

## Water absorption experimental analysis of an orange peel and coconut shell particulate blend reinforcement material for composite fabrication

Oluwaseyi Ayodele Ajibade <sup>1)</sup>, Johnson Olumuyiwa Agunsoye <sup>1)</sup> and Sunday Ayoola Oke\*<sup>2)</sup>

<sup>1)</sup>Department of Metallurgical and Materials Engineering, Faculty of Engineering, University of Lagos, Lagos, Nigeria

<sup>2)</sup>Department of Mechanical Engineering, Faculty of Engineering, University of Lagos, Lagos, Nigeria

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### Abstract

The extant literature on composites has downplayed the merits of orange peel particulates (OPPs) and coconut shell particulates (CSPs) as fillers in mixed forms despite their engineering purposes. An OPP-CSP mixture can be used to suppress the weight disadvantage of CSPs, exploit the water resistance advantage of CSP, enhance the mechanical properties and improve the wear resistance of OPPs as a result of the oily secretions of the OPP. Launching a new research direction of mixed filler experiments, this work examines the water absorption properties of mixed OPPs-CSPs of up to 30 cm<sup>3</sup> mixtures by volume, according to filler literature norms and previous sensitivity tests. A principal result is that the average free swell of the particulate blend increased up to 164.61%, a value attained with an initial volume of CSPs equal to 10 cm<sup>3</sup> in a combined initial volume of 30 cm<sup>3</sup>. Thus, the mixing ratio is 10 CSPs:20 OPPs (Type I). This free swell value can cause considerable changes to loadings and structures, which is a negative outcome. Sensitivity analysis showed that the higher-OPPs-in-particulate blend produced the most favourable free swell values. In practice, the findings of this study meet the growing needs of the composite industry for materials having unusual combinations of the properties of water-resistance for lightweight applications in tennis rackets, household interior decorations and agricultural silos. This novel contribution pioneers efforts to produce filler blends of particulate orange peels and coconut shells in independently varied proportions rather than being embedded in composites. Sensitivity analysis of the critical process parameters was carried out to understand the degree of responsiveness of model parameters of the blends. This is the first time such information has been reported in the literature.

**Keywords:** Agro-wastes, Fillers, Orange peels, Coconut shell, Mixtures

### 1. Introduction

Reinforcement materials (fillers) have long been recognised as critical in composite fabrications, with complementary matrices [1-4]. Indeed, metallic-filled composites are harmful at the disposal stage, exposing citizenry to health hazards and triggering increased health costs due to exposures [5]. Metallic-fillers also contribute to high composite fabrication costs. Thus, reliance of design engineers and composite manufacturers on agricultural wastes as composite fillers may reduce production costs, lower the life-cycle costs and eliminate the health hazards of metallic-fillers [6], since they are biodegradable and renewable [7-9].

To date, the extant literature generally downplays studies on agro-waste fillers that are not embedded into composites. Such tests have also ignored water absorption phenomenon [10]. However, extensive studies have been generally made in several areas, including thermal [11], impact, mechanical, physical [12-13], tribological [14-16], flexural [17], chemical, electrical and hybrids as electro-mechanical [18-19], tribo-physical, thermo-physical [20], and tribo-mechanical [21] properties, among others. The viewpoint of

evaluating filler properties while embedding them in matrices is limited from both the theoretical and practical perspectives [7-9]. Results are not transferable to other independent tests of fillers. Measuring filler properties when they are embedded in matrices of fabricated composites may serve some very useful purposes, but determining the properties of fillers in isolation may give precise, dependable and less controversial experimental results [7-9]. Thus, it is believed that limiting property evaluations of fillers to situations where they are embedded in composites seems to be shortsighted. This may lead material engineers and designers to overlook alternative approaches for material property evaluations of composite fillers, and particularly, agricultural waste materials [8-9]. Indeed, previous work on agricultural wastes has critically considered independent evaluations of properties of fillers before being embedded in a matrix to form a composite. Practical experimental results are needed that recognise the free swell behaviour of orange peel and coconut shell fillers blends prior to incorporation into the matrices of composites.

Similar kinds of mixtures proposed in this study have practical relevance, and could find applications in lightweight materials such as tennis rackets, household

\*Corresponding author.

Email address: sa\_oke@yahoo.com

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interior decorations and agricultural silos. This study is limited to water absorption tests despite performing other tests determining the strength and deformation properties of fillers. This was done as a preliminary study to champion research in this direction. The study provides for initiation and direction for future studies that could perform other tests such as fracture, impact, Young's modulus, tensile strength and hardness determination.

A brief summary of the water absorption literature relevant to the current subject is given. Wang et al. [22] reported on the water lubrication of two polytetrafluoroethylene (PTFE)-oriented composites and concluded that adhesion of the fibre-matrix interface assisted in resisting intrusion of water into the composite. Ghosh et al. [23] reported on the influence of treatment (ultrasonic) on the water resistance behaviour of woven banana fiber composites, while Benyahia et al. [24] examined the resistance to water of an adhesive Adekit Al 40 epoxy-bonded composite. They concluded that there was a negative influence of water absorption on composite properties. Kakroodi et al. [25] reported no observable differences in natural fibre composites from polyethylene and hemp fibre dipped in water. Hosseinaei et al. [26] investigated moisture absorption of wood-based composites and concluded that the samples' water absorption was reduced following the removal of hemicellulose.

Alamri and Low [2] researched an epoxy composite's water resistance and observed that an increase in moisture absorption yielded reduced flexural strength, modulus and fracture toughness. Lu and Xue [27] evaluated the water absorption of composites made of copper and bamboo fabric composites. Tamrakar and Lopez-Anido [28] studied the water absorption and resilience of polypropylene composites. They reported a significant decline in the specimens' mechanical properties in relation to dry control samples. The study of Venkateswaran et al. [29] examined water absorption of a banana/epoxy composite material and concluded that infusing sisal fibre in a banana/epoxy composite up to 50wt% elevated the mechanical properties of the composite and reduced its moisture absorptivity.

Visco et al. [30] discussed the potential of a glass fibre filled composite for water absorption. The authors reported that vinyl ester had the capacity to resist the absorption of seawater in a greater measure than a polyester composite of isophthalic origin. Wang et al. [31] studied the influence of surface treatment of lignocellulosic particles on the water absorption of composites fabricated using poly-vinyl-chloride as well as bamboo (*Phyllostachyspubescens*). They observed enhancement in the water resistance of the samples. Wang et al. [32] noted that polyphenylene sulfide lessened water absorption of some composites.

Researchers worked on composites with fillers such as polytetrafluoroethylene, banana filler, adhesive Adekit Al 40, polyethylene and hemp fibre, bamboo, sisal fibre and glass fibre. Detailed experiments on water absorption of these fillers were done in these studies. They were done with fillers were embedded in matrices. There is no single report in the literature, to the best of the authors' knowledge, where green filler orange peel particulates (OPPs) and coconut shell particulates (CSPs) have been extensively studied in water absorption experiments. The literature has been concerned with fibres (woven banana, hemp and bamboo) and rather than particulates. The closest report deals with lignocellulosic particles, which may exhibit different characteristics from OPPs and CSPs. The absence of relevant literature considering these fillers in isolation and the further omission of blends of these fillers in particulate forms

strengthened the novelty of this work. Consequently, the objective of the current work is to carry out water absorption laboratory-controlled experiments that report the behaviour of various mixtures of OPPs and CSPs in different proportions and examine the sensitivity of the model parameters to changes in their values.

Accordingly, the experimental results reported in the current work contribute to composite filler literature for two perspectives. First, the work reports on blends of OPPs and CSPs in varied proportions in independent examinations of the blends of fillers before being embedded in composites. This study is the first in this respect. Second, sensitivity analysis of the critical parameters of the process was carried out to understand the degree of responsiveness of model parameters of the blend OPPs and CSPs.

The current research unfolds in the following ways. The experimental methodology is given, including experimental details. This is followed by the results from the experiments and discussion. The sensitivity analysis from the experimental outcomes is then done based on the key parameters influencing water absorption. Finally, conclusions of the study are presented.

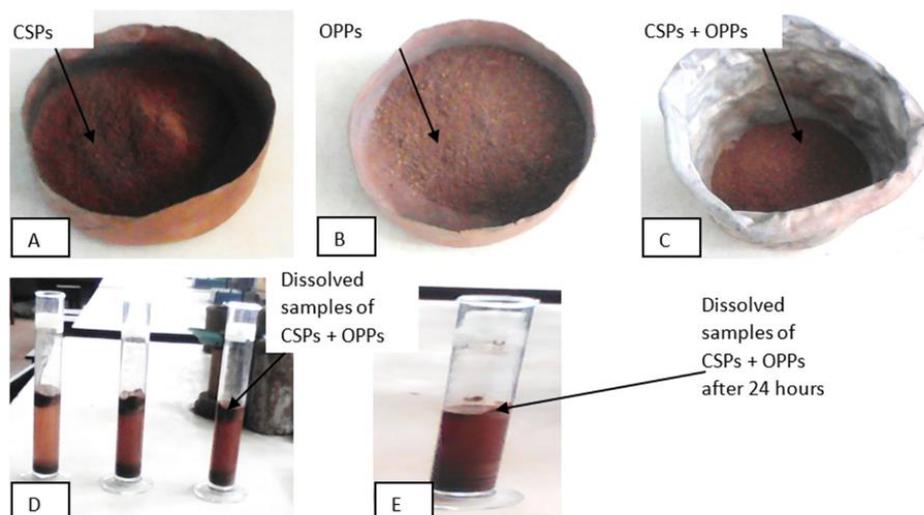
## 2. Methodology

The previous section discussed past investigations done on water absorption. It highlighted the research needed to do experiments to evaluate the free swell index of mixed particulates, in which proportions of OPPs are blended with coconut shells in various proportions. This section presents the methodology for the work.

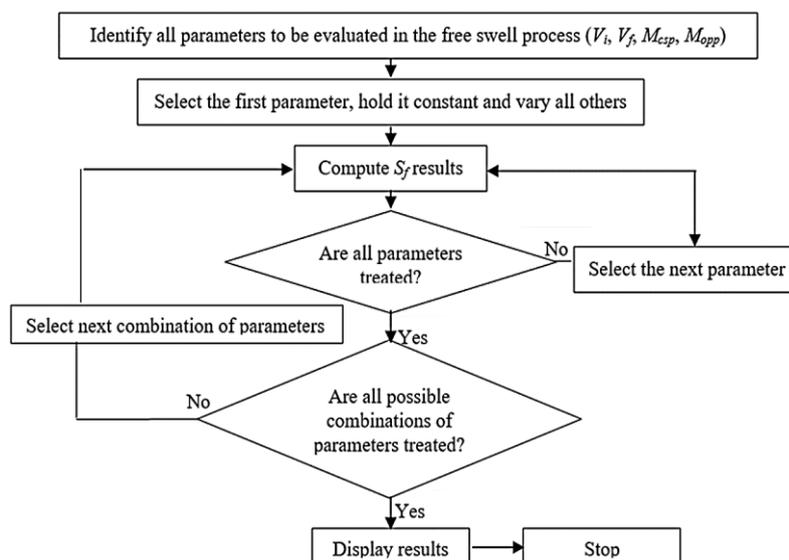
Coconut shell was obtained from the Oyingbo market in Lagos. The coconuts were broken and the shells removed from the edible portions. The shells were then mechanically ground up to thirteen times to obtain a particulate form. They were then sieved using a British standard test sieve series (Wykeham Farrance) partitioned into sizes of 0.075, 0.150, 0.212, 0.300, 0.425 and 0.600 mm. However, the portion on the 0.600 mm screen had the most abundant quantities in the sieve analysis. Hence, it was used in subsequent experiments. The second used consisted of orange peel particulates obtained from orange hawkers, from Abule-Oja, at edge of the University of Lagos. The orange peels were obtained and the skin or outer layer of the oranges was carefully trimmed off. These peels were dried in the sun for several days until there was no moisture remaining in the peels. It was also ground into particulate material. The output was then sieved as was done for the CSPs. The portion on the 0.600 mm screen was used for experimentation as it was the most abundant.

CSPs and orange peel particulates were mixed in desired ratios by volume. If the mixtures, when the amount of CSPs was higher, we referred to this as a "higher-coconut-shell particulate-in-mixture. In the case where the quantities of orange peel particulates were higher, these were referred to as the higher-orange-peel-particulate-in-mixture. Tap water was obtained and experiments done according to ASTM D 570 standards, which stipulate the specific steps to be followed in the dissolution of the materials in the solvent.

Sample preparation was done by hand mixing measured volumes of the different CSPs and the OPPs fractions in a prescribed order to form a homogenous mixture. The sample size was limited to 13 and this involved extensive experimentation. The quantity obtained is poured into a 250 cm<sup>3</sup> graduated cylinder containing 150 cm<sup>3</sup> of tap water. The mixture of the solute and solvent is allowed to interact for 24 hours. Then, the new volume of the solution is measured and



**Figure 1** Stages of mixing of CSPs and OPPs. Legend: A - 15cm<sup>3</sup> of CSPs; B - 15cm<sup>3</sup> of OPPs; C - 15 cm<sup>3</sup> of OPP and 15cm<sup>3</sup> CSPs after hand mixing; D - Three samples of 15cm<sup>3</sup> OPPs and 15cm<sup>3</sup> of CSPs immediately after dissolution; E - One of the 15cm<sup>3</sup> OPPs mixed with 15cm<sup>3</sup> CSPs sample after 24 hours dissolution



**Figure 2** Sensitivity analysis of the  $S_f$  parameters

other parameters measured to obtain the free swell index. The  $V_i$  of the particles dissolved in water is 30 cm<sup>3</sup>. Type A comprised 25 cm<sup>3</sup> OPP and 5 cm<sup>3</sup> CSPs that were thoroughly hand-mixed until a consistent mixture was formed. The 20 cm<sup>3</sup> OPPs and 10 cm<sup>3</sup> CSPs, 15 cm<sup>3</sup> OPPs and 15 cm<sup>3</sup> CSPs as well as 10 cm<sup>3</sup> CSPs and 20 cm<sup>3</sup> OPPs were combined to obtain sample Types B, C and D, respectively. Type E was entirely made of 30 cm<sup>3</sup> of OPPs. In like manner, sample Types F, G, H and I comprised of 25 cm<sup>3</sup> CSPs and 5 cm<sup>3</sup> OPPs, 20 cm<sup>3</sup> CSPs and 10 cm<sup>3</sup> OPPs, 15 cm<sup>3</sup> CSPs and 15 cm<sup>3</sup> OPPs and 10 cm<sup>3</sup> CSPs and 20 cm<sup>3</sup> CSPs, respectively. Type J is made up of only 30 cm<sup>3</sup> CSPs. The water absorption of a mixture was evaluated in terms of its free swell index ( $S_f$ ).

The experimental set-up for evaluating the water absorption or swell characteristics of combined OPPs and CSPs was made by varying the blends (Figure 1).

In Figure 2, details of the sensitivity are schematically depicted.

### 3. Results and discussion

The  $S_f$  of a mixture of orange peel particulates and particulates of coconut shell in water is defined as the ratio of the differences between the final and initial volumes of solution and solvent ( $V_f$  and  $V_i$ ), respectively, to the  $V_i$  of the solvent. It is a true indication of the water absorbed by the green reinforcement material, carried out at different temperatures and humidities, as well as heated and controlled temperatures up to 100°C.

#### 3.1 The $S_f$ performance test

The tabulations for the  $S_f$  performance test are shown in Tables 1 and 2, including Types A to E as well as Types F to J, which are compared.

In this research, four different modes of volumetric measurements are used for the particulates. The two different particulates are combined in the volumetric ratios 25:5,

**Table 1**  $S_f$  and other water absorption indices (Module 1)

S/N	Indices	Type A	Type B	Type C	Type D	Type E
1	$V_f$ (cm <sup>3</sup> )	88.33	78.00	68.33	66.00	84.00
2	$S_f$ (%)	194.44	160.00	127.78	120.00	180.00
3	$V_f/V_i$ (cm <sup>3</sup> )	2.94	2.60	2.28	2.22	2.80
4	$S_f/V_i$	6.48	5.33	4.26	4.00	6.00

Type A: 25 OPPs:5CSPs; Type B: 20 OPPs: 10CSPs; Type C: 15 OPPs:15CSPs;  
Type D: 10 OPPs:20CSPs; Type E: 30 OPPs: 0 CSPs

**Table 2**  $S_f$  and other water absorption indices (Module 2)

S/N	Indices	Type F	Type G	Type H	Type I	Type J
1	$V_f$ (cm <sup>3</sup> )	58.33	61.33	68.00	78.00	50.00
2	$S_f$ (%)	94.33	104.44	126.67	160.00	66.67
3	$V_f/V_i$ (cm <sup>3</sup> )	1.94	2.04	2.27	2.60	1.67
4	$S_f/V_i$	3.14	3.48	4.22	5.33	2.22

Type F: 25 CSPs:5OPP; Type G: 20 CSPs:10OPP; Type H: 15 CSPs:15OPP;  
Type I: 10 CSPs:20OPP; Type J: 30 CSPs: 0OPP

Note: The mixing sequence is the main difference between Types A to D and Types F to I.

20:10, 15:15, 10:20 cm<sup>3</sup> measurements, such that as one where particulates are increasing in steps of 5 cm<sup>3</sup>, the others decreasing in steps of 5 cm<sup>3</sup>. This is done to elucidate the influence of the different volumetric combinations on the  $S_f$  and other water absorption indices such as  $V_f$ ,  $V_f/V_i$  and  $S_f/V_i$ . Thus, the analysis is carried out in two different directions. The first is the higher orange peel, low CSP blend known as Module 1 and described by Table 1, while the second is the higher coconut shell, low orange peel particulate blend presented in Table 2 as Module 2. Each of the values presented in the tables represents average values obtained from three different experimental runs. The  $S_f$  and water absorption indices of Module 1 are described in Table 1, where the  $V_f$  for the Type A is 88.33 cm<sup>3</sup>. The Types B and C particulate blends returned a  $S_f$  value of 78 and 68.33 cm<sup>3</sup> which is 11.69 and 22.64% less than that of the Type A blend. Likewise, the Type D has a  $V_f$  of 66 cm<sup>3</sup>, which is 22.28% less than the value obtained by the Type A blend. The Type E, with only orange peel particulate, was expected to have a higher  $V_f$  value. However, its  $V_f$  of 84 cm<sup>3</sup> is still 4.9% less than the Type A blend.

This trend continued for the  $S_f$  where the Type A blend has the highest  $S_f$  of 194.44 %. As the volume of the OPPs in the blend is reduced, the  $S_f$  is seen to decline to a minimum value of 120% for the Type D blend, which is 38.28% less than that produced by the Type A blend. In the  $V_f/V_i$  row, the influence of the OPPs is still pronounced as the highest and lowest values of 2.94 and 2.22 are obtained in the Type A, and Type D blends, respectively. Again, the Type E produced a  $V_f/V_i$  index of 2.8 which is 4.76% less than that obtained with the Type A blend. The last index to be discussed is the  $S_f/V_i$  index. Here, Type A has an index of 6.48 which is reduced by 17.75 and 34.26% to 5.33 and 4.26% for Type B and Type C, respectively. The  $S_f/V_i$  index is reduced by 38.27% to 4% in the Type D particulate blend. Again, the absence of CSPs in the Type E blend did not translate to a higher  $S_f/V_i$  as was observed in other indices.

The  $S_f$  and water absorption indices described by Table 2 for Module 2 show a new trend. The  $V_f$  for the Type F blend is 58.33 cm<sup>3</sup>, which increased by 5.14% to 61.33 cm<sup>3</sup> for the Type G particulate blend. As the volume of the particulates reached an equilibrium of 15 cm<sup>3</sup>, the  $V_f$  rose by 16.58% to 68 cm<sup>3</sup>. For the Type I particulate blend, a  $V_f$  was obtained as 78 cm<sup>3</sup>. Despite the absence of OPPs in Type J blend, it

behaved in a similar manner to the Type E blend, as can be observed in Table 1. This trend continued for  $S_f$ , where the Type F had the lowest value of 94.33% which increased to 104.44, 126.67 and 160% for Type G, Type H, Type I particulate blends, respectively. The  $V_f/V_i$  and  $S_f/V_i$  indices also showed similar increases as the volume of the OPPs increased, rising from 1.94 and 3.14 to 2.6 and 5.33 respectively. Again, Type J experienced a reduction in the  $V_f/V_i$  and  $S_f/V_i$  indices, dropping to 1.67 and 2.22 from 1.94 and 3.14, respectively.

### 3.2 Relationship between $S_f$ and $V_i$ , $M_{csp}$ and $M_{opp}$

The relationship existing between the  $S_f$  of coconut shell-orange peel particulates with  $V_i$ , mass of CSPs and mass of orange peel particulates is presented in two different ways. The first is when a higher volume proportion of CSPs is used starting from 25 cm<sup>3</sup>, and then reduced to 20, 15 and 10 cm<sup>3</sup>. The second way is when a higher volume proportion of OPPs is used starting from 25 cm<sup>3</sup> and reduced to 20, 15 and 10 cm<sup>3</sup>. In both cases, as the volume of particulates is reduced in steps of 5 cm<sup>3</sup>, the volume of the other particulate increased by the same amount, so that the combined  $V_i$  of both particulates is 30 cm<sup>3</sup>.

### 3.3 Relationship of $S_f$ with $V_i$ , $M_{opp}$ , $M_{csp}$ and higher orange-peels particulate variation

#### Average $S_f$ and $V_i$ of OPP

The average  $S_f$  of the particulates is measured when  $V_i$  of OPPs is 25, 20, 15 and 10 cm<sup>3</sup>. The relationship between the average  $S_f$  and  $V_i$  of OPP is shown in Figure 3. The  $S_f$  increases as the volume of the OPP increases in the particulate mixture. At 10 cm<sup>3</sup> of OPP, the average  $S_f$  is 113.61%. This trend continues until the  $V_i$  reaches 25 cm<sup>3</sup>, which brings the  $S_f$  to a peak of 198.89%. The high  $S_f$  displayed in Figure 4 is caused by higher swelling of the OPPs.

This was caused by a higher volume of OPP in the particulate blend than in the first case. The relationship between the parameters of the system is described as:

$$\bar{S}_f = 0.1167V_i^2 + 1.6045V_i + 85.868 \quad (1)$$

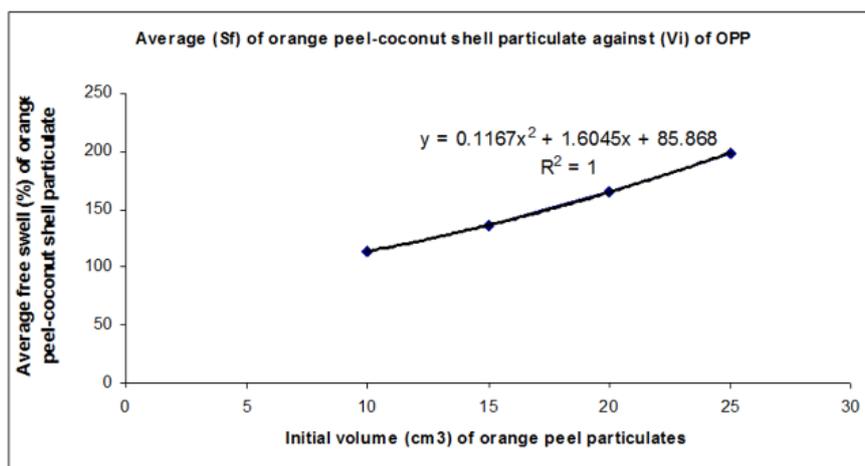


Figure 3 Relationship of  $V_i$  of OPPs with an average  $S_f$  of the higher OPP blend

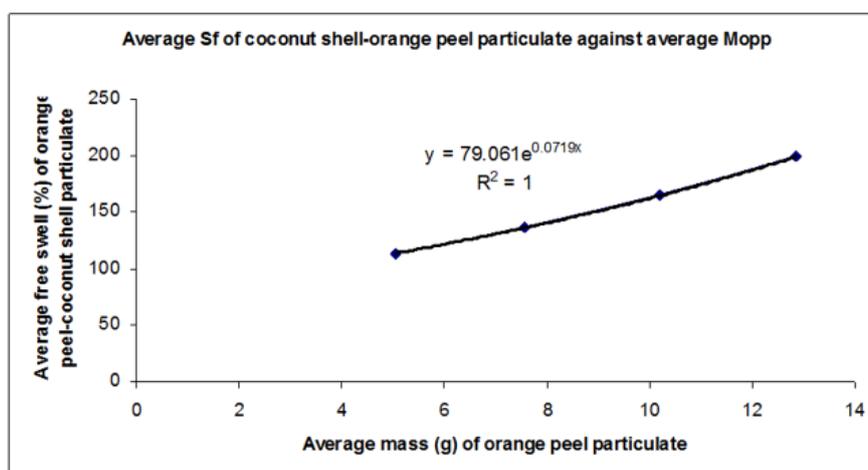


Figure 4 Relationship of average mass of OPPs with an average  $S_f$  of the higher OPP blend

$R^2(1)$  shows a 100% correlation of the curve indicating that the system described by the curve is acceptable.

*Average  $S_f$  and average  $M_{opp}$*

The average  $S_f$  of the particulates is plotted against the average mass of the orange peel particulates obtained at 25, 20, 15 and 10  $cm^3$ , respectively. Figure 4 presents the relationship between the average  $S_f$  of the higher orange peel-coconut shell particulate blend and the average  $M_{opp}$ . The resulting curve in Figure 4 showed a similar behavior to that depicted in Figure 3. Thus, the mass of the orange peel particulates influences the  $S_f$  of the particulates in the same way as the volume of the orange peel particulate. Equation (2) describes the relationship between the elements of the system as follows:

$$\bar{S}_f = 79.061e^{0.0719 M_{opp}} \tag{2}$$

The  $R^2(1)$  shows that the correlation of the system is acceptable.

*Average  $S_f$  and average  $M_{csp}$*

The average  $M_{csp}$  measured when the volume of the OPPs was 25, 20, 15 and 10  $cm^3$  is plotted against the average  $S_f$  of

the particulates obtained at the same volume, as shown in Figure 5.

The behaviour of the curve is different from those of Figures 3 and 4. At 2.97 g of CSPs, the  $S_f$  was 198.99%. However, as the  $M_{csp}$  increased, the average  $S_f$  dropped to 113.61%. This was caused by the lower swelling or water absorbing capacity of the coconut shell particulates. The relationship between the elements of the system is represented by Equation (3).

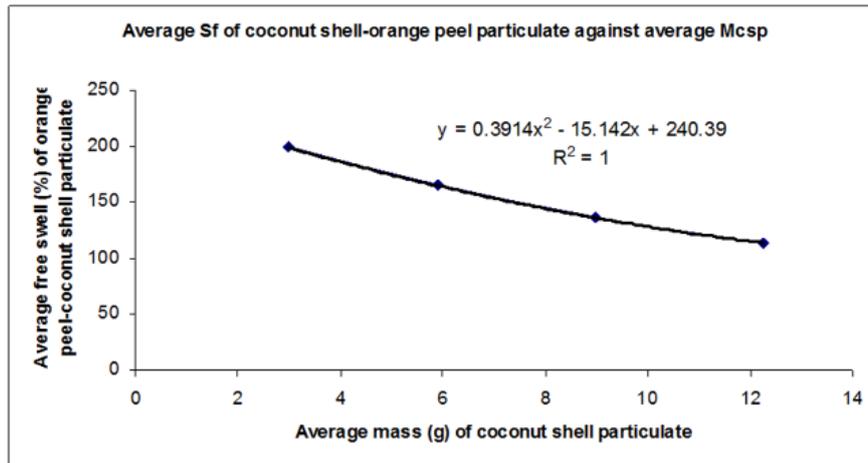
$$\bar{S}_f = 0.3914M_{csp}^2 - 15.142M_{csp} + 240.39 \tag{3}$$

The  $R^2(1)$  correlation indicates that the relationship of the system is acceptable.

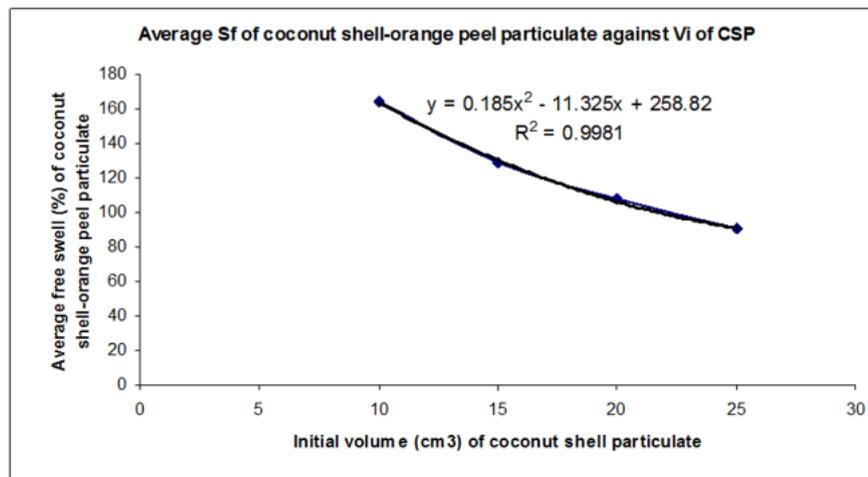
*3.4 Relationship of  $S_f$  with  $V_i$ ,  $M_{csp}$  and  $M_{opp}$  at higher CSP variation*

*Average  $S_f$  and  $V_i$  of CSPs*

The average  $S_f$  of the particulates was measured when the  $V_i$  of the CSPs is 25, 20, 15 and 10  $cm^3$ . The relationship between the average  $S_f$  of the particulate mixture and the  $V_i$  of the CSPs is described by Figure 6. It shows that the average  $S_f$  is highest when the  $V_i$  is 10  $cm^3$  with a value of 164.61%. From Figure 6, it can be observed that a  $S_f$  of



**Figure 5** Variation of average mass of CSPs with average  $S_f$  of the higher OPP blend



**Figure 6** Relationship of  $V_i$  of CSPs and average  $S_f$  of the higher CSP blend

164.61% was attained when  $V_i$  of CSPs was 10 cm<sup>3</sup>. The combined  $V_i$  of the particulates used in this investigation is 30 cm<sup>3</sup>. This means that the  $V_i$  of the OPPs is 20 cm<sup>3</sup>. Thus, the mixing ratio is 10 CSPs:20 OPPs, which is designated as Type I. This  $S_f$  value implies a high percentage of  $S_f$  that can cause considerable changes to loadings and structures according to the Holtz and Gibbs' model. Although this model used a  $V_i$  of 10 cm<sup>3</sup>, it was recommended that materials with  $S_f$  values of 50% cannot cause severe loading damage to structures. Following this precept in the current investigation, which used 30 cm<sup>3</sup> as  $V_i$ , materials with  $S_f$  greater than 150% can cause considerable damage when used in water-based applications. Thus, a  $S_f$  value of 164.61% can be termed a negative outcome. The average  $S_f$  reduces as the  $V_i$  of the CSPs increases. So, a higher volume of CSPs did not increase the free swell of the particulate combination. The decline in the average free swell as the volume of the CSPs rose indicates that the influence of CSPs on the average free swell is not positive. This can be attributed to the low swelling or water absorbing capacity of the CSPs. The correlation between the parameters of the system is described by:

$$\bar{S}_f = 0.185V_i^2 - 11.325V_i + 258.82 \quad (4)$$

The  $R^2$  (0.9981) obtained from the curve indicates that the relationship described by the curve is acceptable.

#### Average $S_f$ and average mass of CSP

The average  $S_f$  of the particulates was plotted against the average  $M_{csp}$  obtained at 25, 20, 15 and 10 cm<sup>3</sup> measurements of the CSP, as shown in Figure 7. The behaviour of the curve is similar to that of Figure 6. Again, the influence of CSP on the average free swell was found to be negative. Figure 7 clearly shows that an increase in the mass of CSP did not contribute positively to the free swell of the particulate combination. Equation (5) describes the correlation between the elements of the system:

$$\bar{S}_f = 532.66M_{csp}^{-0.6477} \quad (5)$$

The correlation value of  $R^2$  (0.9976) shows a strong agreement in the relationship described by the curve.

#### Average $S_f$ and average mass of OPPs

Figure 8 describes the relationship between the average  $S_f$  of the particulates and the average  $M_{opp}$  obtained at 25, 20, 15 and 10 cm<sup>3</sup> measurements of the CSPs. The curve shows that the free swell rises in direct proportion to the increase in  $M_{opp}$ . This indicates that in the higher coconut shell particulate material, the OPP largely influenced the free swell since every increase in the  $M_{opp}$  value resulted in a higher free swell of the particulate combination. In the higher

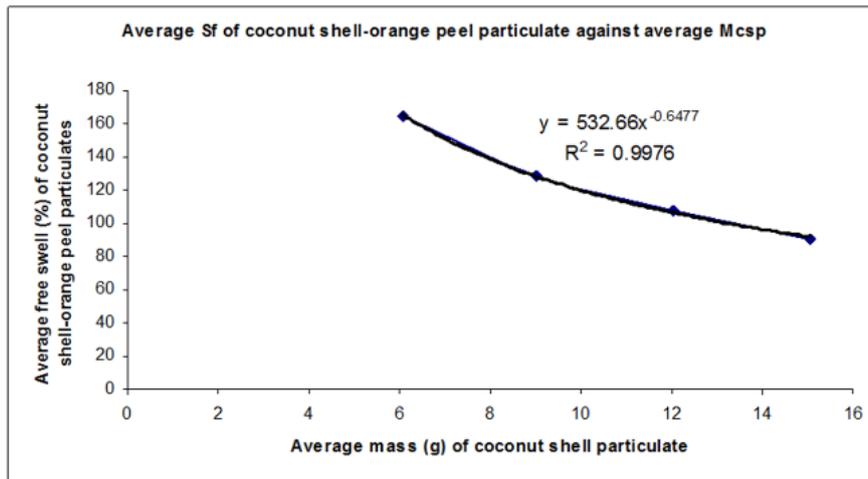


Figure 7 Relationship of average mass of coconut shell particulates and average free swell of the higher coconut shell blend

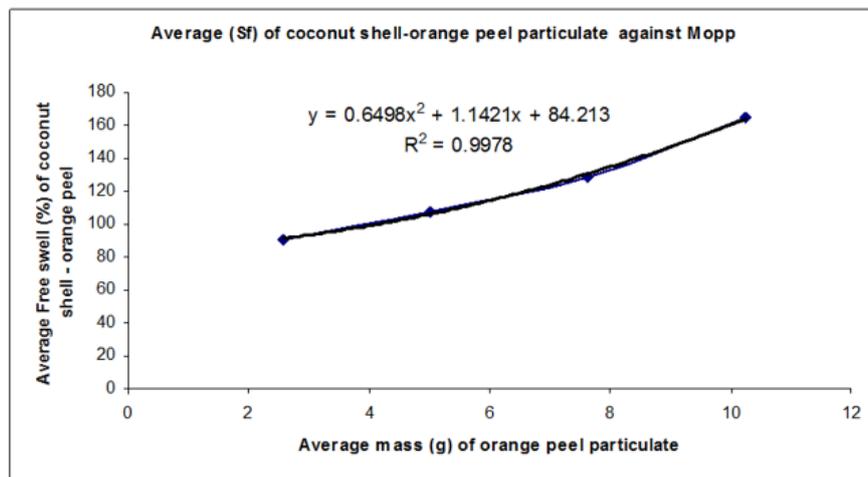


Figure 8 Variation of the average mass of OPPs with and the average  $S_f$  of the higher CSP blend

coconut shell particulate combination, the orange peel particulate was more influential to the free swell. Equation (6) describes the correlation of the system.

$$\bar{S}_f = 0.6498M_{opp}^2 + 1.1421M_{opp} + 84.213 \quad (6)$$

$R^2$  (0.9978) indicates a high acceptability of the system.

The behavior shown in Figures 3, 4 and 8 indicates that the rise in the mass or volume of the orange peel particulates is largely responsible for the free swell of the particulate combination. However, Figures 5, 6 and 7 show that an increase in the mass or volume of coconut shell particulates did not increase the free swell of the combined particulates. This is explained in practical terms by the high swelling and water absorbing capacity of the OPPs and the low swelling and low water absorption of the CSPs.

Equations (1) to (6), which represent the empirical relationship among the free swell variables, are applicable to the test conditions and may be useful in predicting the possible behavior of free swell outside of 30cm<sup>3</sup> volume restrictions to some reasonable extent. However, more experimentation is needed to validate this.

The effect of the ratio of OPPs to CSPs on particle distribution and swelling is to establish the pattern of distribution and swelling for future predictive purposes. The ratio of OPPs to CSPs plays a significant role in the property

formulation of the mixed OPP-CSP reinforced epoxy composites. In independent studies, Ajibade et al. [7] found that OPPs absorb more water than CSPs. Volumetric measurements of the fillers in water shows that a volume of 20 cm<sup>3</sup> of 0.600 mm CSPs yielded a 50% swelling, whereas for the same amount of volume, 20 cm<sup>3</sup> of 0.600 mm OPPs yielded a 100% swelling. This implies that for optimal results, a ratio of the mixture of 2:1 CSPs to OPPs is desirable. It should be understood that when combined, the OPPs swell faster and to a higher degree than CSPs. From the experimental results, although the OPPs have a higher capacity to swell and become distributed, these effects may not be seen in a volumetric proportion of only 25 cm<sup>3</sup> CSPs and 5 cm<sup>3</sup> OPPs or 20 cm<sup>3</sup> CSPs and 10 cm<sup>3</sup> OPPs. Despite this, an equal volumetric ratio of 15 cm<sup>3</sup> OPPs and 15 cm<sup>3</sup> CSPs shows a higher particle distribution and swelling capacity.

The matrix used in a composite acts as a base or parent material to which other reinforcements and fillers may be added. The matrix material often gives the composite its primary properties of brittleness or ductility, strength and hardness. This serves as a basis for adding reinforcing materials to obtain a new material with superior properties to any of its individual constituents. The rheological properties of the matrix are responsible for producing composites with intricate shapes and consistent properties. Additionally,

matrices are known to be hydrophobic (i.e., have poor water absorption), while natural agro-waste fillers are usually hydrophilic (with good water absorption). The inability of a matrix to react with hydrophilic fibre reinforcements leads to poor interface adhesion. This, in return, affects the structural integrity and consistency of the composite. This problem is often solved by surface treatment of the fibres to increase interfacial adhesion.

The average free swell of a particle denotes its rate of water absorption over a period of time. Knowledge of the free swell of particles in water can be used to predict the possible effects that can take place when combined in a composite matrix. For instance, if a reinforcing particle is combined in a matrix that has a viscosity which is 10 times less than of water, then the free swell behaviour of the composite in water will be about 10 times less than the free swell of the particles in water.

Coconut derivatives such as particles, fibres, spathe have been used profitably in composite fabrication with remarkable results. Some of the notable results arising from the use of coconut were discussed by Sarki et al. [33]. They observed that there was good interfacial bonding between the coconut shell particles in an epoxy matrix. They also noted that values of the tensile modulus and tensile strength improved with a higher proportion of coconut shell particles. Kumar et al. [34] also noted that treated coconut sheath fibre composite has superior mechanical strength and thermal stability than an untreated coconut sheath fibre composite.

Other findings include Ali and Chow [35], who found that coconut fibres have the highest toughness among natural fibres. They studied the damping ratio and fundamental frequency of simply supported carbon fibre reinforced (CFRC) beams. The authors concluded that CFRC with added fibre content possessed a higher damping but lower dynamic and static modulus of elasticity. These properties of coconut fibre and particles coupled with the good tensile, bending strength and hardness values was correlated with the use of orange peel particles added to reinforced high density polyethylene (HDPE) composites [36]. Such combined properties make CSPs and OPPs viable reinforcing components in hybrid composites. Investigations on the swelling properties of composites were done by Hassan et al. [37], but literature on the free swell properties of reinforcing materials is scarce. This makes it imperative to study the combined water absorption properties of these two reinforcing materials independently before they are incorporated in any matrix.

#### 4. Sensitivity analysis

Sensitivity analysis will help in identifying the critical variables for performance. In other words, a design engineer seeks to strengthen points of weakness in predicting water absorption parameters. This work further advocates for sensitivity analysis, as it helps in exposing inappropriate computations and thus guides the design engineer to focus on relevant parameters. Sensitivity analysis can be used as a tool of composite design engineers to analyse free swell scenarios, leading to significant insights into the probable value of the free swell index. The principal goal of free swell analysis is to ascertain the responsiveness of  $S_f$  to  $V_i$  and  $V_f$ , which are the principal variables used in its calculation.

Sensitivity analysis done in consideration of three variables,  $V_i$ ,  $V_f$  and  $S_f$ , using the Holtz and Gibbs model to established a simple linear relationship among the three variables. The parameter used to indicate sensitivity is a

percentage since we attempt to simulate free swell. The Holtz and Gibbs' model is expressed as [9]:

$$((V_f - V_i)/V_f)100\% \quad (7)$$

This model is one of the first serves as a reference to evaluate the free swell behaviour of particulates. It has had outstanding success in soil experimental measurements. Two cases were considered in the current study. In the first case,  $V_i$  is varied while  $V_f$  is held constant, while in the second case, both  $V_i$  and  $V_f$  are varied. In both cases, the  $S_f$  is calculated when either or both  $V_i$ , and  $V_f$  are varied from -500 to +500%. For the sensitivity analysis of the higher particulate blend combination, the  $V_i$  of OPP or CSP, as the case may be, drops from 25 to 20, 15 and 10 cm<sup>3</sup> with the corresponding  $V_f$  values remaining constant. For the sensitivity analysis of the lower particulate blend combination, the  $V_i$  increases from 5 to 10, 15 and 20 cm<sup>3</sup> for the OPPs or CSPs as is required, while the respective  $V_f$  values are held constant.

In Tables 3 to 10, the sensitivity analyses are presented. For the higher orange peel particulate blend, where  $V_i$  was varied and  $V_f$  was held constant. For a  $V_i$  of 25 cm<sup>3</sup>, which was varied between -500 - 500% for constant  $V_f$  values ranging from 80 to 95 cm<sup>3</sup>, the 200% increase of  $V_i$  produced  $S_f$  values were suitable for use in light loading of structures according to the Holtz and Gibbs' model. The 0 to -500% decrement and 300 to 500% increase of the  $V_i$  resulted in negative  $S_f$  values, which are not practically obtainable, while the 0 to 100% increase of the  $V_i$  gave high  $S_f$  values that would not be suitable for use according to the Holtz and Gibbs' model. As the  $V_i$  decreases to 20 cm<sup>3</sup>, it is varied from -500 to 500% for constant  $V_f$  values ranging from 70 to 92 cm<sup>3</sup>, new values of  $S_f$  of are obtained. A 200% increase in the  $V_i$  gave much desired  $S_f$  values of the particulate blend suitable for use in light loadings and structures. A 0 to 100% increase in produced  $S_f$  values greater than 100%. Decrementing  $V_i$  from 0 to -500% and incrementing from 300 to 500% resulted in negative  $S_f$  values that are not practically obtainable.

For a  $V_i$  of 15 cm<sup>3</sup> varied from -500 to 500% for constant values of 65, 66, 68, 69, 70, 74, 77 and 78 cm<sup>3</sup>, the trend changed. The resulting  $S_f$  values at a 300% increase in  $V_i$  were found to be less than 50%, which is suitable for use in lightly loaded structures without causing considerable volume change. At 200% increase in  $V_i$  for constant  $V_f$  values ranging from 68 to 78 cm<sup>3</sup>, the  $S_f$  values were found to be slightly higher than 50%. However, the resultant  $S_f$  was below 50% for constant  $V_f$  values of 65 and 66 cm<sup>3</sup>, which makes them suitable according to the Holtz and Gibbs' model. For the volumetric values between 0 to 100%, the obtained  $S_f$  values were found to be greater than 100%, which is not suitable for light loadings and structures. The decrease of  $V_i$  amounted to negative values of  $S_f$ , which are not practically feasible.

Finally, the  $V_i$  reduces to 10 cm<sup>3</sup> and is varied from -500 to 500% at constant values of  $V_f$  producing new values of  $S_f$ . As the  $V_i$  increased between 400 to 500% for constant values of 62, 63, 64, 70 and 74 cm<sup>3</sup>, the values of  $S_f$  were found to be less than 50%, which are suitable for light loadings and structures without significant volume change according to Holtz and Gibbs' model. However, when the  $V_i$  is varied between 0 to 300% at constant  $V_f$  values, the resulting  $S_f$  values were found to be greater than 50%, reaching a peak of 680% at a  $V_f$  value of 78 cm<sup>3</sup>. This high free swell value indicates that an increase in the  $V_i$  values at constant  $V_f$  values

of the particulate blend were not suitable making structures for water-based applications, according to Holtz and Gibbs' model.

A very comprehensive approach to the sensitivity analysis of the parameters of the free swell analysis, viz  $V_i$ ,  $V_f$  and  $S_f$ , was pursued. In this approach, two levels of analysis (i.e.,  $V_i$  varying,  $V_f$  constant with  $S_f$  determined) were evaluated. The analysis then considered the practical data obtained from the OPPs-CSPs mix, one for a situation in which OPPs was in the greater proportion in the mix, i.e., 25:5, 20:10, 15:15 of OPPs to CSPs, and another in which the proportions of CSPs were higher (i.e., 25:5, 20:10, 15:15 of CSPs to OPPs). The aim of the sensitivity analysis was to determine whether  $V_i$ ,  $V_f$  and  $S_f$  are highly sensitive to processing parameters when they are varied. The information obtained here would help in determining which of these measures can be used to obtain an improve water resistance of the samples based.

The uniqueness of the current approach is obvious when the approach is implemented with experimental data obtained from the laboratory through a framework comprising the initial and final  $V_f$ s of solute and solution, as well as an evaluation of the free swell indices. From these results, designers may strategically decide to utilize the particular reinforcing materials in the correct quantities to achieve higher levels of water resistance in composite fabrication, to increase a composite's lifespan and be competitive among alternative composites. The proposed procedure may provide an opportunity for designers to compare the water absorption resistance against other composite reinforcing materials. The industry is looking for composites, made of reinforcing materials that are green and water resistant made from materials of high quality. Designers have the responsibility to satisfy stakeholders' expectations.

## 5. Conclusions

Green composite wastes with metallic fillers are increasingly in demand for environmentally-friendly and cost-effective fabrication. The current study experimentally determined the water absorption of mixed particulate orange peel and coconut shell particulates and did a sensitivity analysis. The following conclusions can be drawn:

### *Water absorption experimental work:*

For the higher-coconut-shell particulate blend,

- The water resistance of the particulate blend improved with an increasing volume and mass of coconut shell particulates.
- The average free swell of the particulate blend

increased with a higher mass of orange peel particulates.

For the higher-orange peels particulate blend, it was observed that:

- The water resistance of the particulate blend declined with an increasing volume of orange peel particulates in the blend.
- The average free swell of a particulate blend reduced with an increasing mass of coconut shell particulate.
- An increase in the mass or volume of the coconut shell particulates did not increase the free swell of either of the particulate blends.
- An increase in the mass or volume of the orange peel particulates was responsible for a higher free swell in both of the particulate blends.

### *Sensitivity analysis work:*

In the higher-OPP blend and higher-CSP blend, free swell values showed that the particulate blends are unsafe for materials with light loadings and structures without experiencing significant volume change or damage since their free swell values are high.

In this work, although extensive analysis has been carried out, the conclusions are limited only to the 30 cm<sup>3</sup> mixture. However, extension of the subject matter may include varying the volume of the solution above 30 cm<sup>3</sup>. Other extensions include the use of saline water from lagoons and rainwater for applications in open spaces. Variations of the mixtures in terms of quantities and the introduction of the third filler may be encouraged in future research. The implications of the findings of this study are practical are multi-dimensional. First, it was established that low cost applications of water resistant structures, such as roofing materials for silos, are possible with an OPP-CSP mixture. This implies that the use of waste as fillers obtainable locally is feasible. The costs associated with indiscriminate dumping of waste OPPs and CSPs could be drastically reduced, thus providing more money for other government programmes.

## 6. Notation

- OPP: Orange peel particles  
 CSP: Coconut shell particles  
 $S_f$ : Free swell index (%)  
 $V_i$ : Initial volume (cm<sup>3</sup>)  
 $V_f$ : Final volume (cm<sup>3</sup>)  
 $V_f/V_i$ : Volumetric ratio of final to initial volume of particulates  
 $S_f/V_i$ : Free swell-initial volume ratio of particulates  
 $M_{esp}$ : Mass of coconut shell particulates (g)  
 $M_{opp}$ : Mass of orange peel particulates (g)

### Module 1 Higher orange peel particulate blend

Description	Details	Remarks
Scenario 1: $S_f$ ( $V_i = 30 \text{ cm}^3$ : OPPs = 25 cm <sup>3</sup> , CSPs = 5cm <sup>3</sup> ) $V_f = 80$ to 95 cm <sup>3</sup>	$S_f$ changes with $V_f \uparrow$ . As $V_f \uparrow$ , $S_f \uparrow$ as the $V_i$ was constant. At $V_f = 80 \text{ cm}^3$ , $S_f = 166.67\%$ . As $V_f \uparrow$ to 86 cm <sup>3</sup> , $S_f = 186.67\%$ .	<i>Note:</i> A new index known as the swelling constant is derived. This is the ratio between the rise in free swell and the rise in $V_f$ . It describes the steady rate at which the swelling proceeds in a particulate blend.
Case 1: ( $V_i$ changing, lowest $V_f$ of 80 cm <sup>3</sup> is held constant)	At 0% increase of the $V_i$ , $S_f = 166.67\%$ . As $V_i \uparrow$ by 100%, $S_f \downarrow$ to 33.33%.	<i>Note:</i> The particulate blend can be used safely to develop lightly loaded structures without suffering considerable damage or volume change. Beyond this, it is unsuitable. A new index, sensitivity range is obtained. The sensitivity range is -200 to 100% of $V_i$ .

## Module 1 Higher orange peel particulate blend (cont.)

Description	Details	Remarks
Case 2: ( $V_i$ changing, highest $V_f$ of 95 cm <sup>3</sup> is held constant)	For 0% increase in $V_i$ , $S_f = 216.67\%$ . As $V_i \uparrow$ by 100%, $S_f$ rate $\downarrow$ to 58.33%. As $V_i \uparrow$ by 200%, $S_f = 5.56\%$ .	Note: The sensitivity range for the particulate blend is -200 to 200%. <i>Decision:</i> The particulate blend cannot be used to develop lightly loaded structures as it is susceptible considerable damage and volume change at $S_f = 216.67\%$ . At $S_f$ rate = 58.33%, a particulate blend may be considered for developing lightly loaded structures with little volume change or damage. At $S_f = 5.56\%$ , the particulate blend can be used safely without experiencing damage or volume change.
Case 3: ( $V_i$ changing, $V_f$ is changing)	Three different pairs of changes exist: (i) A: 20 to 25 cm <sup>3</sup> , (ii) B: 15 to 25 cm <sup>3</sup> and (iii) C: 10 to 25 cm <sup>3</sup> . A new mean average $S_f$ was obtained. The new mean obtained at the 0% change in $V_i$ is taken as the reference value of the pair. Only 100% $V_i \uparrow = 33.7, 19.79$ and 11.54% across pairs A, B and C, respectively.	<i>Note:</i> Only 100% $V_i \uparrow$ has a significant contribution to the new $S_f$ mean across all the pairs.
Scenario 2: $S_f$ ( $V_i = 30$ cm <sup>3</sup> : OPPs = 20 cm <sup>3</sup> , CSPs = 10 cm <sup>3</sup> ) $V_f = 73$ to 92 cm <sup>3</sup> ( $V_i$ is constant, $V_f$ changes), Note: this is a situation where 0% change in $V_i$ is considered)	At 0% $V_i \uparrow$ for all changes in $V_f$ , $S_f$ (using a $V_f$ of 73 cm <sup>3</sup> ) = 143.33%. As $V_f \uparrow$ , $S_f \uparrow$ to a peak at 206.67%.	Note: The particulate blend cannot be used for making lightly loaded structures according to the Holtz and Gibbs' model.
Case 1: ( $V_i$ changing, lowest $V_f$ of 73 cm <sup>3</sup> is held constant)	Combined $V_i$ varies from -500 to 500% while the lowest obtainable $V_f = 73$ cm <sup>3</sup> . The 100% $V_i \uparrow$ produces $S_f = 21.67\%$ . $S_f$ increasingly become negative as $V_i$ rises from 200 to 500%. The negative decrement of $V_i$ also gave negative $S_f$ values.	Note: It is considered safe for making lightly loaded structures without experiencing considerable damage. Values are not feasible and a particulate blend in any of these cases and cannot be considered for use. The sensitivity range of the particulate blend is -200 to 100% variation of $V_i$ .
Case 2: ( $V_i$ changing, highest $V_f$ of 92 cm <sup>3</sup> is held constant)	$S_f = 206.67\%$ at 0% $V_i \uparrow$ . However, as the $V_i$ rises by 100%, a new $S_f$ value of 53.33% was obtained As $V_i \uparrow$ by 200%, $S_f = 2.22\%$ .	Note: The value indicates that the composition of the particulate blend will suffer considerable damage and volume change when utilized in making lightly loaded structures at $S_f = 206.67\%$ but will not at 53.33% and 2.22%.
Case 3: ( $V_i$ changing, $V_f$ is changing)	The average $S_f$ as the $V_f \uparrow$ from 15 to 20 cm <sup>3</sup> and average $S_f$ as the $V_f$ changes from 10 to 20 cm <sup>3</sup> will be pairs A and B respectively. The change in $V_f$ is regarded from the lowest to the highest obtainable values in each of the pairs. Change in $V_f$ for pair A is from 62 to 92 cm <sup>3</sup> , while pair B is from 63 to 92 cm <sup>3</sup> . The comparative percent for the 100% $V_i \uparrow = 16.71\%$ . New $S_f =$ mean for 100% increase of $V_i$ is 16.71%. All other increases and decreases of $V_i$ produced a negative percent to the reference values. This shows that the negative values are insignificant in the new $S_f$ mean. In pair B, the 100% $V_i \uparrow$ was found to give 15.9% of the reference value. The new means obtained at further increases and decreases in $V_i$ were found to be negative. As a result of this, they are not considered to be significant to the new $S_f$ mean that has been obtained.	
Scenario 3: $S_f$ ( $V_i = 30$ cm <sup>3</sup> : OPPs = 15 cm <sup>3</sup> , CSPs = 15 cm <sup>3</sup> ) $V_f = 62$ to 78 cm <sup>3</sup> considering only 0% $V_i$ only.	At $V_f = 56$ cm <sup>3</sup> , $S_f = 86.67\%$ ; As $V_f \uparrow$ , $S_f \uparrow$ and finally, $S_f = 173.33\%$ at $V_f = 83$ cm <sup>3</sup>	<i>Note:</i> All $S_f$ are above safety limits as stated by the Holtz and Gibbs model. <i>Decision:</i> Do not use particulate blend in making structures.
Case 1: ( $V_i$ changing, lowest $V_f$ constant)	A 0% change in $V_f$ gives $S_f = 86.67\%$	<i>Note:</i> Negative $S_f$ obtained are not practical. Sensitivity range is -200 to 0% change in $V_i$ . <i>Decision:</i> Do not use this particulate blend in making structures.
Case 2: ( $V_i$ changing, highest $V_f$ constant)	At 0% change in $V_i$ , $V_f = 173.33\%$ . As $V_i \uparrow$ by 100%, $S_f = 36.67\%$ .	<i>Note:</i> Sensitivity range is -200 to 100%. <i>Decision:</i> Do not use particulate blend in making structures.
Case 3: ( $V_i$ changing, $V_f$ changing)	At 0% change in $V_i$ , $\bar{S}_f = 145\%$ . However, 100% $V_i \uparrow$ comparatively reflects $\bar{S}_f \uparrow$ of 16.22%.	<i>Note:</i> 17.17% of $\bar{S}_f$ (is accounted for) and 83.78% of $\bar{S}_f$ (is unaccounted for)

**Module 1 Higher orange peel particulate blend (cont.)**

Description	Details	Remarks
Scenario 4: $S_f$ (CSPs = 10 cm <sup>3</sup> , OPP=20 cm <sup>3</sup> ; $V_f$ = 73 to 82 cm <sup>3</sup> ). However, 0% $V_i$ is considered, $V_f$ changes	At $V_f$ = 73 cm <sup>3</sup> , $S_f$ = 143.33%. However, $S_f$ ↑ as $V_f$ ↑ and finally, $V_f$ = 206.67%.	<i>Note:</i> All $S_f$ obtained makes the particulate blend unfavourable for making structures according to the Holtz and Gibbs' model.
Case 1: ( $V_i$ changing, lowest $V_f$ constant)	The $S_f$ = 143.33% at 0% change in $V_i$ . As $V_i$ ↑ by 100%, $S_f$ = 21.67%.	<i>Note:</i> Up to $S_f$ = 21.67%, it is suitable for loadings without risk of damage. Beyond this, it is unsuitable. The sensitivity range is from -200 to 100% change in $V_i$ .
Case 2: ( $V_i$ changing, highest $V_f$ constant)	$AV_f$ of 92 cm <sup>3</sup> is kept constant as the $V_i$ ↑ from -500 to 500%. $S_f$ = 206.67% at $V_i$ ↑ by 0%. As the $V_i$ ↑ by 100%, $S_f$ = 53.33%. Other changes in $V_i$ resulted in negative $S_f$ that are not practically obtainable. The sensitivity range is -200 to 200% change in $V_i$ .	<i>Note:</i> At $V_i$ ↑ by 200%, $S_f$ = 2.22% for production without risk of damage. <i>Decision:</i> Consider particulate blend for making lightly loaded structures even though it is 3.33% above the safety limits
Scenario 3: $S_f$ ( $V_i$ = 30 cm <sup>3</sup> : OPPs = 15 cm <sup>3</sup> , CSPs = 15 cm <sup>3</sup> ) $V_f$ = 62 to 78 cm <sup>3</sup> considering only 0% $V_i$ only.		
Case 1: ( $V_i$ changing, lowest $V_f$ of 62 cm <sup>3</sup> is held constant)	$V_i$ = 30 cm <sup>3</sup> varies from -500 to 500% while $V_f$ = 62 cm <sup>3</sup> . A $S_f$ = 106.67% at 0% $V_i$ ↑. As $V_i$ ↑ by 100%, $S_f$ drops to 3.33%. As the $V_i$ is increased further, by 200 to 500%, the obtained $S_f$ ↑ negatively.	<i>Note:</i> The particulate blend can be used safely in making lightly loaded structures without risk of considerable damage or volume change. The sensitivity range is -200 to 100% change in $V_i$ .
Case 2: ( $V_i$ changing, highest $V_f$ of 92 cm <sup>3</sup> is held constant)	The combined $V_i$ of the particulates of 30 cm <sup>3</sup> is allowed to vary from -500 to 500%, while the highest obtainable $V_f$ value of 78 cm <sup>3</sup> remains unchanged. As expected, the $S_f$ value of 160% the particulate blend obtained at 0% $V_i$ ↑ is susceptible to damage when used in fabricating light loadings and structures. However, as the $V_i$ ↑ by 100%, $S_f$ = 30%. As $V_i$ ↑ further, $S_f$ became negative, the ↓ in $V_i$ also gave negative values which are not practically obtainable.	<i>Note:</i> The $S_f$ = 30% is within safety limits. Furthermore, the particulate blend in any of these conditions is not safe for practical use.
Case 3: ( $V_i$ changing, $V_f$ is changing)	Only one pair of $V_i$ change is possible, which is the change from 10 to 15 cm <sup>3</sup> , while the $V_f$ changes from the lowest available of 63 cm <sup>3</sup> to the highest obtainable value of 78 cm <sup>3</sup> . A new set of mean $S_f$ for the pair was calculated. The mean $S_f$ for 0% change in $V_i$ is 129.40% and is the reference value. In this pair, only a 100% increase in $V_i$ gave a positive 11.36%. All other increases and decrements of $V_i$ resulted in negative values. This indicates that only the 100% increase of $V_i$ is relevant in the new calculated $S_f$ mean.	
Scenario 4: $S_f$ ( $V_i$ = 30 cm <sup>3</sup> : OPPs = 10 cm <sup>3</sup> , CSPs = 20 cm <sup>3</sup> ) $V_f$ = 63 to 74 cm <sup>3</sup> considering only 0% $V_i$ only.		
Case 1: ( $V_i$ changing, lowest $V_f$ of 63 cm <sup>3</sup> is held constant)	The lowest obtainable value of $V_f$ is kept constant, while the $V_i$ is varied from -500 to 500% in order to see how they affect the free swell output. At 0% change in $V_i$ , $S_f$ = 110%. However, as the $V_i$ ↑ by 100%, a free swell of 5% was produced. As the $V_i$ ↑ further, $S_f$ ↑ negatively. The $V_i$ ↓ produced negative values which peaked of 310% at -200% $V_i$ ↓.	<i>Note:</i> The particulate blend is not safe for fabricating lightly loaded structures. The sensitivity range of the particulate blend -200 to 100% change in $V_i$ .
Case 2: ( $V_i$ changing, highest $V_f$ of 74 cm <sup>3</sup> is held constant)	In case 2 of scenario 4, the highest obtainable value of 74 cm <sup>3</sup> is unchanged, while the $V_i$ is varied from -500 to 500%. For a 0% increase of $V_i$ , a free swell of 146.67% was obtained. This value makes the particulate blend unsuitable for lightly loaded structures. As the $V_i$ was increased by 100, the $S_f$ = 23.33%, which is within the safety limits. The sensitivity range for the particulate blend in case 2 of scenario 4 is -200 to 100% change in $V_i$ .	<i>Note:</i> The particulate blend is suitable for making lightly loaded structures without any susceptibility to damage or volume change.

**Module 2 Higher coconut shell/orange peels particulate blend (high CSPs: low OPPs)**

Description	Details	Remarks
Scenario 1: $S_f$ (CSPs = 25 cm <sup>3</sup> , OPP=5 cm <sup>3</sup> ; $V_f$ = 53 to 63 cm <sup>3</sup> ) <i>Note:</i> 0% $V_i$ is considered, $V_f$ changes		

**Module 2** Higher coconut shell/orange peels particulate blend (high CSPs: low OPPs) (cont.)

Description	Details	Remarks
Case 1: ( $V_i$ changing, lowest $V_f$ constant)	The combined $V_i$ of the particulate blend is varied from -500 to 500% while the lowest obtainable $V_f$ of 53 cm <sup>3</sup> is kept constant. At 0% change in $V_i$ , the free swell was obtained as 76.67%. This value makes the particulate blend unsafe for making composites for use in lightly loaded structures. As the $V_i$ was increased by 100 to 500%, negative values of free swell were obtained. The -100 to -500% decrement of the $V_i$ produced zero and negative values.	Note: These negative values portends that the particulate blends described in any of these cases cannot be used in lightly loaded structures because their free swell values are not practically obtainable. The sensitivity range is -200 to 0% $V_i$ ↑.
Case 2: ( $V_i$ changing, highest $V_f$ constant)	The combined $V_i$ of the particulate blend is allowed to change from -500 to 500% while keeping the highest obtainable $V_f$ of 63 cm <sup>3</sup> constant. A free swell of 110% is obtained when there is a 0% change in $V_i$ . As the $V_i$ ↑ by 100%, $S_f = 5\%$ .	Note: This is above the safety limits described by the Holtz and Gibbs' model making the particulate blend unsafe for use in lightly loaded structures. The $S_f = 5\%$ is favourable in fabricating composites for use in lightly loaded structures without suffering damage. Further increases and decreases in $V_i$ produces negative free swell values that are not obtainable in practice. Thus, it makes the particulate blend unusable for fabricating lightly loaded structures. The sensitivity range is -200 to 100% change in $V_i$ .
Case 3: ( $V_i$ changing, $V_f$ changing)	The change in $V_f$ for pair A is from 53 to 64, while the changes in $V_f$ for pairs B and C are from 53 to 82 $V_f$ and 53 to 92 $V_f$ respectively. A new mean is calculated from the average free swell values in the pairs and the value obtained at 0% change in $V_i$ is the reference value. The comparative percent is obtained finding the % contribution of the new mean to the reference value. Across all the pairs, only the 100% change had positive comparative percent values of 2.16, 5.46 and 12.11%, respectively. The balance of 97.84, 94.54 and 86.92% in pairs A, B and C is not relevant in the new $S_f$ mean that was obtained..	
Scenario 2: $S_f$ (CSPs = 20 cm <sup>3</sup> , OPP=10 cm <sup>3</sup> ; $V_f$ = 58 to 64 cm <sup>3</sup> ) Note: 0% $V_i$ is considered, $V_f$ changes		
Case 1: ( $V_i$ changing, lowest $V_f$ constant)	The 0% change in $V_i$ produces a free swell of 93.33%. As the $V_i$ is varied from by -500 to 500%, the free swell values became negative.	Note: The negative free swell values are not practically obtainable, which implies that the particulate blend in any of these cases cannot be used in lightly loaded structures without failure. The sensitivity range is between -200 to 0% $V_i$ ↑.
Case 2: ( $V_i$ changing, highest $V_f$ constant)	At 0% change in $V_i$ , a free swell of 113.33% was obtained. However, a 100% increase in the $V_i$ of the particulate blend gives a free swell of 6.67%. Further increase and decrease in $V_i$ produces negative free swell values that are not obtainable.	Note: The particulate blend in any of these cases cannot be used in fabricating lightly loaded structures without experiencing severe damage. The sensitivity range for case 2 of scenario 2 is given as -200 to 100% change in $V_i$ . The particulate blend is safe for manufacturing lightly loaded structures without the risk of volume change or structural damage as $S_f = 6.67\%$ .
Case 3: ( $V_i$ changing, $V_f$ changing)	The changes are 15 to 20 cm <sup>3</sup> (pair A) and 10 to 20 cm <sup>3</sup> (pair B), respectively. The changes in $V_f$ in pairs A and B are given as 56 to 82 cm <sup>3</sup> and 58 to 92 cm <sup>3</sup> , respectively. In pair A, only the 100% $V_i$ ↑ produced + 8.54%. Therefore, in the new mean obtained at 0% $V_i$ ↑, only 8.54% of it is relevant throughout the changes of $V_f$ . The 91.46% is irrelevant. In pair B, the 100% increase results in + 14.37% of the reference value. The 85.63% value is irrelevant.	

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**8. Appendix**

**Table 3** Sensitivity analysis of a particulate blend varying  $V_i = 30 \text{ cm}^3$  only, OPP= 25,20,15 or 10  $\text{cm}^3$  and CSP= 5,10,15 or 20  $\text{cm}^3$

Free swell index	Vi decreased by					Vi increased by					
	-500%	-400%	-300%	-200%	-100%	0%	100%	200%	300%	400%	500%
Mean $S_f$ (Scenario 1)	-174.54	-199.38	-249.07	-398.15	0	198.15	49.07	-0.62	-25.46	-40.37	-50.31
Mean $S_f$ (Scenario 2)	-166.85	-189.13	-233.7	-367.41	0	167.41	33.7	-7.90	-33.15	-46.52	-55.43
Mean $S_f$ (Scenario 3)	-158.24	-177.66	-216.48	-332.96	0	132.96	16.48	-22.34	-41.76	-53.41	-61.17
Mean $S_f$ (Scenario 4)	-156.46	-175.28	-212.92	-325.83	0	125.83	12.92	-24.72	-43.54	-54.83	-62.36

**Table 4** Sensitivity analysis of a particulate blend varying  $V_i = 30 \text{ cm}^3$  only, CSP = 25,20,15 or 10  $\text{cm}^3$  and OPP = 5,10,15 or 20  $\text{cm}^3$

Free swell index	Vi decreased by					Vi increased by					
	-500%	-400%	-300%	-200%	-100%	0%	100%	200%	300%	400%	500%
Mean $S_f$ (Scenario 1)	-149.05	-165.4	-198.09	-296.19	0	96.19	-1.91	-34.6	-50.95	-60.76	-67.3
Mean $S_f$ (Scenario 2)	-150.83	-167.78	-201.67	-303.33	0	103.33	1.67	-32.22	-49.17	-59.33	-66.11
Mean $S_f$ (Scenario 3)	-157.08	-176.11	-214.17	-328.33	0	128.33	14.17	-23.89	-42.92	-54.34	-61.94
Mean $S_f$ (Scenario 4)	-167.81	-188.73	-235.63	-371.25	0	161.67	35.63	-11.27	-32.19	-45.75	-40.9

**Table 5a** Case 3 for Scenario 1, Module 1 Pair A:  $V_i = 20 \text{ to } 25 \text{ cm}^3$ ,  $V_f = 73 \text{ to } 95 \text{ cm}^3$

Average $S_f$	-174.54	-199.38	-249.07	-398.15	0	198.15	49.07	-0.62	-25.46	-40.37	-50.31
Average $S_f$	-166.85	-189.13	-233.7	-367.41	0	167.41	33.7	-7.90	-33.15	-46.52	-55.43
New $S_f$ mean	-170.69	-194.26	-241.39	-382.78	0	182.78	41.39	-4.26	-29.3	-43.45	-52.87
Comparative %	-93.39	-106.28	-132.07	-209.42	0	100	22.64	-2.33	-16.03	-23.77	-28.93

**Table 5b** Case 3 for Scenario 1, Module 1 Pair B:  $V_i = 15 \text{ to } 25 \text{ cm}^3$ ,  $V_f = 62 \text{ to } 95 \text{ cm}^3$

Average $S_f$	-158.24	-177.66	-216.48	-332.96	0	132.96	16.48	-22.34	-41.76	-53.41	-61.17
Average $S_f$	-174.54	-199.38	-249.07	-398.15	0	198.15	49.07	-0.62	-25.46	-40.37	-50.31
New $S_f$ mean	-166.39	-188.52	-232.76	-365.56	0	165.56	32.78	-11.48	-33.61	-46.89	-55.74
Comparative %	-100.5	-113.87	-140.59	-220.8	0	100	19.79	-6.93	-20.3	-28.32	-33.67

**Table 5c** Case 3 for Scenario 1, Module 1 Pair C:  $V_i = 10 \text{ to } 25 \text{ cm}^3$ ,  $V_f = 63 \text{ to } 95 \text{ cm}^3$

Average $S_f$	-156.46	-175.28	-212.92	-325.83	0	12.92	-24.72	-43.54	-54.83	-62.36	-156.46
Average $S_f$	-174.54	-199.38	-249.07	-398.15	0	198.15	49.07	-0.62	-25.46	-40.37	-50.31
New $S_f$ mean	-165.5	-187.33	-230.99	-361.99	0	105.54	12.18	-22.08	-40.15	-51.37	-103.39
Comparative %	-156.81	-177.5	-218.87	-342.99	0	100	11.54	-20.92	-38.04	-48.67	-97.96

**Table 6a** Case 3 for Scenario 2, Module 1, Pair A:  $V_i = 15 \text{ to } 20 \text{ cm}^3$ ,  $V_f = 62 \text{ to } 92 \text{ cm}^3$

Average $S_f$	-158.24	-177.66	-216.48	-332.96	0	132.96	16.48	-22.34	-41.76	-53.41	-61.17
Average $S_f$	-166.85	-189.13	-233.7	-367.41	0	167.41	33.7	-7.90	-33.15	-46.52	-55.43
New $S_f$ mean	-162.55	-183.40	-225.09	-350.19	0	150.19	25.09	-15.12	-37.46	-49.97	-58.3
Comparative %	-108.23	-122.11	-149.87	-233.17	0	100	16.71	-10.07	-24.94	-33.27	-38.82

**Table 6b** Case 3 for Scenario 2, Module 1, Pair B:  $V_i = 10 \text{ to } 20 \text{ cm}^3$ ,  $V_f = 63 \text{ to } 92 \text{ cm}^3$

Average $S_f$	-156.46	-175.28	-212.92	-325.83	0	125.83	12.92	-24.72	-43.54	-54.83	-62.36
Average $S_f$	-166.85	-189.13	-233.7	-367.41	0	167.41	33.7	-7.90	-33.15	-46.52	-55.43
New $S_f$ mean	-161.66	-182.20	-223.31	-346.62	0	146.62	23.31	-16.31	-38.35	-50.68	-58.90
Comparative %	-110.26	-124.27	-152.31	-236.41	0	100	15.9	-11.12	-26.16	-34.56	-40.17

**Table 7** Case 3 for Scenario 3, Module 1, Pair A:  $V_i = 10$  to  $15 \text{ cm}^3$ ,  $V_f = 63$  to  $78 \text{ cm}^3$ 

<i>Average <math>S_f</math></i>	-156.46	-175.28	-212.92	-325.83	0	125.83	12.92	-24.72	-43.54	-54.83	-62.36
<i>Average <math>S_f</math></i>	-158.24	-177.66	-216.48	-332.96	0	132.96	16.48	-22.34	-41.76	-53.41	-61.17
<i>New <math>S_f</math> mean</i>	-157.35	-176.47	-214.70	-329.40	0	129.40	14.70	-23.53	-42.65	-54.12	-61.76
<i>Comparative %</i>	-121.6	-136.38	-165.92	-254.56	0	100	11.36	-18.18	-32.96	-41.82	-47.73

**Table 8a** Case 3 for Scenario 1, Module 2, Pair A:  $V_i = 20$  to  $25 \text{ cm}^3$ ,  $V_f = 53$  to  $64 \text{ cm}^3$ 

<i>Mean <math>S_f</math></i>	-149.05	-165.4	-198.09	-296.19	0	96.19	-1.91	-34.6	-50.95	-60.76	-67.3
<i>Mean <math>S_f</math></i>	-153.2	-170.95	-206.43	-312.86	0	112.86	6.43	-29.05	-46.79	-57.43	-64.52
<i>New <math>S_f</math> mean</i>	-151.13	-168.18	-202.26	-304.52	0	104.52	2.26	-31.83	-48.87	-59.10	-65.91
<i>Comparative %</i>	-144.59	-160.91	-193.51	-291.35	0	100	2.16	-30.45	-46.76	-56.53	-63.06

**Table 8b** Case 3 for Scenario 1, Module 2, Pair B:  $V_i = 15$  to  $25 \text{ cm}^3$ ,  $V_f = 53$  to  $82 \text{ cm}^3$ 

<i>Mean <math>S_f</math></i>	-149.05	-165.4	-198.09	-296.19	0	96.19	-1.91	-34.6	-50.95	-60.76	-67.3
<i>Average <math>S_f</math></i>	-157.08	-176.11	-214.17	-328.33	0	128.33	14.17	-23.89	-42.92	-54.34	-61.94
<i>New <math>S_f</math> mean</i>	-153.07	-170.75	-206.13	-312.26	0	112.26	6.13	-29.25	-46.94	-57.55	-64.62
<i>Comparative %</i>	-136.35	-152.1	-183.62	-278.16	0	100	5.46	-26.05	-41.8	-51.26	-57.56

**Table 8c** Case 3 for Scenario 1, Module 2, Pair C:  $V_i = 10$  to  $25 \text{ cm}^3$ ,  $V_f = 53$  to  $92 \text{ cm}^3$ 

<i>Average <math>S_f</math></i>	-149.05	-165.4	-198.09	-296.19	0	96.19	-1.91	-34.6	-50.95	-60.76	-67.3
<i>Average <math>S_f</math></i>	-166.94	-189.26	-233.89	-367.78	0	167.78	33.89	-10.74	-33.06	-46.44	-43.02
<i>New <math>S_f</math> mean</i>	-158.0	-177.33	-215.99	-331.98	0	131.98	15.99	-22.67	-42.00	-53.60	-55.16
<i>Comparative %</i>	-119.7	-134.36	-163.65	-251.54	0	100	12.11	-17.17	-31.82	-40.61	-41.79

**Table 9a** Case 3 for Scenario 2, Module 2, Pair A:  $V_i = 15$  to  $20 \text{ cm}^3$ ,  $V_f = 56$  to  $82 \text{ cm}^3$ 

<i>Average <math>S_f</math></i>	-153.2	-170.95	-206.43	-312.86	0	112.86	6.43	-29.05	-46.79	-57.43	-64.52
<i>Average <math>S_f</math></i>	-157.08	-176.11	-214.17	-328.33	0	128.33	14.17	-23.89	-42.92	-54.34	-61.94
<i>New <math>S_f</math> mean</i>	-155.14	-173.53	-210.30	-320.6	0	120.60	10.30	-26.47	-44.86	-55.88	-63.23
<i>Comparative %</i>	-128.65	-143.9	-174.39	-265.86	0	100	8.54	-21.95	-37.19	-46.33	-52.43

**Table 9b** Case 3 for Scenario 2, Module 2, Pair B:  $V_i = 10$  to  $20 \text{ cm}^3$ ,  $V_f = 58$  to  $92 \text{ cm}^3$ 

<i>Average <math>S_f</math></i>	-153.2	-170.95	-206.43	-312.86	0	112.86	6.43	-29.05	-46.79	-57.43	-64.52
<i>Average <math>S_f</math></i>	-166.94	-189.26	-233.89	-367.78	0	167.78	33.89	-10.74	-33.06	-46.44	-43.02
<i>New <math>S_f</math> mean</i>	-160.07	-180.11	-220.16	-340.32	0	140.32	20.16	-19.89	-39.92	-51.94	-53.77
<i>Comparative %</i>	-160.07	-128.37	-156.9	-242.55	0	100	14.37	-14.18	-28.45	-37.02	-53.77

**Table 10** Case 3 for Scenario 3, Module 2, Pair A:  $V_i = 10$  to  $15 \text{ cm}^3$ ,  $V_f = 56$  to  $92 \text{ cm}^3$ 

<i>Mean <math>S_f</math></i>	-157.08	-176.11	-214.17	-328.33	0	128.33	14.17	-23.89	-42.92	-54.34	-61.94
<i>Average <math>S_f</math></i>	-166.94	-189.26	-233.89	-367.78	0	167.78	33.89	-10.74	-33.06	-46.44	-43.02
<i>New <math>S_f</math> mean</i>	-162.01	-182.69	-224.03	-348.06	0	148.06	24.03	-17.32	-37.99	-50.39	-52.48
<i>Comparative %</i>	-109.42	-123.39	-151.31	-235.08	0	100	16.22	-11.7	-25.66	-34.03	-35.44