ENGINEERING JOURNAL

Article

A Comparative Analysis of Three Optimisation Approaches to Free Swell Characterisation of Particulate Coconut Shell Reinforcement Composite Material

Oluwaseyi Ayodele Ajibade[1,a], **Johnson Olumuyiwa Agunsoye**[1,b], **and Sunday Ayoola Oke**[2,c,*]

1 Department of Metallurgical and Materials Engineering, University of Lagos, Lagos, Nigeria
2 Department of Mechanical Engineering, University of Lagos, Lagos, Nigeria
E-mail: [a]ayosheyi@yahoo.com, [b]jagunsoye@unilag.edu.ng, [c]sa_oke@yahoo.com (Corresponding author)

Abstract. There is paucity of data relating to the free swell properties of composite reinforcement materials in outdoor applications despite the widely-debated need for more investigations in this area. In this paper, a comparative performance analysis of three optimisation models - Taguchi method, simplex algorithm and Taguchi-simplex method - is pursued. We used experimental data of 0.600 mm particulate coconut shell with the theories behind L_{27} (3^{11}) orthogonal arrays, to achieve our aim for the Taguchi method. The simplex algorithm required modelling the free swell problem as the objective function subject to parametric constraints defined by the factors and their respective levels. For the Taguchi-simplex method, the S/N ratios and the optimal parametric setting of the Taguchi method were used to model the objective function and the new constraints that the simplex algorithm optimised. Parameters include initial and final volumes of coconut shell particulates (CSPs), mass of water, volumes of CSPs and water as well as mass of CSPs. The optimised initial and final volumes were 10 and 34 cm^3 (Taguchi), 20 and 34 cm^3 (simplex) and 16.6 and 24.82 cm^3 (Taguchi-simplex). The optimal masses of water were 141.54, 146.81 and 89.12 g while the volumes of CSPs and water were 152, 152 and 106.4 cm^3, and the mass of CSPs were 12.07, 12.07 and 6.28 g for Taguchi, simplex and Taguchi-simplex methods, respectively. Confirmatory test validated the results. In conclusion, the optimum parametric setting of the Taguchi-simplex method was the best.

Keywords: Coconut shell particulate, optimal parametric setting, composites, analysis of variance, free swell, Taguchi method, water absorption, physical properties, outdoor applications.

ENGINEERING JOURNAL Volume 19 Issue 5
Received 20 February 2015
Accepted 11 May 2015
Published 31 October 2015
Online at http://www.engj.org/
DOI:10.4186/ej.2015.19.5.167

1. Introduction

A robust literature on composites exists [1–6], and recently, a progressive rise in the use of green composites in industries and for research purposes has been experienced. A key stimulant for this growing interest in green composite usage is the increased satisfactory results obtained on the potential energy savings, costs and the enhanced physical properties of agricultural wastes the world over [7–8]. There is ample evidence to show that high health costs in societies are associated with pollutions from waste, resulting in diseases, related health burdens and huge waste treatment costs by agricultural producers. Thus, the adverse effect of indiscriminate dumping of coconut shell wastes has quantifiable impacts on government expenditures, denying governments of diverting this hard-earned income into more profitable ventures for the benefit of the populace. One usually adopted option to reduce this expenditure burden on governments is to attempt a conversion of such wastes into wealth and useful composites of economic value.

An understanding of this benefit has stimulated the current investigation in which coconut shell particulates are being tested for their physical property on free swell water-absorbing characteristics in the laboratory for outdoor applications. Optimisation of the free swell property is sought for the best information on the design parameters to be used in the development of coconut shell-based composites. Thus, the development of this composite based on coconut shell reinforcements may lead to interventions that could prevent the continuing health burdens of governments, through improper waste generation, encourage economic activities on composite development and improve the energy savings obtainable in the development of new composites.

Investigations relating to the physical properties of coconut shell as an input reinforcement material for composite fabrications are very scanty but should be intensified if a smooth transition to green product development in the society is to be encouraged and actualised in the near future. In the past twenty years, significant activities have evolved with respect to the development of optimisation techniques, which are categorised into two: deterministic and stochastic optimisation algorithms [9]. The particulate coconut shell, when used in the fabrication of components and later exposed to outdoor applications has the tendency of absorbing rain water in an open environment and salt water when used in marine applications.

Taguchi method [10] has emerged as a powerful optimisation method of the deterministic class, which has success records of implementation in processes. Taguchi optimisation techniques are one of the most adopted techniques for the optimisation of processes the world over. The ability of Taguchi method to save time and cost during experimentation makes it an excellent tool and a potential candidate for similar unexplored experiments such as the free swell, which is considered in the current study. An effort was made to optimise the process parameters of CSPs for effective reduction of the water absorption capability of the material in use. The process parameters, which include the initial and final volumes and mass of solute as well as the final mass and volume of the solution, appear to have profound influence on the reinforcement's water absorption capacity. Taguchi method is a strong tool with reputation for achieving high quality outputs in literature. The free swell process of CSPs was optimised in order to find the optimal parametric setting that can be used in making light loading composites for water based applications.

The findings obtained from this work would be useful for composite manufacturers who are seeking an optimum combination of free swell parameters of the coconut shell particulates as reinforcement materials. The experiments were carried out according to Holtz and Gibbs' model. Parametric quantities of the free swell process were measured on a daily basis from the time of the last experimental set-up. The use of Taguchi's optimisation method represents the process parameters as factors and their possible outcomes as levels in a specified orthogonal array.

The use of Taguchi method's orthogonal array helps to solve complex experimental problems and processes with a fewer number of experiments, saving time, costs and energy. Taguchi's orthogonal array eliminates the one-factor-at-a-time approach used by traditional design methods where possible interactions between parameters are excluded by studying all the factors involved in a system. Taguchi method also helps to determine the individual effects in a single experiment and in the identification of the optimum combinations of the parameters used in the investigation. Finally, results obtained from using Taguchi's orthogonal array are reproducible [10].

Keeping in mind the above issues, the present work was carried out to develop optimal parameters for the water absorption (free swell) process of particulate coconut shell, using three optimal models, namely, Taguchi, simplex and Taguchi-simplex. Taguchi method is not a new research methodology but new in its applied form to free swell characterisation. The simplex algorithm, although widely known in operations research, has never been applied to free swell characterisation, but a first attempt is made in this paper. However, the marriage of Taguchi and simplex is new and has not been previously applied, to the best of the authors' knowledge, to any reinforcement in composites and in this study, it seems recorded as the first development and application ever in composite material evaluation.

In this paper, an investigation to compare the free swell characteristics using design of experiments and optimising the free swell parameters for minimum water absorption using three methods (Taguchi, simplex and Taguchi-simplex) has been carried out. The investigation focuses on the quantitative assessment of the amount of water absorption by the particulate coconut shell when using composites whose reinforcements are made of coconut shell particulates in outdoor applications. Taguchi's orthogonal array is used and the outputs considered are the optimal mass of water used, the combined volume of CSPs and water as well as the mass of CSPs. Simplex algorithm was used to optimise the free swell characteristics to yield the minimum quantities of the above-mentioned outputs stated for the Taguchi method. A new model, involving the integration of Taguchi method, and simplex algorithm was evolved and used to evaluate the aforementioned output quantities that were obtained for both the Taguchi method and the simplex algorithm and the results compared.

2. Literature Review

The literature review is performed in this paper according to two directions of research. The authors researched into the literature concerning coconut, the general composite literature by searching for relevant reports. The second literature aspect concerns review in accordance to water absorption topics to find out gaps and if the methodology proposed on optimisation (i.e. Taguchi-simplex) has ever been attempted. Thus, the first aspect of the literature review follows.

Previous works have been largely concerned with investigations on the mechanical properties of coconut shell and its fibres under different conditions of activation carbon [11] and under normal conditions [12]. The impact properties of coconut fibres has been investigated [13]. Investigations have also considered the micro-structural characterisation of coconut fibres [14]. The dimension of eco-friendliness was the research focus of Sarki et al. [15]. Recent investigations have been directed to the thermal properties of coconut fibre composites [16]. Further investigations are directed to the tensile strength of the fibre [16] while an attempt has been made on enhancing the wear properties of coconut filler [8]. In the following paragraphs, a detailed account of the literature concerning the subject of the current discussion in this paper is given, that is coconut fibres.

Fiore et al. [4] observed that composites displayed superior tensile moduli, flexural moduli and lower strength properties when compared to the neat resin. Also, changes in storage and the loss moduli slightly above the glass transition temperature in the rubbery region were observed. Findings from the work revealed that natural filler should be regarded as a viable reinforcement of epoxy composites in semi-structural applications. Salleh et al. [11] studied the mechanical properties of prepared natural activated carbon composite in order to categorise their qualities. The peak tensile stresses were found in the sample 4 wt% and a value of 30 MPa. Mulinari et al. [12] observed the surface of the fractured specimens of chemically-treated coconut fibres using alkaline treatment of chemically-treated coconut fibres with alkaline treatment. The findings revealed a reduction in fatigue life of composites when greater tensions is applied as a result of interfacial bonding which was not sufficient.

Nuthang et al. [13] prepared untreated and treated flexible epoxy composites using various weight reinforcement contents of bamboo filler by injection moulding. They reported that the peak reduction in impact strength was 23.8, 27.3, and 56.2% for bamboo fiber/PLA, vetiver glass/PLA and coconut fibre/PLA composites, respectively. Vijayakumar et al. [14] used the hand lay-up process to impregnate natural fibres such as kenaf and coconut spathe in polymer matrix. Alkali treated coconut spathe and kenaf blast fibres were uniformly distributed within the epoxy resin and cured using tri-ethylene tetra amine (TETA) at 25ºC. They analysed the tensile, flexural, impact properties of the composites. The authors employed the use of scanning electrons microscope (SEM) to carry out fracture analysis of fibre reinforced composites and the effect of alkali treatment on the fibres. Sarki et al. [15] investigated the morphology and mechanical properties of coconut shell particles reinforced epoxy composites and observed that scanning electron microscopy (SEM) showed that there was relatively good interfacial adhesion between the coconut shell particles and epoxy matrix. They observed that the value of tensile modulus and tensile strength values improved with higher coconut shell particles content, while the impact strength reduced as against the neat epoxy resin.

Kumar et al. [16] used hand lay-up approach followed by compression moulding technique to prepare untreated (raw) coconut sheath fibre reinforced epoxy (UTCSE) composite and treated coconut sheath fibre reinforced epoxy (TCSE) composite. They observed that the treated coconut sheath fibre reinforced epoxy composite (TCSE) has superior mechanical and thermal properties as against untreated (raw) coconut sheath fibre reinforced epoxy composite (UTCSE).

Albano et al. [7] investigated the dynamics of thermal degradation and degradation process of neat nitrite rubber (NBR)–coconut flour (treated and non-treated) compounds. They observed that the addition of coconut flour to the NBR improved its thermal stability from an Einv of 89 to 277 kJ/mol. Fernandes et al. [17] used the compression moulding process to fabricate composites from high density polyethylene filled with cork powder and coconut short fibres in two different properties. The authors concluded that the inclusion of 10wt % short coconut fibres can be used profitably as reinforcement strategy of cork-based composite materials, especially with the use of 2 wt of CA.

From the literature review, studies have shown that several parts of the coconut could be studied but the literature has been silent on what parts of the coconut could interact with water. Diao et al. [20], Brahmakumar et al. [20], Vijayakumar et al. [14], Kumar et al. [16] as well as Fernandez et al. [17] and Jang et al. [18] all investigated on coconut fibre. Albano et al. [7] worked on coconut flour while Salleh et al. [11] worked on coconut shell. Unfortunately, since their directions of research were not on water absorption of reinforcements in independence, literature has not captured what parts of coconut might react with water. This propelled the current investigation, which suggested that the particulate coconut shell utilised in this work interacted with water.

Keeping in mind the above discussions, the next attempt was limited to water absorption topics. There is a large literature on water absorption evaluating the resistance of composites. Previous experimental exercises have concentrated on the mechanical properties of hemp, kenaf, sisal, jute, basalt and glass-reinforcement composites with findings that water absorption negatively affects the mechanical properties such as tensile and flexural behaviour [21–25] and the fiber content (Alomayri et al., [27]). A brief discussion of the water absorption literature is then given. Alomayri et al. [27] indicated that the magnitude of maximum water uptake and diffusion coefficient increased when the fibre content increased. Furthermore, they asserted that water absorption negatively impacted on the mechanical properties of cotton fabrics such as to decrease their flexural strength, modulus, impact strength (see also Woldesenbet et al., [28]), hardness, and fracture toughness. Gao et al. [29] asserted that permittivity and the loss tangent of the composites was in close relationship with water content and filler particle size.

Rashdi et al. [21] noted that the performance of kenaf fibre reinforced composites may suffer with such materials exposed to adverse environments for long periods. They reported a decrease in tensile properties of kenaf fibre (i.e. mechanical properties) compared to dry samples. Furthermore, they commented that the percentage of moisture uptake increased as the weight percentage of fibre increased and that water of absorption pattern of kenaf fibre-based composites was according to Fickian behaviour. Huang and Sun [25] studied the effect of water immersion on the tensile strength and bending behaviour of the composite and concluded that major reductions in tensile strength took place but with improvement in bending behaviour. Patel et al. [26] studied the water absorption properties of red-mud filled jute fiber/polymer composite. They reported that chemical modification of fibres reduced the total water uptake of the jute fibres, thereby exhibiting a significantly increased flexural strength with modified fibres in comparison to untreated fibre. Woldeserbet et al. [28] investigated the effects of absorbed moisture in high strain rate tests of a unidirectional graphite/epoxy composite. It was concluded that significant variations of high strain rate properties occurred from static properties.

Empirical evidence, however, shows that results are not robust with respect to independent treatment of reinforced composites without considering them in composite forms when the matrices have reacted with them; water absorption topics concerning bi- or multi-reinforcement analysis are missing in literature. There are also missing data concerning the treatments of single, bi- or multi-reinforcement without being added to matrices to improve properties. In addition, interests have not been centred on the optimisation of water absorption properties of reinforcements in general, and coconut shell particulates, specifically has not been treated in detail on this issue. Consequently, such optimisation methods as Taguchi, simplex and Taguchi-simplex have not been fully exploited for their potentials in providing optimal values for the water absorption resistance goal of composite design engineers. This is clearly a puzzle for composite reinforcement theory and experiments and appears as one that is worth publishing. Furthermore, scholars have made no attempts to test the robustness of previous results with respect to optimisation when the reinforcements considered are even the established ones in literature (i.e. cotton fabrics, EPDM/AL$(OH)_3$, hemp and kenaf fibers - see Gao et al. [29], Diao [30] and Vijayakumar et al. [31], Topgaard and Soderman [32], Isa et al. [33], Songok et al. [34], Malasri et al. [35] and Agu et al. [36]). That is, studies on green reinforcements in isolation, in mixed or blends or in treated forms, with all test done without the matrices need to be reported. Furthermore, the effect of temperature changes has been sparingly treated in literature.

Such tests and optimisation procedures may be necessary, particularly in the height of an expanding body of literature proposing the possible advancement in the improvement of properties with special consideration to particle sizes and the arguments advocating for surface treatments of reinforcements for improved properties. The theme of the current paper is that recommendations about water absorption of reinforcements need to be based on optimisation guidance, which would be aided by practicable optimisation models. It is only through this endeavour that maximum water absorption resistance capacities could be developed for composites in real time applications.

3. Materials and Methods

3.1. Experimental Details

The coconut shell used as samples were extracted from coconut obtained at the Oyingbo market, Lagos, Nigeria. The supplier was a local retailer of the product. All the materials were not treated but used in their raw forms. The water used in this study was tap water supplied by the water unit of the Works Department of the University of Lagos. The coconut shells were removed from the coconut and ground in a local grinding station at the Bariga market, Lagos. The grinding was done severally until the particles that emanated were fine enough for significant sieving success with very little wastes remaining after passing through the various sieving grades. Thus, after grinding, the coconut shell particulates were sieved into the following particulate grades: 0.075, 0.150, 0.212, 0.300, 0.425, 0.600, 1.180, 2.360 mm. For this experiment, the 0.600 mm particulates (sixth position in the grades) were used. It should be noted that 0.600 mm particulates were used for the experiments due to the availability of that grade, which was obtained from the sieving activity. In attempts to utilise finer grades, it was obvious that only small quantities of lower grade (i.e. < 0.600mm) particulates were obtained. Hence, it was difficult to obtain sufficient sample quantities to use. Since, the largest quantities of particulates are usually obtained in the grade 0.600 mm, it was then taken as a convenient sample grade. Sieving of the ground particulates into grades and free swell experiments were carried out in the Soil laboratories of the Department of Civil Engineering in Yaba College of Technology, Yaba, and University of Lagos, Akoka, Lagos, respectively.

The objective of this investigation is attained by conducting free swell experiments on 0.600 mm particulate coconut shell using measuring cylinder filled with tap water and analysing the resulting data on initial and final volumes of CSPs, mass of water used in dissolution, volume of CSPs and the combined mass of water and CSPs. Free swell experiment is carried out by dissolving different measured volumes of 0.600 mm CSPs into a graduated cylinder filled with 150 cm^3 tap water obtained through laboratory supplies. The volume of the settled CSPs is then evaluated after 24 hours of dissolution.

The literature was surveyed to assess the ASTM standards for water absorption to adopt for experimentation. The results of the survey indicated that ASTMD 2842-06 and ASTMD570 are good fits. A close reading of the standards revealed that ASTMDS 70 is the most appropriate for the current experiment despite that it suits more of plastics than the organic substance considered. These testing procedures were followed under the ASTIMD 570 standard. The first was to conduct the water absorption test after 24 hrs. The description of the procedure is that the coconut shell particulate specimens were immersed in water. Absorption took place and the results read. The test was carried out with the coconut shell particulates immersed in water at 23°C until the water absorption significantly stopped. Coconut shell particulate, as the name suggests is obtained from grinding the hard outer covering of edible coconut into particulate form. In the free swell experiments conducted, the coconut shell particulate is wholly dissolved in water. This means that every part of the coconut shell particulate, which comprises of the coconut shells interacts with water.

In this work, Taguchi method is used to find the optimum parametric combinations for the free swell process of coconut shell particulate. The free swell test reflects the water absorption properties of coconut shell particulates when used as composites in practical applications.

DOI:10.4186/ej.2015.19.5.167

3.2. Research Scheme

The research scheme implemented in this study is a progressive movement from the identification of the need to optimize the free swell properties of coconut shell particulates to the conclusion of the study. The research scheme follows the aim of the study, which is centred on determining the values of the various quantities of parameters of the system such that the 0.600 mm particulates of coconut shell would exhibit the greatest resistance to water absorption. The decision to select the appropriate optimization tools led us to streamline to three models. Two models, Taguchi and simplex algorithm exists and the third, Taguchi-simplex was formulated. For each of the models (Fig. 1), the procedures to achieve the results are illustrated in the scheme. For the Taguchi method, definition of the factors, decision on orthogonal arrays and the calculation of the signal-to-noise ratios are optimal. Optimal parametric settings are decided and ANOVA used to understand the contributions of the various parameters.

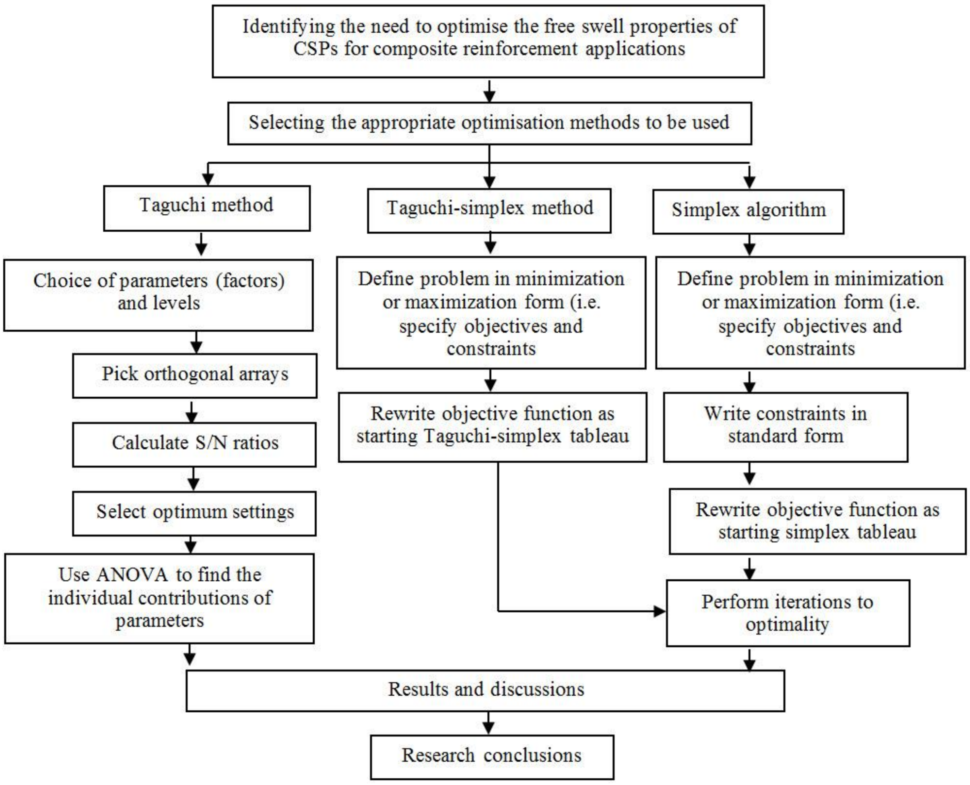

Fig. 1. Research scheme.

The traditional simplex algorithm, applied to the free swell optimization problem entails the definition of the problem involving the statement of the objective function, which could be a minimization or maximization problem. Then, the constraints including the non-negativity constraints are defined. Iterations are made until the final one, which gives the optimal results. The third method, Taguchi-simplex, is based on utilizing the optimal Taguchi setting as the objective function of a simplex problem in order to improve the existing Taguchi optimal settings. The overall results from the three approaches are then compared and assertions are made on what parametric values are the best for the free swell optimization problem.

4. Results

The input parameters for this experiment, which are the factors in the orthogonal array, are the initial volume of CSP (*P*) in cm^3, final volume of C.S.P (*Q*) in cm^3, mass of water (*R*) in g, volume of CSP and water (*S*) in cm^3 and mass of CSP (*T*) in g. Details of the levels for the free swell process parameters are given in Table 1.

Table 1. Free swell process parameters with their values at three levels.

Factors	Levels		
	I	II	III
Initial volume of coconut shell particulates (cm)^3	10	15	20
Final volume of coconut shell particulates (cm)^3	20	30	34
Mass of water (g)	94.72	141.54	146.81
Volume of coconut shell particulates + water (cm)^3	151	152	153
Mass of coconut shell particulates	6	9.06	12.07

The experiments were performed using the Taguchi orthogonal array standard. The choice of the orthogonal array was made on the condition that the number of columns of the orthogonal array should be greater or equal to the number of the free swell parameters (Vanna and Vizhian, 2014). In this work, an L_{27} orthogonal array having 27 rows and 13 columns was used, as shown in Table 2.

Table 2. Orthogonal array L_{27} (3^{13}).

S./No	1	2	3	4	5	6	7	8	9	10	11	12	13
1	I	I	I	I	I	I	I	I	I	I	I	I	I
2	I	I	I	I	II	II	II	II	II	II	II	II	II
3	I	I	I	I	III	III	III	III	III	III	III	III	III
4	I	II	II	II	I	I	I	II	II	II	III	III	III
5	I	II	II	II	II	II	II	III	III	III	I	I	I
6	I	II	II	II	III	III	III	I	I	I	II	II	II
7	I	III	III	III	I	I	I	III	III	III	II	II	II
8	I	III	III	III	II	II	II	I	I	I	III	III	III
9	I	III	III	III	III	III	III	II	II	II	I	I	I
10	II	I	II	III	I	II	III	I	II	III	I	II	III
11	II	I	II	III	II	III	I	II	III	I	II	III	I
12	II	I	II	III	III	I	II	III	I	II	III	I	II
13	II	II	III	I	I	II	III	II	III	I	III	I	II
14	II	II	III	I	II	III	I	III	I	II	I	II	III
15	II	II	III	I	III	I	II	I	II	III	II	III	I
16	II	III	I	II	I	II	III	III	II	I	II	III	I
17	II	III	I	II	II	III	I	II	III	I	I	II	III
18	II	III	I	II	III	I	II	II	III	I	I	II	III
19	III	I	III	II	I	III	II	I	III	II	I	III	II
20	III	I	III	II	II	I	III	II	I	III	II	I	III
21	III	I	III	II	III	II	I	III	II	I	III	II	I
22	III	II	I	III	I	III	II	II	I	III	III	II	I
23	III	II	I	III	II	I	III	III	II	I	I	III	II
24	III	II	I	III	III	II	I	I	III	II	II	I	III
25	III	III	II	I	I	III	II	III	II	I	II	I	III
26	III	III	II	I	II	I	III	I	III	II	III	II	I
27	III	III	II	I	III	II	I	II	I	III	I	III	II

The Taguchi design matrix comprises of 27 tests (representing each row in the L_{27} orthogonal array) while parameters were assigned to initial volume of CSP, column 2 was assigned to final volume of CSP columns 3, 4 and 5 were allotted to mass of water, volume of coconut shell particulates and water and mass of CSP, respectively. The experiments were carried out in accordance with Taguchi orthogonal array with each level of the parameters specified in each row. The results were further subjected to analysis of variance (ANOVA).

4.1. S/N Ratio Response

Free swell was considered as the output response with the quality characteristics category "the smaller- the better". The S/N ratio for this response was obtained by using Eq. (1) for each parametric setting and their corresponding values, Table 3.

Table 3. S/N ratios for free swell of coconut shell particulate parameters.

Exp. No.	Initial volume of CSP (cm^3)	Final volume of CSP (cm^3)	Mass of water (g)	Volume of CSP and water (cm^3)	Mass of CSP (g)	S_f	S/N ratio (dB)
1	10	20	94.72	151	6	100	3.47
2	10	20	94.72	151	9.06	100	0.19
3	10	20	94.72	151	12.07	100	0.38
4	10	30	141.54	152	6	200	0.54
5	10	30	141.54	152	9.06	200	0.69
6	10	30	141.54	152	12.07	200	0.51
7	10	34	146.81	153	6	240	0.66
8	10	34	146.81	153	9.06	240	0.81
9	10	34	146.81	153	12.07	240	0.18
10	15	20	141.20	153	6	33.33	0.34
11	15	20	141.54	153	9	33.33	0.48
12	15	20	141.54	153	12.07	33.33	0.60
13	15	30	146.81	151	6	100	0.76
14	15	30	146.81	151	9.06	100	0.91
15	15	30	146.81	151	12.07	100	0.76
16	15	34	94.72	152	6	126.67	0.94
17	15	34	94.72	152	9.06	126.67	1.12
18	15	34	94.72	152	12.07	126.67	0.39
19	20	20	146.81	152	6	-	0.55
20	20	20	146.81	152	9.06	-	0.70
21	20	20	146.81	152	12.07	-	0.82
22	20	30	94.72	153	6	50	1.00
23	20	30	94.72	153	9.06	50	1.18
24	20	30	94.72	153	12.07	50	1.02
25	20	34	141.54	153	6	70	1.18
26	20	34	141.54	153	9.06	70	1.33
27	20	34	141.54	153	12.07	70	

Signal-to-noise ratios of each experimental run is derived from the following equation and the values are:

$$\text{S/N } (\eta) = 10 \log_{10} \left(\frac{\mu^2}{\sigma^2}\right) \tag{1}$$

where

$$\mu = \frac{1}{n}\sum Y_i \text{ and } \sigma^2 = \frac{1}{(n-1)}\sum (Y_i - \mu)^2 \tag{2}$$

and Y_1, Y_2, Y_3, …, Y_n are the response of the free swell and 'n' is the number of observation.

The free swell process parameters namely, initial volume of CSP, final volume of CSP, mass of water, volume of CSP and water and mass of CSP are being optimised in order to achieve the desired optimum free swell that would exhibit minimal damage when used in making composites for lightly loaded structures (Holtz and Gibbs, 1956). For the purpose of finding the optimum level of the process parameters, the average S/N ratio response was obtained for each of the parameters used in the study. The corresponding results are shown in Table 4. The optimum level of each parameter was based on the smallest value of the S/N ratio.

Table 4. Average S/N ratio response.

	P	Q	R	S	T
Level 1	0.83	0.84	1.08	1.08	1.05
Level 2	0.9	0.82	0.63	0.7	0.82
Level 3	0.86	0.73	0.68	0.73	0.52
Max-Min	0.07	0.11	0.45	0.38	0.53
Rank	5	4	2	3	1
Optimum	P_1	Q_3	R_2	S_2	T_3

The optimum level of each parameter was based on the smallest value of S/N ratio (P:1st level; *Q*: 3rd level; *R*: 2nd level; *S*: 2nd level; *T*: 3rd level) was noted. The optimum free swell parametric setting $P_1Q_3R_2S_2T_3$ i.e. (initial volume of CSP of 10 cm^3, final volume of CSP of 34 cm^3, mass of water of 141.54 g, volume CSP and water of 152 cm^3 and mass of solute of 12.07 g) as the derived output response described by a response graph in Fig. 2.

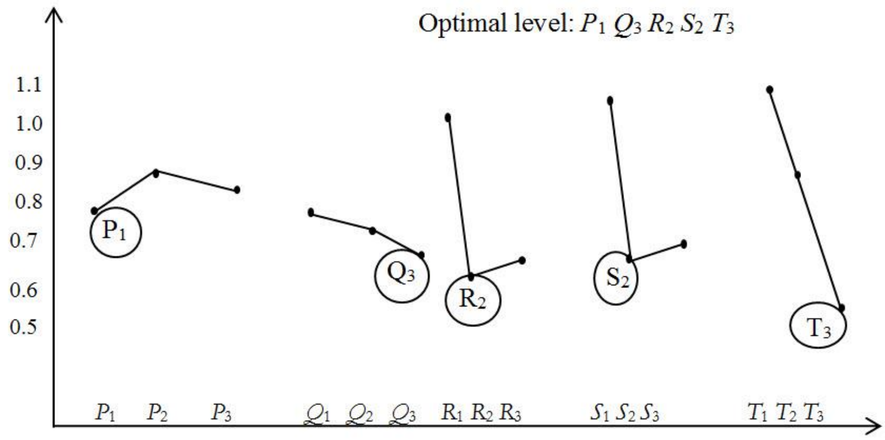

Fig. 2. Response graph.

From the graph in Fig. 2, it can be observed that parameters *P* and *Q* showed lesser variations on the output responses. Analysis of variance (ANOVA) and *F* test were used to carry out further analysis on the experimental data for forecasting significant process parameters.

4.2. Analysis of Variance

Analysis of variance (ANOVA) is a statistical analysis tool that is used to evaluate significant process parameters. It is used to find the relative significance of the process control parameters and their individual input over the performance of the process. The following terms were derived through the use of ANOVA.

The sum of squares for parameter *Q* was found to be the least in this study, having a negative value. Its influence on the output response was assumed to be insignificant and has been termed an error (pooled error). Sum of squares due to pool error was obtained as:

$$SS_{poolederror} = SS_B = -0.0839 \tag{3}$$

The calculated F_{ratio} for parameters *P*, *R*, *S* and *T* were found to be greater than the *F* distribution value ($F_{1,6}$ = 5.9874 at 5% level of significance). Parameters *P, R, S* and *T* were confirmed as significant parameters in the free swell optimisation process of CSP. The overall parametric setting (initial volume of 10 cm^3, mass of water of 141.54 g, volume of CSP and water of 152 cm^3 and mass of solute of 12.07 g) was obtained as the final output response after leaving out the pooled variables. The percentage contribution each of the relevant process parameters is shown in the ANOVA summary in Table 5.

(i) Sum of squares due to mean, $S_m = \mathrm{N}\,\overline{K^2} = 17.28$

(ii) $SS_P = n_{P1} \times \overline{P}_1^2 + n_{P2} \times \overline{P}_2^2 + n_{P3} \times \overline{P}_3^2 - SS_m = 2.87$

$$SS_Q = n_{Q1} \times \overline{Q}_1^2 + n_{Q2} \times \overline{Q}_2^2 + n_{Q3} \times \overline{Q}_3^2 - SS_m = -0.0839$$

$$SS_R = n_{R1} \times \overline{R}_1^2 + n_{R2} \times \overline{R}_2^2 + n_{R3} \times \overline{R}_3^2 - SS_m = 0.95$$

$$SS_S = n_{S1} \times \overline{S}_1^2 + n_{S2} \times \overline{S}_2^2 + n_{S3} \times \overline{S}_3^2 - SS_m = 0.52$$

$$SS_T = n_{T1} \times \overline{T}_1^2 + n_{T2} \times \overline{T}_2^2 + n_{T3} \times \overline{T}_3^2 - SS_m = 1.12$$

(iii) Total sum of squares, $TSS = SS_P + SS_Q + SS_R + SS_S + SS_T = 5.38$

(iv) Degree of freedom for parameter

$DOF_{parameter}$ = No. of levels of parameter – 1=2

$DOF_P = DOF_Q = DOF_R = DOF_S = DOF_T = 2$

$DOF_{poolederror} = 2$

(v) Mean Sum of Squares due to parameter

$$MSS_P = \frac{SS_P}{DOF} = 1.44 \qquad MSS_{poolederror} = \frac{SS_Q}{DOF} = -0.042$$

$$MSS_R = \frac{SS_R}{DOF} = 0.48 \qquad MSS_S = \frac{SS_S}{DOF} = 0.26$$

$$MSS_T = \frac{SS_T}{DOF} = 0.56$$

(vi) F $_{ratio}$ for parameter *P*

$$F_{ratio}P = \frac{MSS_P}{MSS_{poolederror}} = 34.28, \qquad F_{ratio}R = \frac{MSS_R}{MSS_{poolederror}} = 11.43$$

$$F_{ratio}S = \frac{MSS_S}{MSS_{poolederror}} = 6.19, \qquad F_{ratio}T = \frac{MSS_T}{MSS_{poolederror}} = 13.3$$

The calculated F_{ratio} for parameters *P*, *R*, *S* and *T* were found to be greater than the *F* distribution value ($F_{1,6}$ =5.9874 at 5 % level of significance). Parameters *P*, *R*, *S* and *T* were confirmed as significant parameters in the free swell optimsation process of coconut shell particulate.

(vii) Pure sum of squares due to parameters, PSS

$$PSS_P = MSS_P - DOF_P \times MSS_{poolederror} = 1.52 \qquad PSS_R = MSS_R - DOF_R \times MSS_{poolederror} = 0.56$$

$$PSS_S = MSS_S - DOF_S \times MSS_{poolederror}\ 0.344 \qquad PSS_T = MSS_T - DOF_T \times MSS_{poolederror}\ 0.644$$

(vii) Percentage contribution due to parameters, PC_P = 28.25 %, PC_R = 10.4 %, PC_S = 6.39 %, PC_T = 11.90 %, The overall parametric setting (initial volume of CSP of 10 cm^3, mass of water of 141.54 g, volume of CSP and water of 152 cm^3 and mass of solute of 12.07 g) was obtained as the final output response after leaving out the pooled variables. The percentage contribution each of the relevant process parameters is shown in the ANOVA summary table in Table 5

Table 5. Analysis of variance.

Source	Pool	SS	DOF	MSS	F ratio	PSS	PC (%)
P		2.87	2	1.44	34.28	1.52	28.25
Q	Yes	-0.0839	2	-0.042			
R		0.95	2	0.48	11.43	0.56	10.4
S		0.52	2	0.26	6.19	0.34	6.39
T		1.12	2	0.56	13.3	0.64	11.9
Pooled error		-0.0839	2	-0.042		2.32	43.06
TSS		5.38				5.3	

4.3. Confirmatory Test for the Taguchi Method

A relevant and acceptable approach towards concluding the analysis based on Taguchi method is the use of confirmatory test. Consequently, this test was carried out based on the results of the association of the variables (factors) considered in this investigatory study. Thus, the data on PC % (Table 5) for the significant process parameters *P*, *R*, *S* and *T* obtained as 28.25, 10.4, 6.39 and 11.90 % was used as a polynomial curve and was fitted for this data representing the best option ($R^2 = 0.9966$) which yielded the confirmatory equation:

$$S_f = 5.84x^2 - 34.506x + 56.7 \tag{4}$$

Since *x* represents the significant process parameters used in this work. Evolving equations incorporating this, yielded two main terms, according to the additive and multiplicative properties of the significant process parameters *P*, *R*, *S* and *T*. The confirmatory equations used then becomes two

$$S_f = 5.84(P + R + S + T)^2 - 34.506(P + R + S + T) + 56.7 \tag{5}$$

which follows the additive properties of the interactions among the significant process parameters and

$$S_f = 5.84(PRST)^2 - 34.506(PRST) + 56.7 \tag{6}$$

which also follows the multiplicative properties of the interactions among the significant process parameters. Recall, that the coefficient of determination is $R^2 = 0.9966$ showing the accuracy of the model in representing the output response/process performance. The proximity of R^2 to unity indicates that the model is acceptable and can be used as an objective function for applying optimisation algorithms through which better parametric settings can be obtained. For the additive properties of the confirmatory test, S_f = 6.07 %, and the multiplicative properties of the confirmatory test yields S_f = 56.72 % . Since the only reasonable one is the later, S_f is taken as 56.72 %.

4.4. Simplex Method of Optimising Coconut Shell Particulates

$$\text{Minimise } S_f = \sum_{p=1}^{q} \phi_p k_p \tag{7}$$

Subject to:

Constraints

Initial volume, V_i (cm³): $10 \leq V_i \geq 20$ (8)

Final volume, V_f (cm³): $20 \leq V_f \geq 34$ (9)

Mass of water, M_w (g): $94.72 \leq M_w \geq 146.81$ (10)

Volume of CSP and water, V_a (cm³): $151 \leq V_a \geq 153$ (11)

Mass of CSP, m_s (g): $6.00 \leq m_s \geq 12.07$ (12)

Using the above given constraints, where $\phi_1, \phi_2, \phi_3, \phi_4, \phi_5 = 1$ and $K_1 = V_i, K_2 = V_f, K_3 = M_w, K_4 = V_a$, $K_5 = m_s$, Eq. (7) can be written as

Minimise $$S_f = V_i + V_f + M_w + V_a + m_s \quad (7a)$$

Equations (8) to (12) can be further broken down since they both have "≤" and "≥" attached to them.

Thus we have

Minimise $S_f = V_i + V_f + M_w + V_a + m_s$

Subject to:

Constraints:

Initial volume, V_i (cm³)

$$V_i \geq 10 \quad (8a)$$

$$V_i \leq 20 \quad (8b)$$

Final volume, V_f (cm³)

$$V_f \geq 30 \quad (9a)$$

$$V_f \leq 34 \quad (9b)$$

Mass of water, M_w (g)

$$M_w \geq 94.72 \quad (10a)$$

$$M_w \leq 146.81 \quad (10b)$$

Volume of CSP and water, V_a (cm³)

$$V_a \geq 151 \quad (11a)$$

$$V_a \leq 153 \quad (11b)$$

Mass of CSP, ms (g)

$$ms \geq 6 \quad (12a)$$

$$ms \leq 12.07 \quad (12b)$$

Expressing the free swell optimisation problem in standard form, where slack and surplus variables are used, J_1, J_2, J_3, J_4 and J_5 are used for Eq. (8a) to (12b), respectively. Thus, the following equations are valid

Minimise $S_f = V_i + V_f + M_w + V_a + m_s$

$$V_i - J_1 = 10 \quad (13a)$$

$$V_i + J_1 = 20 \quad (13b)$$

$$V_f - J_2 = 30 \quad (14a)$$

$$V_f + J_2 = 34 \quad (14b)$$

$$M_w - J_3 = 94.72 \quad (15a)$$

$$M_w + J_3 = 146.81 \quad (15b)$$

$$V_a - J_4 = 151 \quad (16a)$$

$$V_a + J_4 = 153 \quad (16b)$$

$$ms - J_5 = 6 \quad (17a)$$

$$ms + J_5 = 6 \quad (17b)$$

The non-negativity constraint is given as

$$V_i, V_f, M_w, V_a, m_s \geq 0$$

Assume that $J_1 = -10$ or 20, $J_2 = -30$ or 34, $J_3 = -94.72$ or 146.81, $J_4 =$ -151 or 153, $J_5 = -6$ or 12.07, where the variables J_1, J_2, J_3, J_4 and J_5 are the slacks associated with the respective constraints. This is followed by writing the objective equation as:

Minimise $S_f - V_i - V_f - M_w - V_a - m_s = 0$

The starting simplex table is given as follows:

Table 6. The starting simplex algorithm tableau.

Basic	S_f	V_I	V_f	M_w	V_a	m_s	J_1	J_2	J_3	J_4	J_5	*Solution*
S_f	1	-1	-1	-1	-1	-1	0	0	0	0	0	0
J_1	0	1	0	0	0	0	1	0	0	0	0	20
J_2	0	0	1	0	0	0	0	1	0	0	0	34
J_3	0	0	0	1	0	0	0	0	1	0	0	146.81
J_4	0	0	0	0	1	0	0	0	0	1	0	153
J_5	0	0	0	0	0	1	0	0	0	0	1	12.07

Considering the optimality condition, m_s is selected as the entering variable while J_5 becomes the leaving variable. Therefore, a new set of basic and non- basic variable are produced. J_5 is replaced in the basic column with m_s. The swapping process is done through the Gauss-Jordan row operations.

(i) New m_s row = current m_s row $\div$ 1
$= (0 \quad 0 \quad 0 \quad 0 \quad 0 \quad 1 \quad 0 \quad 0 \quad 0 \quad 0 \quad 12.07 \quad 12.07)$

(ii) New S_f = current S_f row $-$ (-1) $\times$new m_s row
$= (1 \quad -1 \quad -1 \quad -1 \quad -1 \quad 0 \quad 0 \quad 0 \quad 0 \quad 0 \quad 12.07 \quad 12.07)$

(iii) New J_1 row = current J_1 row $-$ (0) $\times$ new m_s row
$= (0 \quad 1 \quad 0 \quad 0 \quad 0 \quad 0 \quad 20 \quad 0 \quad 0 \quad 0 \quad 0 \quad 20)$

(iv) New J_2 row = current J_2 row – (0) $\times$ new m_s row
$= (0 \quad 0 \quad 1 \quad 0 \quad 0 \quad 0 \quad 0 \quad 34 \quad 0 \quad 0 \quad 0 \quad 34)$

(v) New J_3 row = current J_3 row $-$ (0) $\times$ new m_s row
$= (0 \quad 0 \quad 0 \quad 1 \quad 0 \quad 0 \quad 0 \quad 0 \quad 146.81 \quad 0 \quad 0 \quad 146.81)$

(vi) New J_4 row = current J_4 row $-$ (0) $\times$ new m_s row
$= (0 \quad 0 \quad 0 \quad 0 \quad 1 \quad 0 \quad 0 \quad 0 \quad 0 \quad 153 \quad 0 \quad 153)$

Having obtained the starting simplex tableau with values, the procedure for simplex is carried out for iterations 2 to 5 and a final table is obtained. The descriptions in table are obtained. The descriptions are omitted as it could be found in standard operations research textbooks. However, the results obtained at these intermediate stages are discussed in the relevant section. The final table for the simplex is hereby shown:

Table 7. Final simplex algorithm tableau.

Basic	S_f	V_i	V_f	M_w	V_a	m_s	J_1	J_2	J_3	J_4	J_5	Solution
S_f	1	0	0	0	0	0	20	34	146.81	153	12.07	365.88
V_i	0	1	0	0	0	0	1	0	0	0	0	20
V_f	0	0	1	0	0	0	0	1	0	0	0	34
M_w	0	0	0	1	0	0	0	0	1	0	0	146.81
V_a	0	0	0	0	1	0	0	0	0	1	0	153
ms	0	0	0	0	0	1	0	0	0	0	1	12.07

Based on the optimality condition, none of the S_f row coefficients associated with the non-basic variables is negative. Hence, Table 7 is optimal. The interpretation of the table is presented as follows:

Table 8. Interpretation table.

Decision Variable	Optimal value	Recommendations
V_i	20	Use 20 cm^3 of coconut shell particulate
V_f	34	To obtain a final volume of 34 cm^3
M_w	146.81	Use mass of water of 146.81g
V_a	153	Volume of CSP and water 153 cm^3
m_s	12.07	Mass of CSP of 12.07 g
S_f	70*	Obtainable by calculation

* Calculated value

4.5. Taguchi-Simplex Method Optimisation of Coconut Shell Particulates

Taguchi method was used to optimise the free swell process of coconut shell particulate (CSP) taking note of Eq. (8) to (12) which produce an optimum parametric setting of $P_1Q_3R_2S_2T_3$ from the S/N ratios of Taguchi's orthogonal array, which translates to:

$$[P_1Q_3R_2S_2T_3] = [0.83, 0.73, 0.63, 0.7, 0.52] \quad (18)$$

The optimal parametric setting obtained from Taguchi method was further optimised with the simplex method according to the objective function stated in Eq. (7). The optimal parametric values obtained from the Taguchi method were used to derive the lower and upper constraints of the Taguchi-simplex method in order to obtain improved results.

Using the above given constraints, where $\phi_1, \phi_2, \phi_3, \phi_4, \phi_5 = 1$ and $K_1 = V_i, K_2 = V_f, K_3 = M_w, K_4 = V_a, K_5 = m_s$, Eq. (18) could be further treated as:

Minimise $$S_f = 0.83V_i + 0.73V_f + 0.63M_w + 0.7V_a + 0.52m_s \quad (18a)$$

Subject to:

Constraints:

Initial volume, V_i (cm^3)

$$V_i \geq 10 \quad (19a)$$

$$V_i \leq 20 \quad (19b)$$

Final volume, V_f (cm^3)

$$V_f \geq 20 \quad (20a)$$

$$V_f \leq 34 \quad (20b)$$

Mass of water, M_w (g)

$$M_w \geq 94.72 \quad (21a)$$

$$M_w \leq 141.54 \quad (21b)$$

Volume of CSP and water, V_a (cm[3])

$$V_a \geq 151 \quad (22a)$$

$$V_a \leq 152 \quad (22b)$$

Mass of CSP, $m_s ms$ (g)

$$m_s \geq 6 \quad (23a)$$

$$m_s \leq 12.07 \quad (23b)$$

Equations (19a) to (23b) can be further broken down since they both have "≤" and "≥" attached to them. Thus, we have:

Minimise $S_f = 0.83V_i + 0.73V_f + 0.63M_w + 0.7V_a + 0.52\, m_s$

Subject to Eq. (19a) to (23b).

Expressing the free swell optimisation problem in standard form, where slack and surplus variables are used. Then J_1, J_2, J_3, J_4 and J_5 used in Eq. (13a) to (17b) respectively are adapted to the present problem.

Thus, the following equations are valid:

Minimise $\quad S_f = 0.83V_i + 0.73V_f + 0.63M_w + 0.7V_a + 0.52\, m_s$

$$0.83V_i - J_1 = 10 \quad (19a)$$

$$0.83V_i + J_1 = 20 \quad (19b)$$

$$0.73V_f - J_2 = 20 \quad (20a)$$

$$0.73V_f + J_2 = 34 \quad (20b)$$

$$0.63M_w - J_3 = 94.72 \quad (21a)$$

$$0.63M_w + J_3 = 141.54 \quad (21b)$$

$$0.7V_a - J_4 = 151 \quad (22a)$$

$$0.7V_a + J_4 = 152 \quad (22b)$$

$$0.52\, m_s - J_5 = 6 \quad (23a)$$

$$0.52\, m_s + J_5 = 12.07 \quad (23b)$$

The non-negativity constraints are given as

$$V_i, V_f, M_w, V_a, m_s \geq 0$$

Assume that $J_1 = -10$ or 20, $J_2 = -30$ or 34, $J_3 = -94.72$ or 141.54, $J_4 = -151$ or 152, $J_5 = -6$ or 12.07, where the variables J_1, J_2, J_3, J_4 and J_5 are the slacks associated with the respective constraints. This is followed by rewriting the objective equation as:

Minimise $S_f - 0.83V_i - 0.73V_f - 0.63M_w - 0.7V_a - 0.52\, m_s = 0$

The starting Taguchi-simplex tableau is given as:

Table 9. Starting Taguchi-simplex algorithm tableau.

Basic	S_f	V_i	V_f	M_w	V_a	m_s	J_1	J_2	J_3	J_4	J_5	*Solution*
S_f	1	-0.83	-0.73	-0.63	-0.7	-0.52	0	0	0	0	0	0
J_1	0	1	0	0	0	0	10	0	0	0	0	20
J_2	0	0	1	0	0	0	0	34	0	0	0	34
J_3	0	0	0	1	0	0	0	0	141.54	0	0	141.54
J_4	0	0	0	0	1	0	0	0	0	152	0	152
J_5	0	0	0	0	0	1	0	0	0	0	12.07	12.07

Based on the optimality condition, V_i is selected as the entering variable while J_1 becomes the leaving variable in the basic column. Therefore, a new set of basic and non- basic variable are produced. J_1 is replaced in the basic column with m_s. The swapping process is done through the Gauss – Jordan row operations.

(i) New V_i row = current $J_1 \div 1 = \begin{pmatrix}0 & 1 & 0 & 0 & 0 & 0 & 20 & 0 & 0 & 0 & 0 & 20\end{pmatrix}$

(ii) New S_f row = current S_f row − (−0.83) × New V_i row

$$= \begin{pmatrix}1 & 0 & -0.73 & -0.63 & -0.7 & -0.52 & 16.6 & 0 & 0 & 0 & 0 & 16.6\end{pmatrix}$$

(iii) New J_2 row = current J_2 row − (0) × New V_i row

$$= \begin{pmatrix}0 & 0 & 1 & 0 & 0 & 0 & 0 & 34 & 0 & 0 & 0 & 34\end{pmatrix}$$

(iv) New J_3 row = current J_3 row − (0) × New V_i row

$$= \begin{pmatrix}0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 141.54 & 0 & 0 & 141.54\end{pmatrix}$$

(v) New J_4 row = current J_4 row − (0) × New V_i row

$$= \begin{pmatrix}0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 152 & 0 & 152\end{pmatrix}$$

(vi) New J_5 row = current J_5 row − (0) × New V_i row

$$= \begin{pmatrix}0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 12.07 & 12.07\end{pmatrix}$$

From the starting Taguchi-simplex tableau and first iteration, which produced the values, the procedure for simplex is carried out for iterations 2 to 5 and a final tableau is obtained. The descriptions of the tableau are obtained are omitted as they could be found in standard operations research textbooks. However, the results obtained at these intermediate stages are discussed in the relevant section. The final tableau for the Taguchi-simplex algorithm is hereby shown.

Table 10. The final tableau for the Taguchi-simplex algorithm.

Basic	S_f	V_i	V_f	M_w	V_a	m_s	J_1	J_2	J_3	J_4	J_5	*Solution*
S_f	1	0	0	0	0	0	16.6	24.82	89.17	106.4	6.28	242.87
V_i	0	1	0	0	0	0	20	0	0	0	0	20
V_f	0	0	1	0	0	0	0	34	0	0	0	34
M_w	0	0	0	1	0	0	0	0	141.54	0	0	141.54
V_a	0	0	0	0	1	0	0	0	0	152	0	152
m_s	0	0	0	0	0	1	0	0	0	0	12.07	12.07

Based on the optimality condition, none of the S_f row coefficients associated with the non–basic variables is negative. Hence, the last tableau is optimal. The optimum solution can be read from Table 11 in the following manner.

Table 11. Interpretation table for Taguchi-simplex algorithm results.

Decision Variable	Optimal value	Recommendations
V_i	16.6	Use 16.6 cm^3 of coconut shell particulate
V_f	24.82	To obtain a final volume of 24.82 cm^3
M_w	89.12	Use mass of water of 89.12 g
V_a	106.4	Volume of CSP and water 106.14 cm^3
m_s	6.28	Use a mass of CSP of 6.28 g
S_f	49.33*	Obtainable by calculation

*Calculated value.

5. Discussion of Results

In composite fabrication practices, much effort has been devoted to discussing the contributions of the mechanical (tensile, hardness, Young's modulus) and the chemical properties of composites on performance during usage. However, many composite researchers still complain that: (1) a number of outdoor composite applications still fall short of performance standards despite designer's intentions in creating high performance-driven composites in view of the in-built mechanical and chemical properties that are attractive; and (2) there is insignificant leads on the approach to adopt in studies that will reveal the related water absorption criteria. Thus, the current literature on composites has a significant gap in the aspect of considering the physical properties of reinforcement materials as they affect the overall performance of the composite in outdoor applications. This issue, relating to green composite materials such as coconut shell particulates has not been treated in literature.

While some chemists claim to have investigated the physical properties of some green composites such as orange peel particulates and kenaf, their contributions are at best an ad-hoc analysis of such materials without any linkages to green composite fabrication. A prospective approach that considers not only the measurement of such water absorption behaviour of a green composite reinforcement material but also its optimisation does not exist. Thus, considering the engineering needs analysed earlier, this paper's contribution is in the development of an optimisation approach to the measurement of the free swell characteristics of particulate coconut shell reinforcement material for green composite formulation. A novel methodical analytical approach has been created in which the strengths of tested optimisation approaches of the Taguchi method and simplex algorithm and Taguchi-simplex method have been tested for a more efficient output than for the individual considerations of the approaches (i.e. Taguchi method alone or the simplex algorithm).

The optimisation of the free swell process of coconut shell particulates (CSPs) was performed in order to find the parametric settings for the free swell of CSP such that it would not experience significant volume change when used as an input material for composite fabrication in water-based applications. Holtz and Gibbs (1956) suggested that soils having a free swell below 50% would hardly experience considerable volume change when used in light loadings. Although, soils are often mixed with binders like cement and other reinforcements like granite or gravel to form a concrete aggregate to be used in water-based applications, the swelling capacity of soils cannot be ignored before being utilised for such purposes. Hence, the suggestion by Holtz and Gibbs (1956) that soils having a free swell value below 50% are safe for use for light loadings and water-based applications.

In like manner, CSPs has been effectively used as a binder in composite fabrication. It has been used in combination with polymer matrices to give added strength and improved properties to composites. Therefore, the swelling capacity of CSPs in composites cannot be ignored, because composites are utilised in diverse uses such including water-based applications. Thus, it is expedient to optimise the free swell of CSPs in order to find the optimum parametric settings which will not experience severe change in volume when used as an input for composite for water-based applications. To this end, the optimisation of free swell of CSPs was carried out using Taguchi method, simplex method and the integration of Taguchi-simplex methods. The parametric quantities that were optimised are the initial volume of CSPs, final volume of CSPs, mass of water, volume of CSPs and water as well as the mass of CSPs.

5.1. Taguchi Method

Taguchi method designates each of these parameters as factors having 3 possible values, known as levels. Taguchi methods L_{27} orthogonal array was used to study the factors and their parametric levels. The desired quality characteristic of 'smaller-the-better' was used to determine the S/N ratio for each of the 27 trials performed in the orthogonal array. The average S/N ratio of each parametric level was calculated in Table 4 and the quality characteristic of 'smaller-the-better' was used to pick an optimum parametric setting of $P_1Q_3R_2S_2T_3$. Analysis of variance (ANOVA) showed that the influence of Q_3 was insignificant. The optimisation process using the Taguchi method was concluded with a confirmatory test having additive and multiplicative properties. The results obtained for the additive and multiplicative properties are 6.07 and 56.72 %, respectively. However, 56.72% was taken as the feasible optimised value of the free swell of CSPs.

5.2. Simplex Method

The optimisation of the free swell of CSP was also carried out using the simplex method. The Simplex method was used to minimise the objective function which represents the equation of the optimisation problem that is to be solved. The 'smaller-the-better' quality characteristics as described in the Taguchi method means the objective function is to be minimised using the Simplex method. The objective function is subject to constraints, which are the governing equations that define the limits of each parameter's values. The non-negativity constraint of the parameters is given by

$$V_i,\ V_f,\ M_w,\ V_a,\ m_s\ \geq 0 \tag{25}$$

The starting objective function for the simplex method optimisation is given as

$$\text{Minimise } S_f - V_i - V_f - M_w - V_a - m_s = 0 \tag{26}$$

From the starting simplex table shown in Table 6, the optimality condition requires that the variable having the highest negative coefficient is picked as the entering variable, while the variable having the minimum non-negative ratio is selected as the leaving variable and is replaced in the basic column. However, all the variables were found to have the same negative coefficient value. This means the entering value would be picked based on the variable that could give the minimum non-negative ratio in the basic column as the leaving variable. In the first iteration, m_s and J_5 were chosen as the entering and leaving variables from the non-basic and basic variables respectively. The iterations were performed using Gauss-Jordan row operations to obtain a new simplex table. The solution of the S_f was given as 12.07, while four of the non-basic variables in the S_f row were still found to be negative. The second iteration selected V_i as the entering variable which makes J_1 as the leaving variable. The Gauss-Jordan row operations increases the solution of the S_f to 32.07 and produces a new simplex table, which still has three negative non-basic variables in the S_f row. In the third iteration, V_f is picked as the entering variable while J_2 becomes the leaving variable. The Gauss-Jordan row operation increases the solution of the S_f to 66.07 and a new simplex table is produced. Two of the non-basic variables in the S_f row are still negative.

The fourth iteration is performed by picking M_w as the entering variable, while J_3 was selected as the leaving variable. Gauss-Jordan operations increase the solution of the S_f to 212.88 and produced a new simplex table which still has a negative non-basic variable in the S_f row. The fifth iteration selects V_a as the entering variable which makes J_4 as the leaving variable to be replaced in the basic column. The solution of the S_f increases to 365.88 with the use of Gauss-Jordan row operations which produced the optimal simplex table in Table 7.

Based on the optimality condition, none of the S_f row coefficients associated with the non-basic variables is negative. Hence, Table 7 is optimal. From the simplex table obtained in Table 7, the procedure is that the optimal solution of the free swell is given by the solution value which is 365.88. The free swell value of 365.88 % is not feasible from the experimental data obtained. Therefore, the optimal free swell value is calculated using the Holtz and Gibbs model which gives 70 %.

5.3. Taguchi-Simplex Method

The integration of the Taguchi and simplex optimisation methods was done to combine the merits of both methods, leaving out any drawbacks in the process. After the Taguchi method was used to obtain an optimal parametric setting of [$P_1Q_3R_2S_2T_3$], which translates to S/N ratios [0.83, 0.73, 0.63, 0.7, 0.52]. This can be further translated to 0.83 V_i, 0.73 V_f, 0.63 M_w, 0.7 V_a, 0.52 m_s. Therefore, the Taguchi optimal parametric setting becomes the simplex algorithm objective function as follows:

$$\text{Minimise } S_f = 0.83V_i + 0.73V_f + 0.63M_w + 0.7V_a + 0.52m_s \tag{27}$$

which is re-written as:

$$\text{Minimise } S_f - 0.83V_i - 0.73V_f - 0.63M_w - 0.7V_a - 0.52m_s = 0 \tag{27a}$$

The starting Taguchi-simplex table is shown in Table 9. In the first iteration, V_i was picked as the entering variable in line with the optimality condition, while J_1 becomes the leaving variable to be replaced in the basic column. Gauss-Jordan row operations increase the solution of the S_f -row to 16.6 and a new Taguchi-simplex tableau is produced. The second iteration picks V_f as the entering variable while J_2 becomes the leaving variable. Gauss-Jordan row operations increased the solution of the S_f -row to 41.42 and produced a new Taguchi-simplex tableau. The third iteration is performed by selecting V_a as the entering variable and J_4 becomes the leaving variable. The solution of the S_f -row is increased to 147.82 using the Gauss-Jordan row operations while a new Taguchi-simplex table is produced. The fourth iteration picks M_w as the entering variable while J_3 becomes the leaving variable. Gauss-Jordan operations increased the solution value of the S_f -row to 236.99 and a new Taguchi-simplex table is produced. The fifth iteration picks m_s as the entering variable which makes J_5 the leaving variable in the basic column. The Gauss-Jordan row-operations increased the solution of the S_f -row to 243.27 and produced a new Taguchi-simplex table in Table 10. In this table, none of the S_f coefficients associated with the non-basic variables are negative. Therefore, Table 10 is optimal. From the Taguchi-simplex tableau obtained in Table 10, the procedure is that the optimal solution of the free swell is given by the solution value which is 243.27 %. However, the free swell value of 243.27 % is not obtainable from the given experimental data. Therefore, the optimal free swell value is calculated using the Holtz and Gibbs model which gives 49.51%.

6. Conclusion

The following conclusions have been drawn from the results of the three optimisation methods applied to the free swell process of CSP:

- The optimisation of the free swell process of CSP using the Taguchi method offers an efficient method for the design optimisation of CSP parameters for composite fabrication to be used in light loadings and water-based applications. Furthermore,
    - ✓ The optimal values for the CSP free swell process using the Taguchi method optimisation are an initial volume of 10 cm^3, final volume of 34 cm^3, mass of water of 141.54 g, volume of CSP and water 152 cm^3 and mass of solute of 12.07 g.
    - ✓ Based on the confirmatory test, the improvement of the free swell from the initial free swell parameters to Taguchi's free swell parameters was found to be 43.28 %.
    - ✓ The ANOVA test showed that the initial volume, mass of water, volume of CSP and water as well as mass of solute were the most significant factors that influenced the free swell.
- The free swell process optimisation of CSP using the simplex method provides an efficient method for the design optimisation of CSP parameters for composite fabrication to be used in light loadings and water-based applications. Consequently,
    - ✓ The optimal values for the CSP free swell process using the simplex method optimisation are initial volume of 20 cm^3, final volume of 34 cm^3, 146.81 g of water, volume of CSP and water 153 cm^3 and mass of solute of 12.07 g.
    - ✓ The solution of the free swell obtained from the simplex tableau is 365.88 %, but the optimal free swell value obtained by calculation is 70 %.
    - ✓ Based on the final recommendations from the simplex method, the improvement of the free swell of CSP from the initial free swell parameters to the optimal swell parameters was obtained to be 30%.
- The optimisation of the free swell process of CSP using the Taguchi-simplex method provides an excellent method for the design optimisation of CSP parameters for composite fabrication to be used in light loadings and water-based applications. Accordingly,
    - ✓ The optimal values for the CSP free swell process parameters using the Taguchi-simplex method optimisation are initial volume of 16.6 cm^3, final volume of 24.82 cm^3, mass of

water of 89.12 g, volume of CSP and water 106.4 cm^3 as well as 6.28 g of CSP were obtained from the S_f –row of the optimal tableau .

- ✓ The solution of the free swell obtained from the Taguchi-simplex tableau is 243.27 %, but the optimal free swell value was obtained by calculation to be 49.51 %.
- ✓ Based on the final recommendations from the Taguchi-simplex method, the improvement of the free swell of CSP from the initial free swell parameters to the optimal swell parameters was obtained to be 50.49 %.

This work provides answers to the water absorption capacity of coconut shell particulate which has not been considered previously in its optimised setting for composite fabrication.

References

[1] S. M. Sapuan, A. Leenie, M. Harimi, and Y. K. Berg, "Mechanical properties of woven banana fibre reinforced epoxy composites," *Materials and Design*, vol. 27, pp. 689–693, 2006.

[2] S. Bijwas and A. Satapathy, 2010. "A comparative study on erosion characteristics of red mud filled bamboo-epoxy and glass-epoxy composites," *Materials and Design*, vol. 31, pp. 1752–1767, 2010.

[3] C. Diao, T. Dowding, S. Hemsri, and R. S. Parnas, "Toughened gluten and treated coconut and treated coconut fibre composite," *Composite: Part A*, vol. 58, pp. 90–97, 2014.

[4] V. Fiore, T. Scalici, G. Vitale, and A. Valenza, "Static and dynamic mechanical properties of *Arundo Donax* fillers-epoxy," *Composites and Design*, vol. 57, pp. 456–464, 2014.

[5] V. Fiore, G. Di Bella and A. Valenza, "The effect of alkaline treatment on mechanical properties of kenaf fibres and their epoxy composites," *Composites: Part B*, vol. 68, pp. 14–21, 2015.

[6] K. Liu, X. Zhang, H. Takagi, Z. Yang, and D. Wang, "Effect of chemical treatment on transverse thermal conductivity of unidirectional abaca fibres/epoxy composite," *Composites: Part A*, vol. 66, pp. 227–236, 2014

[7] C. Albano, M. N. Ichazo, I. Boyer, M. Hernandez, J. Gonzalez, A. Karam, and A. Covis, "Study on the thermal stability of nitrite rubber-coconut flour compounds," *Polymer Degradation and Stability*, vol. 97, pp. 2202–2211, 2012.

[8] W. Sujaritjun, P. Uawongsuwan, W. Pivsa–Art, and H. Hamanda, "Mechanical property of surface modified natural fibre reinforced PLA biocomposites," *Energy Procedia*, vol. 34, pp. 664–672, 2013.

[9] V. C. Mariani, L. G. J. Luvizotto, F. A. Guerra, and L. S. Coello, "A hybrid shuffled complex evolution approach based on differential evolution for unconstrained optimisation," *Applied Mathematics and Computation*, vol. 217, pp. 5822–5829, 2011.

[10] V. Chand, S. S. Sen, and M. S. Sethi, "Taguchi analysis of forging defects for gears," *International Journal of Advanced Technology in Engineering and Science*, vol. 2, no. 8, pp. 52–59, 2014.

[11] Z. Salleh, M. M. Islam, M. M. Yusop, M. Y. M. Yusop, and M. A. Idrus, "Mechanical properties of activated carbon coconut shell reinforcement polypropylene composite encapsulated with epoxy resin," *APCBEE Procedia*, vol. 9, pp. 92–96, 2014.

[12] D. R. Mulinari, C. A. R. P. Baptista, J. V. C. Souza, and H. J. C. Voorwald, "Mechanical properties of coconut fibres reinforced polyester composites," *Procedia Engineering*, vol. 10, pp. 2074–2079, 2011.

[13] W. Nuthang, P. Uawongsuwan, W. Pivsa-Art, and H. Hamanda, "Impact property of flexible epoxy treated natural fibre reinforced PLA composites," *Energy Procedia*, vol. 34, pp. 839–847, 2013.

[14] S. Vijayakumar, T. Nilavarasan, R. Usharani, and L. Karunamoorthy, "Mechanical and microstructural characterisation of coconut spathe fibres and kenaf bast fibres reinforced epoxy polymer matrix composites," *Procedia Materials Science*, vol. 5, pp. 2330–2337, 2014.

[15] J. Sarki, S. B. Hassan, V. S. Aigbodion, and J. E., Oghenevweta, "Potential of using coconut shell particle fillers in eco-composite materials," *Journal of Alloys and Compounds*, vol. 509, pp. 2381–2385, 2001.

[16] S. M. S. Kumar, D. Duraibabu, K. Subramanian, "Studies on mechanical, thermal and dynamic mechanical properties of untreated (raw) and treated coconut sheath fibre reinforced epoxy composites," *Materials and Design*, vol. 59, pp. 63–69, 2014.

[17] E. M. Fernandez, V. M. Correlo, J. F. Mano, and R. L. Renaturis, "Novel cork-polymer composites reinforced with short natural coconut fibres: Effect of fibre loading and coupling agent addition," *Composites Science and Technology*, vol. 78, pp. 56–62, 2013.

[18] J. Y. Jang, T. K. Jeong, H. J. Oh, J. Y. Youn, and Y. S. Song, "Thermal stability and flammability of coconut fibre reinforced poly (lactic acid) composites," *Composites: Part B*, vol. 43, pp. 2434–2438, 2012.
[19] C. Diao, H. Xia, I. Noshadi, B. Kanjilal, and R. S. Parnas, "Wheat gluten blends with a macro-molecular cross-linker for improved mechanical properties and reduced water absorption," *ACS Sustainable Chemical Engineering*, vol. 2, no. 11, pp. 2554–2561, 2014.
[20] M. Brahmakumar, C. Pavithran, R. M. Pillai, "Coconut fibre reinforced polyethylene composites: Effect of natural waxy surface layer of the fibre on fibre/matrix interfacial bonding and strength of composites," *Composites Science and Technology*, vol. 65, no. 3–4, pp. 563–569, 2005.
[21] A. A. A. Rashdi, S. M. Sapuan, M. M. H. M. Ahmad, and A. Khalina, "Combined effects of water absorption due to water immersion, soil buried and natural weather on mechanical properties of kenaf fiber unsaturated polyester composites," *International Journal of Mechanical and Materials Engineering*, vol. 5, no. 1, pp. 11–17, 2010.
[22] A. Shahzad, "Effect of water absorption on mechanical properties of hemp fiber composites," *Polymer Composites*, vol. 33, no. 1, pp. 120–128, 2012.
[23] F. H. M. M. Costa and J. R. M. D'Almeida, "Effect of water absorption on the mechanical properties of sisal and jute fibre composites," *Polymer-Plastic Technology and Engineering*, vol. 38, no.5, pp. 1081–1094, 1999.
[24] A. Pandian, M. Vairavan, W. J. J. Thangaiah, and M. Lithayakumar, "Effect of moisture absorption behaviour on mechanical properties of basalt fibre reinforced polymer matrix composites," *Journal of Composites*, vol. 2014, pp. 1–8, 2014.
[25] G. Huang and H. Sun, "Effect of water absorption on the mechanical properties of glass polyester composites," *Materials & Design*, vol. 28, no. 5, pp. 1647–1650, 2007.
[26] B. C. Patel, S. K. Acharya, and D. Mishra, "Environmental effect of water absorption and flexural strength of red mud filled jute fiber/polymer composite," *International Journal of Engineering, Science and Technology*, vol. 4, no. 4, pp. 49–59, 2012.
[27] T. Alomayri, H. Assaedi, F. U. A. Shaikhe, and I. M. Low, "Effect of water absorption on the mechanical properties of cotton fabrics-reinforced geopolymer composites," *Journal of Asian Ceramic Societies*, vol. 2, no. 3, pp. 223-230, 2014.
[28] E. Woldesenbet, N. Gupta, and J. R. Varison, "Determination of moisture effects on impact properties of composite materials," vol. 37, no. 13, pp. 2693-2698, 2000.
[29] N. Gao, X. Jiaotong, H. Xie, and Z. Peng, "Effect of water absorption on dielectric properties of EPDM/AL(OH)$_3$ composites," in *Proceedings of the 6th International Conference on Properties and Applications of Dielectric Materials*, 2000, pp. 905–907.
[30] C. Diao, T. Dowding, S. Hemsris, and R. S. Parras, "Toughened wheat gluten and treated coconut fibre composite," *Composites Part A: Applied Science and Manufacturing*, vol. 58, pp. 90–97, 2014.
[31] S. Vijayakumar, S. Manikandan, and L. Karunamoorthy, "The experimental investigation on water absorption characteristic of natural fiber composites, *Advanced Material Research*, vol. 984–985, pp. 248-–252, 2014.
[32] D. Topgaard and O. Soderman, "Diffusion of water absorbed in cellulose fibres studied with 1H-NMR," *Langmuir*, vol. 17, no. 9, pp. 2694-2702, 2001.
[33] M. T. Isa, S. Usman, A. O. Ameh, O. A. Ajayi, O. Omorogbe, and S. U. Ameru, "The effect of fibre treatment on the mechanical and water absorption properties of short okra/glass fibers hybridized epoxy composite," *International Journal of Materials Engineering*, vol.4, no 5, pp. 180-184, 2014.
[34] J. Songok, P. Salminen, and M. Toivakka, "Temperature effects on dynamic water absorption into papers," *Journal of Colloid and Interface Science*, vol. 418, pp. 373–377, 2013. doi: 10.1016/j.jcis. 2013.12.017
[35] S. Malasri, A. Pourhashenri, P. Aung, M. Harvey, and R. Moats, "Water absorption of wooden pullets," *International Journal of Applied Science and Technology*, vol. 2, no. 9, pp. 1–10, 2010.
[36] H. O. Agu, M. H. Badau, and U. M. Abubakar, "Modeling the water absorption characteristics of various local pearl millet grains and hungry rice (Digitaria exilis) during soaking using Peleg's equation," *Focusing on Modern Food Industry*, vol. 2, no. 4, pp. 161–169, 2013.