CHAPTER 5

DEVELOPMENT OF COIR FIBRE REINFORCED RECYCLED PAPER PULP COMPOSITES AND THEIR PROPERTIES

5.1 INTRODUCTION

This chapter presents investigation conducted on the development of coir fibre reinforced paper pulp biocomposites. The investigations focus on parameters, mainly, fiber length, fibre volume fraction and composite thickness those affect properties of the biocomposites. Regression models, using Box and Behnken experimental design, have been developed to predict acoustic performance of the biocomposite along with the analysis of these parameters.

5.2 PREPARATION OF BANANA FIBRE REINFORCED PAPER PULP BIOCOMPOSITES

Coir-fibre reinforced paper pulp matrix biocomposite blocks of 30 cm$^2$ with varying thicknesses (2, 4 and 6 cm) were prepared. Samples with average cut fibre lengths (1.5 cm, 2.5 cm and 3.5 cm) and fibre volume fractions (0.15, 0.20 & 0.25) were manufactured (Table 3.4).

The biocomposites preparation procedure has already been given in chapter-4. Physical and mechanical properties were measured according to the relevant standards (as given in section 3.4 and 3.5).
5.3 FACTORS INFLUENCING NRC OF BIOCOMPOSITE BLOCKS

5.3.1 Influence of Fibre Cut Length

Figure 5.1 shows the effect of cut length of the fibres on NRC with respect to thickness of the composites. With the increases in cut length of the fibres, NRC increases linearly and then achieves the maximum (0.56) at 3.5 cm with 6 cm thickness of the biocomposites. Higher fibre volume fraction and cut length give better sound absorbency due to better pores and higher number of fibre to fibre contact points (Jayaraman 2005, Hoda 2009 and Jorge et al 2010). The minimum (0.40) and maximum (0.56) NRC is achieved in 1.5 cm and 3.5 cm fibre cut length at 2 cm and 6 cm thickness of the biocomposites with $V_f$ of 0.20 respectively.

![Figure 5.1 Effect of fibre cut length on NRC with composite thickness](image-url)
5.3.2 Influence of Fibre Volume Fraction (\(V_f\))

Figure 5.2 shows the effect of fibre volume fraction (\(V_f\)) on NRC with respect to fibre cut length of the biocomposites. The increase \(V_f\) practically increases the number of fibres per unit area, resulting in the increase in porosity of the biocomposite and increase in compactness of the structure. According to figure 5.2, with the increase in \(V_f\), NRC increases linearly, except sample number S10 due to lower thickness (2 cm) of the biocomposites. The maximum NRC is achieved at \(V_f\) of 0.20, same as that of banana fibre reinforced biocomposite with same porosity of 0.80. The experimental study is in consonance with the previous research in terms of higher \(V_f\) (Hoda 2009, Jorge et al. 2010).

![Figure 5.2 Effect of fibre volume fraction on NRC with fibre cut length](attachment:image.png)
5.3.3 Influence of Biocomposite Thickness

Figure 5.3 shows the effect of composite thickness on NRC with respect to $V_f$. As composite thickness increases in the range of 2 cm to 6 cm, the NRC steadily increases (Jayaraman 2005, Hoda 2009). At the same fibre volume fraction (0.20), the NRC increases with the increase in thickness of the composites. Figure 5.3 shows that with the increase in composite thickness, NRC increases. The maximum NRC is observed at a composite thickness of 6 cm. Jayaraman (2005) proved that the sound absorption coefficient of nonwoven composite increases with material thickness increasing and this relationship is more distinct for low (125-500 Hz), mid (1000-2000 Hz) and higher (2000-8000 Hz) frequencies. The experimental results show that the NRC of the biocomposites correlated with above mentioned study in terms of thickness.

![Image of Figure 5.3 showing the effect of composite thickness on NRC with fibre volume fraction.](image-url)

**Figure 5.3** Effect of composite thickness on NRC with fibre volume fraction
5.3.4 Influence of Biocomposite Porosity

Considering that the bulk density has a significant influence on porosity, the maximum NRC is occurring at porosity of 0.80 and 0.79, at bulk density of 160 and 158 kg/cm$^3$ respectively, and beyond that point NRC decreases. The above statement is in agreement with the results of an earlier study (Glé et al 2011 & Shoshani and Yakubov 2001) as discussed in section 4.3.4 (Figure 5.4 and Table 5.1).

![Figure 5.4 Effect of bulk density on NRC with porosity](image)

5.3.5 Influence of the Biocomposites Density

According to the above analysis NRCs is related to fibre cut length, fibre volume fraction and composite thickness, but they were considered separately. Even though lower fibre length, thickness and fibre volume fraction of the composites (S11, S12, S13, S14 & S15; S3, & S15 and S11&
S7 respectively) show higher NRC, samples with higher cut fibre length, higher thickness and higher fibre volume fraction of the composites (S3, S2, and S10) showed lower NRC, which is counter intuitive. The reason for this seemingly anomalous pattern is explained by the fact that the NRC is dependent on the interaction between these three parameters. The bulk density of the samples with higher cut fibre length, higher thickness and higher fibre volume fraction went beyond the threshold limit of 160Kg/m³, as shown in the table 5.1.

The above hypothesis is supported in a previous study that stated that (Hoda 2009, Young et al. 2007, Teli et al. 2007) the number of fibres per unit area increases when the apparent density is high. This increase in bulk density manifests itself as decreased porosity. Porosity has an optimum level, beyond or below which, NRC drops. This means, there should be enough pores on the surface of the material for the sound to pass through and get dampened. Results indicate that a composite bulk density of about 160 kg/m³ gives better NRC (0.56) averaged throughout the range of frequencies 250 Hz to 4000 Hz.

5.4 SOUND ABSORPTION COEFFICIENT OF VARIOUS BIOCOMPOSITES

This section presents a summary of the variables that have been taken into account in this study: density, porosity and thickness that are likely to influence the acoustic performance of sound absorptive materials. The above said parameters of the composite are directly related to the fibre volume fraction, cut length and composites thickness. Higher fibre volume fraction and cut length of the fibre yield more fibres per unit weight of the composite and greater possibilities for a sound wave to interact with the fibres in the composite structure. Figure 5.5 clearly show the difference in sound absorption coefficients (α) with various compositions of composite. The
sound absorption coefficient ($\alpha$) increased as the sound frequency increased for all the composites. This result was the same as that of conventional fibre fabrics (Kuku et al. 2012, Elammaran & Sinin 2013).
Table 5.1 Physical, mechanical and NRC of biocomposite blocks (coir fibre based)

<table>
<thead>
<tr>
<th>Sample code</th>
<th>Average cut length cm (X₁)</th>
<th>Average Composite thickness cm (X₂)</th>
<th>Fibre Volume fraction (X₃)</th>
<th>Experimental values (y₁)</th>
<th>Predicted values (y)</th>
<th>Residual values ŷ = (y₁-y)</th>
<th>Bulk density kg/m³</th>
<th>Absolute Density kg/m³</th>
<th>Porosity (H)</th>
<th>Bending Strength (N/mm²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>S1</td>
<td>1.5</td>
<td>2</td>
<td>0.20</td>
<td>0.40</td>
<td>0.40</td>
<td>0.000</td>
<td>150</td>
<td>800</td>
<td>0.81</td>
<td>0.510</td>
</tr>
<tr>
<td>S2</td>
<td>1.5</td>
<td>6</td>
<td>0.20</td>
<td>0.47</td>
<td>0.49</td>
<td>-0.020</td>
<td>161</td>
<td>800</td>
<td>0.80</td>
<td>0.651</td>
</tr>
<tr>
<td>S3</td>
<td>3.5</td>
<td>2</td>
<td>0.20</td>
<td>0.46</td>
<td>0.46</td>
<td>0.000</td>
<td>151</td>
<td>800</td>
<td>0.81</td>
<td>0.502</td>
</tr>
<tr>
<td>S4</td>
<td>3.5</td>
<td>6</td>
<td>0.20</td>
<td>0.56</td>
<td>0.55</td>
<td>0.010</td>
<td>160</td>
<td>800</td>
<td>0.80</td>
<td>0.695</td>
</tr>
<tr>
<td>S5</td>
<td>1.5</td>
<td>4</td>
<td>0.15</td>
<td>0.45</td>
<td>0.44</td>
<td>0.010</td>
<td>156</td>
<td>763</td>
<td>0.80</td>
<td>0.553</td>
</tr>
<tr>
<td>S6</td>
<td>1.5</td>
<td>4</td>
<td>0.25</td>
<td>0.46</td>
<td>0.45</td>
<td>0.010</td>
<td>162</td>
<td>838</td>
<td>0.81</td>
<td>0.579</td>
</tr>
<tr>
<td>S7</td>
<td>3.5</td>
<td>4</td>
<td>0.15</td>
<td>0.50</td>
<td>0.50</td>
<td>0.000</td>
<td>157</td>
<td>763</td>
<td>0.79</td>
<td>0.562</td>
</tr>
<tr>
<td>S8</td>
<td>3.5</td>
<td>4</td>
<td>0.25</td>
<td>0.49</td>
<td>0.51</td>
<td>-0.020</td>
<td>164</td>
<td>838</td>
<td>0.80</td>
<td>0.596</td>
</tr>
<tr>
<td>S9</td>
<td>2.5</td>
<td>2</td>
<td>0.15</td>
<td>0.43</td>
<td>0.43</td>
<td>0.000</td>
<td>145</td>
<td>763</td>
<td>0.81</td>
<td>0.536</td>
</tr>
<tr>
<td>S10</td>
<td>2.5</td>
<td>2</td>
<td>0.25</td>
<td>0.44</td>
<td>0.44</td>
<td>0.000</td>
<td>152</td>
<td>838</td>
<td>0.82</td>
<td>0.496</td>
</tr>
<tr>
<td>S11</td>
<td>2.5</td>
<td>6</td>
<td>0.15</td>
<td>0.51</td>
<td>0.51</td>
<td>0.000</td>
<td>158</td>
<td>763</td>
<td>0.79</td>
<td>0.653</td>
</tr>
<tr>
<td>S12</td>
<td>2.5</td>
<td>6</td>
<td>0.25</td>
<td>0.53</td>
<td>0.52</td>
<td>0.010</td>
<td>164</td>
<td>838</td>
<td>0.80</td>
<td>0.667</td>
</tr>
<tr>
<td>S13</td>
<td>2.5</td>
<td>4</td>
<td>0.20</td>
<td>0.48</td>
<td>0.48</td>
<td>0.000</td>
<td>156</td>
<td>800</td>
<td>0.81</td>
<td>0.590</td>
</tr>
<tr>
<td>S14</td>
<td>2.5</td>
<td>4</td>
<td>0.20</td>
<td>0.47</td>
<td>0.48</td>
<td>-0.010</td>
<td>154</td>
<td>800</td>
<td>0.81</td>
<td>0.522</td>
</tr>
<tr>
<td>S15</td>
<td>2.5</td>
<td>4</td>
<td>0.20</td>
<td>0.49</td>
<td>0.48</td>
<td>0.010</td>
<td>156</td>
<td>800</td>
<td>0.81</td>
<td>0.586</td>
</tr>
</tbody>
</table>
5.5 BENDING STRENGTH ANALYSIS

The measured value of bending strength is plotted against block density for various parameter combinations such as fibre length, fibre content and composite thickness in figure 5.6 and table 5.1 respectively.

However, the maximum bending strength was observed with the sample number S4 with the fibres cut length of 3.5 cm at 6 cm thickness. This is due to that the better adhesion between coir fibres and recycled paper pulp. Therefore, it was concluded that the optimum fibre length was 3.5 cm with 0.20 fibre volume fraction at 6 cm thickness. The coir fibre and recycled paper pulp composite boards had better flexural properties.
Figure 5.6  Effect of NRC on composite bulk density with bending strength

Sample code S4, S12, S11 and S2 have better bending strength (0.695 N/mm$^2$, 0.667 N/mm$^2$, 0.653 N/mm$^2$ 0.651 N/mm$^2$ respectively) at bulk density (160 kg/m$^3$, 164 kg/m$^3$, 158 kg/m$^3$, 161 kg/m$^3$ respectively) among the combinations. There is a direct correlation between bulk density and bending strength. However, it must be noted from the previous results that increasing the bulk density beyond a certain point, will reduce the NRC. This point may be considered for efficient construction in preference to materials with otherwise identical parameters.

The composite blocks are used as construction material for sound control in buildings. The bending strength and sound absorption is increased when the fibre length and content were increased (Lou & Chou 1992, Pilato & Michno 1994, TIFAC 2014, Gupta 1998, Faruk et al. 2010, Peters 1998, Agarwal an Broutman 1990, Pigott 1980, IPMA 2014, Bledzki & Gassan
The higher thickness (6 cm) of the porous surface has a large effect on sound absorption in terms of frequency. Generally, the thicker the porous surface the better the sound absorption in lower frequency range (250-1000 Hz).

5.6 REGRESSION ANALYSIS

Table 5.1 shows the values of sound reduction level obtained from the testing. To establish the relationships between the independent and the dependent variables, regression analysis is done. The regression coefficients ($\beta_0: 0.304, \beta_1: 0.0288, \beta_2: 0.0212, \beta_3: 0.0750$) are used in the equation (5.1) for the determination of predicted response values. The correlation coefficients between the observed values and the predicted values by proposed model show a very good correlation of coefficient 0.93. This indicates that observed values of the coir reinforced biocomposites has a real degree of association with the predicted values of the composite blocks. The effects of variables or interaction of variables on NRC can effectively be interpreted and explained by regression coefficients along with 3D mesh Figures 5.1-5.6. The information available from regression model and 3D mesh figures regarding the interactions of parameters on NRC behavior is very useful to design a coir fibre reinforced recycled paper pulp composite for sound control applications. The mathematical model is given below:

$$NRC \ (y) = 0.304 + (0.0288 \times X_1) + (0.0212 \times X_2) + (0.0750 \times X_3) \quad (5.1)$$

5.7 ANALYSIS OF VARIANCE

The analysis of variance is summarized in Table 5.2. Since $F = 56.059 > f_{0.05, (3, 11)} = 3.59$ (the P-value is <0.001) we conclude that the various parameters in the coir fibre and paper pulp significantly affects the
NRC of the composites. In addition the p-value is considerably smaller than $\alpha = 0.05$.

Table 5.2 ANOVA of the proposed model (coir fibre based biocomposites)

<table>
<thead>
<tr>
<th>Source of Variation</th>
<th>DF*</th>
<th>SS*</th>
<th>MS*</th>
<th>F</th>
<th>P</th>
</tr>
</thead>
<tbody>
<tr>
<td>Regression</td>
<td>3</td>
<td>0.0212</td>
<td>0.00706</td>
<td>56.059</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>Residual</td>
<td>11</td>
<td>0.00139</td>
<td>0.000126</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>14</td>
<td>0.0226</td>
<td>0.00161</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*DF – Degree of freedom; SS – Sum square; and MS – Mean square

5.8 CONFIRMATION OF THE PROPOSED MODEL

A coir fibre reinforced recycled paper pulp composite block of 6 cm thickness has been prepared separately with 2.5 cm fibre cut length and 0.25 $V_f$ using the same set-up and parameters of manufacturing. The tested (NRC – 0.53) and predicted (NRC – 0.52) (using proposed model) values of NRC show a good agreement, showing an accuracy of 98.11%. This confirms that the proposed model will work well.

5.9 CONCLUSIONS

It is concluded that for coir fibre reinforced recycled paper pulp composites:

- There is good NRC when noise passes through the coir fibre reinforced biocomposite blocks. The various parameters such as fibre cut length, fibre volume fraction and thickness of the composites significantly affect the NRC when the composite acts as sound control material. A mathematical model
multiple linear regression model has been suggested to predict the NRC with respect to these parameters.

- The minimum and maximum NRC is achieved at 1.5 cm and 3.5 cm fibre cut length with 2 cm and 6 cm thickness at $V_f$ of 0.20 of the composites of S1 and S4 respectively.

- The outcomes indicate that a composite bulk density of about 160 kg/m$^3$ gives maximum NRC averaged throughout the range of frequencies 250 Hz to 4000 Hz.

- There is a positive relationship between better NRC values and higher bending strength upto a certain bulk density.

- The optimum combination is seen when the fibre length is 3.5 cm with 0.20 fibre volume fractions at 6 cm thickness of the composites (S4).

Hence, coir fibre reinforced biocomposites could be used as construction material for sound control in buildings. Further investigation is still, however, recommended regarding their durability before introduction into the local market.

The comparison between banana and coir fibre reinforced biocomposites on NRC in terms of physical and morphological structures are presented in the chapter 7 in a detailed manner. In addition, the comparisons between three different lignocellulosic fibre based biocomposites have been discussed statistically.