressive strength of CWLB. The identified optimal parameter settings; 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 in wall construction (viz: 2.71 MPa average compressive strength and 901.5 kg/m^3 average density, 989.9 m/s average UPV, and 883.4 MPa estimated elastic modulus). 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. The innovation presented in this paper thus includes; the development of an optimum mix composition for the novel CWLB which provides information on the mix ratio of the constituent material of same for research repeatability and subsequent, the identification of factors that affects its strength properties along with determination of the engineering properties of the resulting optimal CWLB which ascertains its suitability for the intended application. In order to take the subjected matter further, future research will investigate the; capillary water absorption, reaction to fire and the thermal conductivity of CWLB.

References:

[1] Hoornweg, Daniel; Bhada-Tata, Perinaz. 2012. *What a Waste: A Global Review of Solid Waste Management*. World Bank, Washington, DC. © World Bank. Available at: https://openknowledge.worldbank.org/handle/10986/17388

[2] Hawken, Paul., Lovins, Amory B., Lovins,L.Hunter, (1999) *Natural capitalism : creating the next industrial revolution*. [online] Boston: Little, Brown and Co.

[3] U.S. Geological Survey (USGS), (2013) “Sand and gravel (construction) statistics”, in: *Kelly, T.D., Matos, G.R., (Eds.), Historical statistics for mineral and material commodities in the United States. U.S. Geological Survey Data Series 140*, Reston

[4] Oss, H.G. and Padovani, A.C. (2003) Cement manufacture and the environment part II: environmental challenges and opportunities. *Journal of Industrial Ecology*, 7(1), pp. 93-126.

[5] Mehta, P.K., (2002) Greening of the Concrete Industry for Sustainable Development. *ACI Concrete International*, 24(7): pp. 23-28.

[6] Okeyinka Oriyomi M., Oloke David A., Khatib Jamal M., (2015a) A Review on Recycled Use of Solid Wastes in Building Materials. *International Journal of Civil, Environmental, Structural, Construction and Architectural Engineering,* Vol: 9, No:12. Available at: http://waset.org/publications/10003128/a-review-on-recycled-use-of-solid-wastes-in-building-materials

[7] Ashori, A., Tabarsa, T. and Valizadeh, I. (2011) Fiber reinforced cement boards made from recycled newsprint paper. *Materials Science and Engineering*, [online], 528(25), pp. 7801-7804.

[8] Akinwumi, I.I., Olatunbosun, O.M., Olofinnade, O.M. and Awoyera, P.O. (2014) Structural Evaluation of Lightweight Concrete Produced Using Waste Newspaper and Office Paper. *Civil and Environmental Research* [online], 6(7), pp. 160-167.

[9] Modry,S. (2001) Use of Waste Paper as a Constituent of Concrete. *Recovery and recycling of paper international symposium*, Thomas Telford Publishing, United Kingdom. pp.77-80.

[10] Fuller,B., Fafitis,A. and Santamaria,J. (2006) Structural Properties of a New Material Made of Waste Paper AEI 2006: *Building Integration Solutions*. ASCE, pp.1-16.

[11] Esmeralda, Y. A. O.; Marcos, A. E. S.; Mario Rabelo S.; Utilization of wastepaper to manufacture low density boards. *Bioresource Technology*, 2000, 73, 77 –79.

[12] Aciu, C., Iluţiu–Varvara, D.A., Cobirzan, N. and Balog, A. (2014) Recycling of paper waste in the composition of plastering mortars. Procedia Technology [online], 12pp. 295-300

[13] Titzman, L.C. (2006) Analysis of low-cost building material for the MixAlco process. *Master's thesis, Texas A&M University*.Available electronically from http://hdl.handle.net/1969 [online].

[14] Okeyinka Oriyomi M. and Idowu Oluwatobi J. (2014) Assessment of the Suitability of Paper Waste as an Engineering Material. *Engineering, Technology & Applied Science Research*, Vol. 4, No. 6, pp. 724-727

[15] Decard J. D.; West R. P.; Prichard S. J (2001)The impact response of recycled paper waste concrete. In : Ravindra Dhir K., Mukesh C. Limbachiya Ed., Proceedings of the International symposium on recovery and recycling of paper ,United Kingdom, 2001,81-92

[16] Yun,H., Jung,H. and Choi,C. (2007) Mechanical properties of papercrete containing waste paper . *18th International Conference on Composite Materials*. [online].

[17] Mohamad Shukeri, R., Ghani, A. and Naser, A. (2008) Concrete Mix With Wastepaper. *2nd International Conference On Built Environment In Developing Countries (ICBEDC 2008).* [online]. Available at: http://eprints.usm.my/25137/1/BUILDING_ENGINEERING_AND_CONSTRUCTION_6.pdf

[18] Okeyinka O.M., David D.A, Jamal Khatib. (2015b). Development of Environmentally Friendly Light weight block from Waste paper. *2nd International Sustainable Buildings Symposium (ISBS 2015)*, 28-30 May, Gazi University, Ankara –Turkiye. 406-416. Available At: <http://www.isbs2015.gazi.edu.tr/belgeler/bildiriler/407-411.pdf>

[19] Okeyinka O.M., Oloke D.A., Khatib J.M. (2016) Salient Parameters Influencing the Strength Properties of Cement-Less Wastepaper Based Lightweight Block. *Fourth International Conference on Sustainable Construction Materials and Technologies (SCMT4)* [online]. University of Nevada, Nevada, Las Vegas 7-11 August. Available at: < http://www.claisse.info/2016%20papers/S147.pdf >.

[20] Roy, R.K., 1990. *A Primer on the Taguchi Method*. Van Nostrand Reinhold, New York, pp.100-154.

[21] Montgomery D.C., (2013) *Design and Analysis of Experiments*, John Wiley &Sons, Inc., 2013

[22] Nuruddin M.F., Bayuaji R.(2009) Application of Taguchi's approach in the optimization of mix proportion for Microwave Incinerated Rice Husk Ash Foamed Concrete. *International Journal of Civil & Environmental Engineering* IJCEE: Vol 9 (9) pp.121-129

[23] Davies R., Coole T., Osypiw D., (2015), A review of traditional and Taguchi design of Experiment: devising a method selection criteria, *Proceedings of 25th Flexible Automation and Intelligent Manufacturing*, Wolverhampton, United Kingdom 2015, pp.308-315.

[24] Zarmai, M., Ekere, N., Oduoza, C. and Amalu, E. (2016) Optimization of thermo-mechanical reliability of solder joints in crystalline silicon solar cell assembly. *Microelectronics Reliability* [online], 59 pp. 117-125 .

[25] BSI (2000). BS EN 772-13: *Methods of test for masonry units. Determination of net and gross dry density of masonry units (except for natural stone*). British Standards Institute.

[26] BSI (2011). BS EN 772-1: *Methods of test for masonry units. Determination of compressive strength*. British Standards Institute.

[27] BSI (1986). BS EN 1881:1986: *Testing concrete. Recommendations for measurement of velocity of ultrasonic pulses in concrete*, (1986) British Standards Institute.

[28] BSI (2004). BS EN 12504-4:2004: *Testing concrete. Determination of ultrasonic pulse velocity*, (2004), British Standards Institute.

[29] BSI (2011). BS EN 772-4: *Specification for masonry units. Autoclaved aerated concrete masonry units.* British Standards Institute.

[30] BSI (1975). BS EN 2028: *Specification for precast concrete blocks* (1975), British Standards Institute.

[31] Brooks, J. (2014) Concrete and masonry movements. [online] Butterworth-Heinemann.

[32] Santamaria J., Fuller B., Fafitis A, (2007) Structural properties of a new material made of waste paper. *Computational Methods and Experimental Measurements XIII, WIT Transactions on Modelling and Simulation*, 46, pp.557-567.