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Modelling of sound absorption properties of sisal fibre reinforced paper pulp composites using regression model

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Multiple linear regression models have been developed to predict the sound absorption properties of sisal fibre reinforced recycled paper pulp composites (light in weight), with varying fibre volume fraction, average cut-length of the fibres and composite thickness. The composites are produced using Box and Behnken experimental design and evaluated by relevant standards. An attempt has also been made to study the effect of various parameters in multiple linear regression models. The actual experimental data are compared with predicted results using multiple linear regression model. The correlation coefficient between experimental and predicted value is found to be 0.977. The maximum noise reduction coefficient is observed (through experimental) in the bulk density of 171 kg/m^3 at frequency ranges between 125 Hz and 4000 Hz with the average value of 0.58.

Keywords: Bending strength, Composites, Paper pulp, Sisal fibre, Sound absorption

1 Introduction

The sound absorption property of sisal fibre reinforced recycled paper pulp composite material is one of the essential properties which decide the suitability of these composites in construction applications to control sound. Natural fibre reinforced composites are well suited for sound absorption in conference halls, auditoriums, theatres, classrooms, hospitals, offices, aeroplanes and automobiles. These composites can be implemented as ceiling panels, graphic panels or hanging baffles and floor covering[1-2]. The factors that mainly influence acoustic performance of sound absorptive materials are fibre type, fibre dimension, material thickness, density, airflow resistance and porosity, which can change the sound absorption behavior[3-7].

Numerous studies have proved the suitability of wool[4], cotton[5, 6], viscose[6], polyester[6], polypropylene[6], coir[7, 8] kenaf[9], jute[9], flax[9] and rice-straw[10] as a raw materials for acoustic control materials in terms of density, thickness and porosity[3-7]. Recycled rice straw–waste tire particle composite boards have good acoustic insulating properties over a wide range of frequency (125–8000 Hz), because of the larger pores with lower density[10]. Previous study stated that, in designing a material to have a high sound absorption coefficient, density should increase along with the propagation of the sound wave[3-5, 11].

Previous study showed the increase in sound absorption only at low frequencies, as the material gets thicker[3-6,11,12]. However, at higher frequencies thickness has insignificant effect on sound absorption. Therefore, the main structural properties of the porous materials affecting sound absorption are density, thickness and porosity. On the other hand, the porosity has a significant effect on sound absorption[6,7,11]. It can be concluded from the above studies that the acoustical properties of material depends on the various parameters chosen and the interaction between the parameters. In such cases, developing a model will help to understand the effect of a chosen variable on sound absorption properties. A regression equation can be developed from the input composites particulars and output predicted values, which can be used as an empirical model for predicting acoustical properties. A number of research workers have successfully used regression model for modeling of various properties of textile materials[13-15].

However while the acoustical properties of many natural fibres have been investigated, the acoustical characteristic of sisal fibre is rarely studied. It is found that the scientific data on acoustical properties of sisal fibre reinforced recycled paper pulp composites is not available. Hence, the present investigation deals with the modeling of acoustical properties of light-weight composites produced from sisal fibre reinforced recycled paper pulp. The selected variables are fibre volume fraction (V_f), average cut length of the fibres and composite

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thickness. An attempt has also been made to develop a model for predicting the acoustical properties of sisal fibre reinforced recycled paper pulp composites using multiple linear regression models.

2 Materials and Methods

2.1 Materials

The sisal fibres with average cut length of 1.5, 2.5 and 3.5 cm were sourced locally and used for reinforcement. Old newsprint (recycled) paper was chopped to give a density of approximately 650 kg/m^3 for the matrix.

2.2 Preparation of Sisal Fibre Reinforced Recycled Paper-pulp Composites

Square sisal fibre reinforced recycled paper-pulp composite (SFRRPC) blocks of 30 cm with varying thickness (2, 4 & 6 cm) were prepared. Samples with average cut lengths of the fibres (1.5, 2.5 and 3.5 cm) and fibre volume fraction (0.15, 0.20 and 0.25) were manufactured. The recycled paper was chopped and ground using adequate quantity of water to ease pulp formation process. The excess water was drained from the pulp using cloth, which was made up of very fine nylon woven fabric. Sisal fibres were cut to required length. After getting a homogeneous mix of sisal fibres and recycled paper pulp, the mixture was transferred to a mould to get the desired size of composite blocks. The specimens were removed from the mould after 24 h and then kept at room temperature for one week to dry completely. The composite blocks were then conditioned at 25^0 C and 65% RH for 24 h before testing. The specimens' physical (density and sound absorption) and mechanical (bending strength) properties were measured according to relevant Japanese Industrial Standard (JIS A 5908-1994)[16].

2.3 Specimen Property

Bulk density (ρ_b) of composite was calculated using the following relationship:

$$\rho_b \text{ (kg/m}^3\text{)} = W/t \qquad \text{. . . (1)}$$

where W is the weight per unit are; and t, the thickness (determined as per ASTM D 3776). Average absolute density (ρ_a) of composite blocks was calculated using the following relationship:

$$\rho_a \text{ (kg/m}^3\text{)} = (P_f D_f + P_p D_p) / (P_f + P_p) \qquad \text{. . . (2)}$$

where P_f and P_p are the % blend proportion of fibre and recycled paper pulp respectively; and D_f and D_p, the absolute densities of fibre (1450 kg/m^3 for sisal and 650 kg/m^3 for recycled papers). Each value represents the average of five samples.

Porosity (H) was calculated using the following equation[17]:

$$H = 1- (\rho_b / \rho_a) \qquad \text{. . . (3)}$$

Each value represents the average of five samples.

Three-point bending strength was determined using a Universal testing machine (TUE-C-1000) and the standard JIS A 5908-1994 method. A load of approximately 10 mm/min was applied at a mean deformation speed on the test piece and measure the maximum load (P). Each value represents the average of five samples.

The reverberation chamber method (Fig. 1), a facility available at PSG College of Technology, Coimbatore, India, was used for the determination of sound absorption coefficient (SAC) and noise reduction coefficient (NRC) in the absence and presence of the sample, following the procedure described by Clemson-Boston differential sound insulation tester. The frequency value, such as low (125 and 250 Hz), lower middle (500 Hz), upper middle (1000 Hz) and high (2000 and 4000 Hz), were selected which are harmful to human ear at high decibels. The percentage sound reduction was calculated as mentioned in previous research work[6].

2.4 Experimental Design and Empirical Model

Box and Behnken experimental design for three variables was used as the basis for producing the samples[16]. The three levels for the chosen variables are given in Table 1 and the experimental combinations for producing the samples are given in

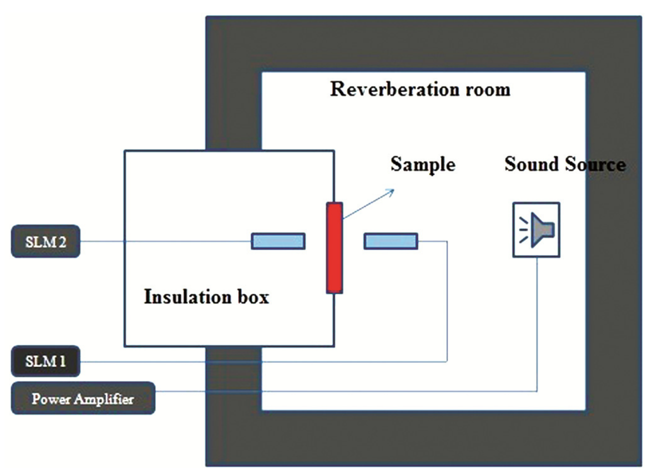

Fig. 1—Schematic diagram of sample made for reverberation chamber method

Table 2. An empirical model of multiple linear regression equation was derived to predict the acoustic properties of the samples produced using Box and Behnken experimental design[13-15].

3 Results and Discussion

3.1 Physical Property

The sound-absorbing capabilities of SFRRPC blocks are related to their density, as shown in Fig. 2. NRC increases proportional to the composite bulk density of about 171 kg/m^3, and beyond that point NRC decreases. This may be due to the fact that the increase in sisal fibre contents in the composite increases the porosity. The above statement is in agreement with the results of a previous study, stating that in designing a material to have a high sound absorption coefficient, density should increase along with the propagation of the sound wave[3-5, 11]. Results indicate that a composite bulk density of about 171 kg/m^3 gives better sound absorption averaged throughout the range of frequencies (125-4000 Hz). The pores structure is the most important factor that one should consider while studying sound absorption mechanism in porous materials. NRC increases proportional to the composite porosity of about 0.79, and beyond that point NRC decreases. The above statement is in agreement with the results of a previous study, stating that in designing a material to have a high sound absorption coefficient, porosity should increase along the propagation of the sound wave[6,7,11].

3.2 Mechanical Property

The final mechanical properties of the composite are culmination of a three-stage process, combining chemical and physical interactions. The first stage is chemical, corresponding to early sisal fibre and used

Table 1—Actual levels of corresponding to coded levels

Variable	Coded levels		
	-1	0	1
Average cut length, cm (X_1)	1.5	2.5	3.5
Average composite thickness, cm (X_2)	2	4	6
Fibre volume fraction, V_f (X_3)	0.15	0.20	0.25

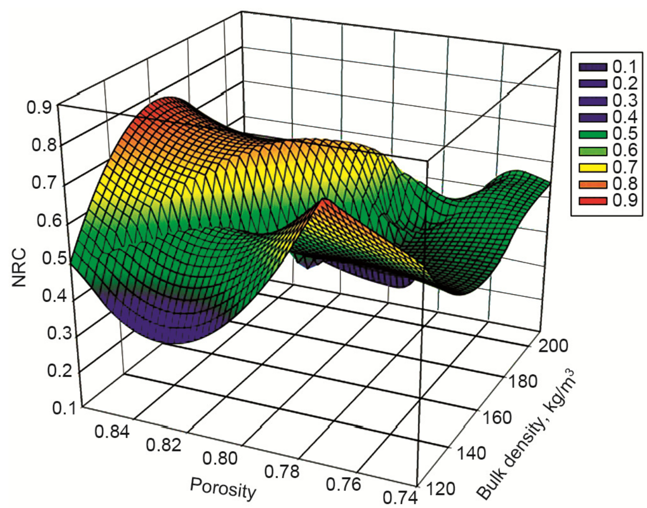

Fig. 2—Effect of bulk density on NRC with porosity

Table 2—Experimental and predicted NRC values of SFRPPCs

Samples No.	Average cut length cm (X_1)	Average composite thickness, cm (X_2)	Fibre volume fraction, V_f (X_3)	NRC		
				Experimental values (y)	Predicted values yi	Residual values [e = (y-yi)]
S1	1.5	2	0.20	0.4200	0.4221	-0.0021
S2	1.5	6	0.20	0.5200	0.5173	0.0027
S3	3.5	2	0.20	0.4900	0.4921	-0.0021
S4	3.5	6	0.20	0.5800	0.5873	-0.0073
S5	1.5	4	0.15	0.4700	0.4622	0.0078
S6	1.5	4	0.25	0.4800	0.4772	0.0028
S7	3.5	4	0.15	0.5400	0.5322	0.0078
S8	3.5	4	0.25	0.5600	0.5472	0.0128
S9	2.5	2	0.15	0.4500	0.4496	0.0004
S10	2.5	2	0.25	0.4600	0.4646	-0.0046
S11	2.5	6	0.15	0.5400	0.5448	-0.0048
S12	2.5	6	0.25	0.5600	0.5598	0.0002
S13	2.5	4	0.20	0.5000	0.5047	-0.0047
S14	2.5	4	0.20	0.5100	0.5047	0.0053
S15	2.5	4	0.20	0.4900	0.5047	-0.0147

paper pulp hydration reactions. The second stage is chemical and physical, when the paper pulp begins to crystallize and forms a matrix around the fibres and the final stage is physical, which could continue for many years. Thus, fibres and recycled paper pulp materials are probably bonded together by several complex physical and chemical mechanisms. The mechanical interlocking process is probably an important mechanism contributing to strength. The fluid paper pulp flows into cracks and cell lumens on the rough fibre surface and then crystallizes to form paper plugs, which interlock the paper pulp and fibres[18]. The measured value of bending strength is plotted against composite density and porosity for various parameter combinations such as fibre cut length, content and composite thickness (Fig. 3 and Tables 2 & 3). It can be found that the sample number S4 has good bending strength and NRC in terms of composite density among the combinations.

However, the better bending strength is observed for the sample numbers S4 and S11 having the fibres average cut length of 3.5 cm and 2.5 cm respectively (Table 2). This is due to the better mechanical interlocking process between sisal fibres and recycled paper pulp. Therefore, it is concluded that the optimum fibre length is 2.5-3.5 cm with 0.15-0.20 fibre volume fraction and 6 cm thickness of the composites, because all measured data of prepared composites are within the satisfactory range of construction blocks. As the sisal fibres reinforced recycled paper pulp composite boards have better flexural properties than the wood particleboard[10], it can

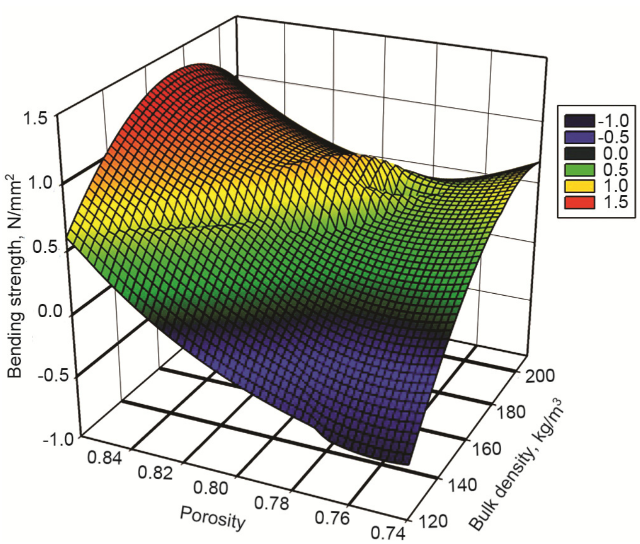

Fig. 3—Effect of bulk density on porosity with bending strength

be used for specific purposes, such as for producing flexural materials. Thus, the composite board can be used as sound control panel in construction.

3.3 Acoustic Property

The empirical equation, derived by using multiple linear regression model for predicting the acoustic properties of SFRRPC blocks, is given below:

$$NRC = 0.292 + (0.0350 * X_1) + (0.0238 * X_2) + (0.150 * X_3) \quad \ldots (4)$$

$R^2 = 0.977$ (Sigma Plot 12.5 output)

Since the coefficient of determination (R^2) is very high; it may concluded that the empirical model fits the data very well. Table 2 shows the relationship between experimental and predicted values of acoustic properties of SFRRPC blocks. The correlation coefficient between observed and predicted value was found to be 0.977. In addition, the prediction by multiple linear regression model is closer to the experimental values and the variations in error among the samples are also lower. The reliability has been checked with six new samples. It can be concluded that the empirical equation fits the data very well. A good correlation (correlation coefficient, 0.997) is observed between experimental and predicted values of new six composite samples. Thus, it has been confirmed that the results of new samples are following the same trend of already projected results.

Table 3—Physical and mechanical properties of SFRPPCs

Sample No.	Bulk density (ρ_b), kg/m^3	Average absolute density (ρ_a) kg/m^3	Porosity (H)	Bending strength, N/mm^2
S1	160	820	0.80	0.467
S2	190	820	0.76	0.584
S3	176	820	0.78	0.569
S4	171	820	0.79	0.715
S5	197	770	0.78	0.566
S6	184	862	0.78	0.486
S7	164	820	0.80	0.658
S8	189	862	0.78	0.598
S9	180	820	0.78	0.533
S10	122	862	0.85	0.476
S11	210	820	0.74	0.675
S12	210	862	0.75	0.578
S13	120	862	0.86	0.599
S14	150	820	0.81	0.476
S15	180	820	0.78	0.638

Table 4—Analysis of Variance on SAC and NRC of SFRRPCs

Source of variation	DF*	SS*	MS*	F*	P
Regression	3	0.0283	0.00943	154.109	<0.001
Residual	11	0.000673	0.0000612		
Total	14	0.0290	0.00207		

DF* – Degrees of freedom, SS*— Sum of squares, MS* – Mean sum of squares, F* – Variance ratio.

The composite sample number S4 has higher NRC than other samples, with bulk density of 171 kg/m^3 and porosity of 0.79 in the frequency range of 125-4000 Hz. This may be due to the increase in sisal fibre contents and average fibre cut length in the composite as well as increased the porosity; thus, it shows that a composite porosity of about 0.79 gives the better sound absorption averaged throughout the entire range of frequencies (125-4000 Hz). The sisal fibres reinforced recycled paper pulp composite boards have better acoustic properties than plywood[19, 20]; it can be used for specific purposes, such as for acoustic control materials. Then, the composite board can be used as sound control panel in construction. As sample number S4 has the lower bulk density (171 kg/m^3) and higher bending strength (0.715 N/mm^2), it shows the better NRC values in terms of both bulk density and bending strength. Therefore, it may be considered for efficient construction in preference to materials with otherwise identical parameters.

3.4 Analysis of Variance on SAC and NRC of SFRRPCs

The results of analysis of variance (ANOVA) for SFRRPCs are listed in Table 4. It shows that the average cut lengths of the fibres, volume fraction of fibres and composite thickness significantly affect the NRC in terms of bulk density, thickness and porosity. The critical value is the number that the test statistics must exceed to reject the test. In this F_{crit} (3, 11) = 3.59 at $\alpha = 0.05$. Since F= 154.109 > 3.59, the results are significant at the 5% significance level. One would reject the null hypothesis, concluding that there is strong evidence that the expected values in the 15 samples differ. The P-value for this test is $P<0.001$.

4 Conclusion

In this study, the development of sisal fibre based light weight construction materials is reported. The findings indicate that the composite with bulk density of about 171 kg/m^3 gives maximum NRC throughout the range of frequencies 125-4000 Hz. It is concluded that for the production of sisal fibre reinforced recycled paper-pulp composite blocks, the optimum fibre length is 3.5 cm with 0.20 fibre volume fraction and 6 cm thickness of the composites in terms of NRC. The multiple linear regression model can be used successfully for predicting the acoustic properties of SFRRPC blocks. Prediction of acoustic properties by empirical model shows considerable lower error when compared to the experimental values. Coincidence in accuracy among the samples is also higher (0.977). This will minimize the time taken for designing and developing a composite to a specific acoustic property. As compared to commercial plywood, the acoustic properties of SFRRPC blocks show good characteristics. They have additional properties of being light in weight with low cost. Hence, SFRRPC blocks could be used as construction material for sound control in buildings. Further investigation is still, however, recommended to assess their durability before introduction into the local market.

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