AN EVALUATION OF ANALYSIS METHODS TO ELIMINATE THE EFFECT OF DENSITY VARIATION IN PROPERTY COMPARISONS OF WOOD COMPOSITES

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ABSTRACT

The objective of this research was to evaluate commonly used data analysis methods in property comparisons of wood composites to eliminate the effect of the density variation among board test specimens and to suggest a more reasonable and robust method. The methods reviewed included average, specific strength, and analysis of covariance. The indicator variable method was also applied to the property comparison and compared to the other methods. The modulus of rupture of wood fiber/polymer fluff composites manufactured with different material combinations and press temperatures was tested in the experiment for evaluation of the different analysis methods. The results of this study indicated that the statistical analysis method employed was very important in the study of the physical and mechanical properties of wood composites. The specific strength method is limited to the analysis of strength comparison for the high density composites. The analysis of covariance can be applied to all the property comparisons for either high or low density composites in eliminating the density variation effect. However, error exists in the property comparison using the analysis of covariance method when the slopes of the regression lines of property vs. specific gravity (SG) are different for the different composites being tested. The indicator variable method is shown to be more reliable than the specific strength and analysis of covariance methods because it compares the linear regression lines of property vs. SG by testing both the intercept and slope based on the data in the whole specific gravity range of test specimens.

Keywords: Wood composites, density variation, data analysis, indicator variable method.

INTRODUCTION

In manufacturing wood composites, such as particleboard and fiberboard, density variation within the panel in the horizontal direction is always a problem because of the inherent wood density variation, discontinuity of wood furnish, variability in the mat forming process, temperature differences, and mat moisture contents. Density variation is a difficult characteristic to control, especially if the boards are processed in the laboratory when the mat formation is performed by hand. When the specimens used to conduct the physical and mechanical tests are selected, the density of the specimens can be quite varied. Furthermore, the behavior of thickness springback after hot pressing will be different when the material composition and processing parameters are different. The board thickness change will affect the final board density. In a lot of research on the physical and mechanical properties of wood composites, the properties of the specimens selected from the same type of

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board are simply regarded as replicates without considering the effect of the density variation among the specimens. Therefore, only the average value is used to represent the board property. Also, in the property comparison for the composites with the same target density, the density differences within different board types caused by the different processing parameters and material combinations are usually neglected. Because the mechanical and physical properties of the wood composites are very sensitive to board density, it is difficult to make a useful property comparison when differences in density occur with different boards. Several analysis methods have been used to adjust for these properties considering the density variation among different board types before the property comparison. These methods include analysis of covariance (Boggio and Gertjejansen 1982; Filho 1981; Hughes and Gertjejansen 1984; and Hawke et al. 1992, 1993), and specific strength (Sun and Hawke 1997a, b). However, no comprehensive study has been conducted to compare the accuracy and applicability of these data analysis methods for wood composites.

OBJECTIVES

1. To evaluate the commonly used data analysis methods in property comparison for wood composites;
2. To introduce the indicator variable method, which is more reasonable and robust, to eliminate the effect of density variation among the test specimens.

DATA ANALYSIS METHODS FOR THE PROPERTY COMPARISONS OF WOOD COMPOSITES

Average method

For the average method, the property variation among the test specimens is regarded as random error without considering the effect of specimen density difference on the properties. Therefore, only the averaged value (mean) of all the specimens cut from representative places within the board is used for the property comparison. Analysis of variance (ANOVA) and multiple comparison tests, such as the Tukey test or Student-Newman-Keuls method, are used to conduct the statistical comparison. However, it is well known that the mechanical and physical properties of wood composites have a relationship with board density. The variation occurring in physical and mechanical properties of wood composites is caused not only by the random error, but also by the systematic errors due to the density variation among the test specimens. Therefore, the effect of density differences on the board properties should be accounted for when comparing the properties of the wood composites.

Specific strength method

Specific strength is an indicator of the board strength, which is expressed as:

$$SS = \frac{S}{SG} \tag{1}$$

where SS is the specific strength; S is the strength of the composites such as modulus of rupture (MOR) and modulus of elasticity (MOE); and SG is the specific gravity of composites.

The strength of wood composites is dependent on the specific gravity. The higher the SG, the greater the strength (Bodig and Jayne 1993). If it is assumed that a linear relationship exists between the composite strength and its specific gravity with the regression line going through the zero coordinate, the ratio of the strength to the specific gravity (slope), also called specific strength (SS) which is shown in Eq. (1), can be used for the property comparison from which the effect of density difference within the board types has been eliminated. The property comparison results based on the specific strength data of all the specimens should be more reliable than that based on the original measured data. The adjusted board strength value at the target SG can be obtained by the specific strength value times the target SG.

For wood composites, the strength will remain zero when the board SG falls below a certain value. Therefore, the regression line of the strength vs. SG for wood composites does not pass through the original coordinate. The above assumption for the specific strength method is obviously not realistic. The smaller the SG, the greater the error it has for the specific strength. Also, the specific strength method may be applied only to the comparison of some mechanical properties of the composites. It won't work for the other board properties such as thickness swelling (TS) and water absorption (WA).

Analysis of covariance method

The analysis of covariance method uses specific gravity as a covariate in the property comparison. The statistical model can be expressed as (Montgomery 1991):

$$Y_{ij} = \mu + \beta(X_{ij} - \bar{X}) + \tau_n + \epsilon_{ij} \quad (2)$$

where β is the true linear regression coefficient (or slope) between Y (property) and X (specific gravity) over all the data; $\bar{X}$ is the mean of the X value; μ is the common effect; τ_n is the effect of the level being evaluated; and ϵ_{ij} is the random error.

Unlike the specific strength method, the analysis of covariance assumes that a linear relationship exists between the property and the SG in a certain short density range. The intercept differences for the regression lines of the property vs. SG for different board types are compared. The analysis of covariance method can be applied to all the property adjustments for SG, if a linear relationship can be established. However, the analysis of covariance method has also assumed that the property increase or decrease rates (slopes of the regression lines) as a function of the board SG are the same for all board types to be investigated. This assumption may not be necessarily true for the comparison of some types of wood composites. For example, Fig. 1 shows the different regression lines of MOR vs. SG for wood fiber/polymer fluff composites manufactured with different material combinations. It is seen from Fig. 1 that the differences among these regression functions are

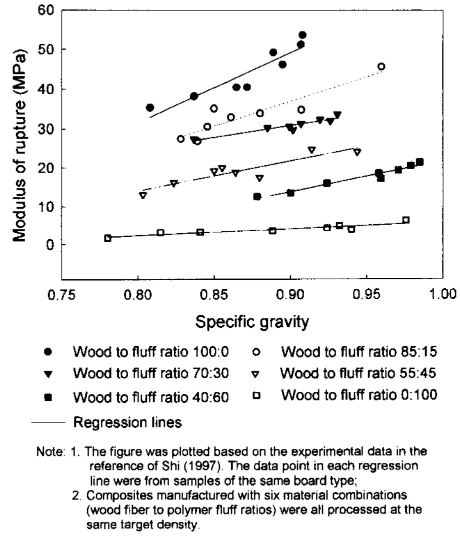

FIG. 1. MOR vs. SG for wood fiber/polymer fluff composites manufactured with different material combinations.

not only for the intercept, but also for the slope. The different regression behaviors of the property vs. SG have also been shown in many other research papers, for example, Rowell et al. (1995) and Suchsland et al. (1983). Therefore, the property comparison results and the adjusted property value of each board type by the analysis of covariance method may not be reliable when these composites have different regression slopes of property vs. SG.

APPLYING THE INDICATOR VARIABLE METHOD TO PROPERTY COMPARISONS

The indicator variable method is a powerful statistical tool for the comparison of regression lines. For example, the following statistical model can be used to compare the property of two board types:

$$Y_i = b_0 + b_1X_{i1} + b_2X_{i2} + b_3X_{i1}X_{i2} + \epsilon_i (3)$$

where Y_i is the property at case i to be calculated; X_{i1} is the specific gravity; X_{i2} is the indicator variable; and b_0, b_1, b_2, and b_3 are the coefficients of the model.

This model uses one regression function to express the two sets of data from the two levels by introducing an indicator variable X_{i2} (also called the dummy variable), which is equal to 1 for the first set of data and 0 for the other. If the coefficients for both the indicator variable and the interaction term $(X_{i1}X_{i2})$ are zero, the two sets of data may be expressed by one function since there is no difference in the relationship of the property vs. SG between the two board types. Otherwise, there is a significant difference in this relationship. Therefore, the following hypothesis can be used:

$$H_0:\quad b_2 = b_3 = 0$$

$$H_a:\quad \text{not both}\quad b_2 = 0\quad \text{and}\quad b_3 = 0 \qquad (4)$$

The coefficients of the regression function can be determined by multiple regression analysis. The p-value for each coefficient, the probability of the coefficient being zero, can also be calculated. It can be determined whether there is a difference in the relationship of property vs. SG in the SG range of the test specimens between the two types of board by comparing the calculated p-value to the significance level (α). If the p-values of the coefficients for both the indicator variable term (test the intercept) and the interaction term (test the slope) are lower than 0.05, then H_0 in Eq. (4) is rejected. Otherwise, H_0 is not rejected and there is not sufficient evidence to conclude that there is a difference between the two board types. Also, by plugging the determined coefficients and the indicator variable value (1 or 0) in Eq. (3), the regression functions for the two board types may be obtained, and then their estimated property values can be calculated. The standard deviation of each regression line can be calculated using the following equation (Neter et al. 1989):

$$s^2\{\hat{Y}_h\} = MSE\left[\frac{1}{n} + \frac{(X_h - \bar{X})^2}{\sum (X_i - \bar{X})^2}\right] \qquad (5)$$

where MSE is the error mean square: $MSE = \Sigma(Y_i - \hat{Y}_i)^2/(n - 2)$; Y_i is the property of specimen i; $\hat{Y}_i$ is the estimated property value for specimen i; X_h is the target specific gravity; $\bar{X}$ is the averaged specific gravity of the samples; n is the sample number; and X_i is the specific gravity of specimen i.

Compared to the specific strength method and analysis of covariance, the indicator variable method is more reliable, because it compares both the intercepts (b_2) and slopes (b_3) of the regression lines of property vs. SG for different board types. Another advantage of the indicator variable method is that it accounts for the entire density range among the test specimens instead of comparing only the adjusted property values by specific strength or analysis of covariance methods.

Table 1 shows an example using the indicator variable method to analyze the MOR properties of two different composites, neat wood fiberboard and wood fiber/polymer fluff composites. The indicator variable X_2 is equal to 1 for neat wood fiberboard and 0 for wood fiber/polymer fluff composites. It can be seen from the multiple regression results in Table 1 that the p-values for the coefficients of both the indicator variable term (X_2), b_2, and the interaction term (X_1X_2), b_3, are less than 0.05, indicating that there are significant differences for both the intercepts and the slopes between the two regression lines. This result shows again that considering only the intercept difference (analysis of covariance) for the property adjustment is not adequate. The regression functions for both neat wood fiberboard and wood fiber/polymer fluff composites in Table 1 were obtained by plugging the coefficients into Eq. (3). The adjusted MOR values of each board type for the target SG of 0.9 were calculated by each of their regression functions, and the standard deviations were calculated by Eq. (5).

Equation (3) may be extended to compare more than two levels through comparing their regression lines by introducing more indicator variables (X_{i2}, X_{i3}, ...) using the following model:

$$Y_i = b_0 + b_1X_{i1} + b_2X_{i2} + b_3X_{i3} \ldots + b_kX_{i1}X_{i2} + b_{k+1}X_{i1}X_{i3} + \ldots + \epsilon_i \qquad (6)$$

TABLE 1. *Comparison of the MOR for neat wood fiberboard and wood fiber/polymer fluff composites using the indicator variable method.*

Raw data[1] and analysis:

Levels Board type	Y MOR (MPa)	X_1 SG	X_2 Indicator variable	X_1X_2 Interaction	Average value
WF	35.24	0.808	1	0.808	
	40.36	0.865	1	0.865	
	38.08	0.837	1	0.837	average SG:
	49.11	0.889	1	0.889	0.873
	40.40	0.872	1	0.871	average MOR:
	53.62	0.908	1	0.908	44.25 MPa
	51.16	0.907	1	0.907	
	46.05	0.895	1	0.895	
WFF	33.60	0.931	0	0	
	29.68	0.902	0	0	
	30.49	0.899	0	0	average SG:
	32.29	0.919	0	0	0.901
	31.25	0.907	0	0	average MOR:
	27.36	0.837	0	0	30.85 MPa
	30.20	0.885	0	0	
	31.95	0.926	0	0	

Results of the multiple regression:

Terms	Intercept	X_1	X_2	X_1X_2
Coefficient (b)	−22.544	59.277	−86.153	116.003
p-value	0.334	0.032	0.010	0.003
Significant		*2	*2	*2

Estimation of the property values:

Board type	Regression functions	MOR (MPa) when SG = 0.900	Standard deviation
WF[3] (X_2 = 1)	MOR = −108.69 + 175.28 × SG	49.05	0.933
WFF[3] (X_2 = 0)	MOR = −22.54 + 59.28 × SG	30.80	0.062

[1] Experimental data of Shi (1997).
[2] Significant difference.
[3] WF: neat wood fiberboard; WFF: wood fiber/polymer fluff composites (fiber to fluff ratio 70 : 30)

The conclusion on the significant difference among the levels can be made directly from the results of the multiple regression analysis.

COMPARISON OF THE INDICATOR VARIABLE METHOD WITH THE OTHER METHODS

An experiment was conducted to investigate the effect of press temperature on the modulus of rupture of polymeric diphenylmethane diisocyanate (PMDI)-bonded wood fiber/polymer fluff composites. All the three previous described methods, average, specific strength, and analysis of covariance, and the proposed indicator variable method were used and evaluated through this experiment.

Materials and methods

Wood fiber/polymer fluff composites were processed from wood fibers and automobile polymer fluff materials by the dry-process method using PMDI resin as a binder. Automobile fluff materials obtained from East Kingsford Iron Works, MI, were processed into polymer fluff particles (18 mesh) according to the procedure of separation, cleansing, and granulating are described in the reference of Shi (1997). Wood fibers obtained from Georgia Pacific Company, WI, were composed of 75% aspen and 25% mixed hardwood species. The PMDI resin used to process the composites was obtained from Bayer Corporation at Pittsburgh, PA (Mondur 541) with NCO-weight percentage of 31.5%, viscosity of 200 mPa·s (at 25°C), and specific gravity of 1.24.

To manufacture a board, wood fibers and polymer fluff particles were blended at a wood fiber to fluff ratio of 55:45 in a drum blender for 15 to 20 min. Four percent PMDI resin was used as a binder. The mat moisture content was 6%. Subsequently, to reach a target board specific gravity, a suitable amount of the blended mixture was hand-formed into a mat in a 400- × 400-mm box former. After mat formation, consolidation was achieved in a hot press. Two parallel steel stops with a thickness of 3.18 mm were placed at two opposite outer edges of the mat to ensure uniform board thickness. The press closing time for all the boards was 6–10 sec. A release agent was used on the caul plate to avoid adhesion between the board and the plate. Five press temperatures were investigated: 110°C, 130°C, 150°C, 170°C, and 190°C. Press time for all the boards was 4 min. The target board specific gravity for all the composites was 0.9. Two boards were processed at each temperature.

Before the static bending tests, the boards were conditioned in an environmental chamber at 20 ± 3°C and 65 ± 1% relative humidity to reach their equilibrium conditions. The equilibrium moisture content (EMC) after conditioning of all board types was about 4.85–5.29%. Three 50.8- × 127.0-mm specimens were selected from each board, which represented different spots in the board. Six specimens were tested for each type of composite. The specific gravities of all the specimens were also measured based on the oven-dry weight and volume at test. The bending test was performed according to the methods outlined in ASTM D1037 (ASTM 1987).

Discussion

Press temperature has a significant effect on the thickness springback of wood composites. As it is shown in Fig. 2, the higher the temperature, the less the thickness springback.

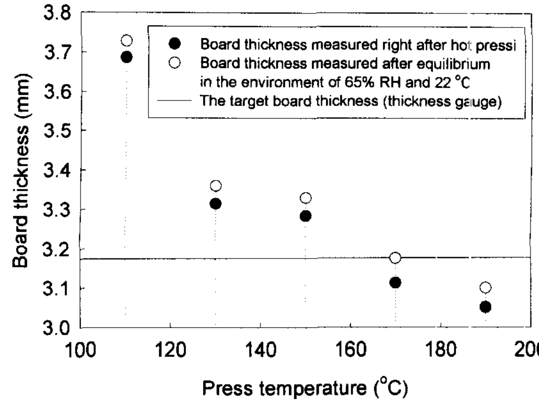

FIG. 2. Thickness springback of the wood fiber/polymer fluff composites processed at different press temperatures.

Wood and plastics are all viscoelastic materials. The higher the temperature, the more plastic flow in the mat materials, and the greater the dimensional stability of the composites. The big difference in thickness springback among the boards manufactured at different temperatures may influence the difference in specific gravity. Table 2 shows the average SG and MOR values for the different boards. As the temperature increases, the average MOR increases. However, the SG also increases with an increase in press temperature. The higher the SG, the greater the MOR. Therefore, in the analysis of the press temperature effect on the MOR, the effect of SG among the specimens on the MOR should be eliminated in the data analysis.

It is also seen from Table 2, for high temperature boards processed at temperatures such as 170°C and 190°C, the average SGs (0.922 for 170°C and 0.924 for 190°C) are higher than the target SG, which is 0.900. Therefore, the adjusted MOR for high temperature boards should be lower than the average MOR. For the same reason, the adjusted MOR for the lower temperature boards should be higher than the average MOR. The MOR values adjusted by the three methods, specific strength, analysis of covariance, and indicator variable, show the appropriate trend because they are all based on the assumption that the

TABLE 2. *Results of the multiple comparison and adjusted MOR values at a target board SG of 0.9 by the specific strength method, analysis of covariance method, and the indicator variable method for the wood fiber/polymer fluff composites manufactured at different press temperatures (MPa).*

Temperature (°C) Average board SG	110 0.770	130 0.842	150 0.898	170 0.922	190 0.924
Analysis methods					
Average	14.64a	19.19a,b	23.18b,c	26.59c	28.64c
Specific strength	17.02a	20.50a,b	23.24b,c	25.94b,c	27.90c
Analysis of covariance	25.13a	23.84a,b	23.36b	24.78b	26.73b
Indicator variable	21.64a	21.67b	23.36c	24.65c	26.40c
	intercept: a	intercept: b	intercept: c	intercept: c	intercept: c
	slope: a	slope: b	slope: c	slope c	slope: c

The pairwise multiple comparison for the average, specific strength, and analysis of covariance methods were using student-Newman-Keuls test.
The same letter shared by the factor levels indicates no significant differences between the levels.

MOR and SG have a linear relationship. However, discrepancies were found for these adjusted MOR values among the methods.

For both the lower temperature boards (110°C and 130°C) and higher temperature boards (170°C and 190°C), the MOR values adjusted by the analysis of covariance method (25.13 MPa for 110°C, 23.84 MPa for 130°C, 24.78 MPa for 170°C, and 26.73 MPa for 190°C) are all higher than those obtained by the indicator variable method (21.64 MPa for 110°C, 21.67 MPa for 130°C, 24.65 MPa for 170°C, and 26.40 MPa for 190°C). This result occurs primarily because the analysis of covariance method assumes that all the regression lines have the same slope. Figure 3 shows the relationship of MOR vs. SG for the five types of boards. It is seen in Fig. 3 that the regression function for each temperature board is obviously different from the others. Larger slopes were found for the higher temperature boards (95.61 for 170°C and 94.08 for 190°C) and smaller slopes were found for the lower temperature boards (53.71 for 110°C and 43.03 for 130°C). Therefore, the slope used in the analysis of covariance adjustment is smaller than the actual slope of the higher temperature boards and larger than the actual slope of the lower temperature boards. Also, the MOR should be adjusted down for higher SG boards (over 0.9) and up for lower SG boards (under 0.9). Therefore, in this case, the adjusted MOR values for both lower and higher temperature boards by analysis of covariance method are all higher than that obtained by the indicator variable method which uses their actual individual regression functions.

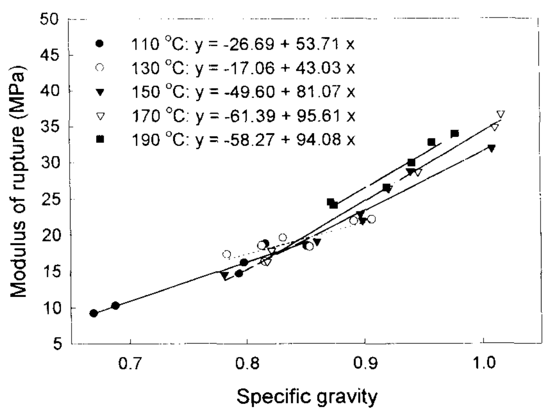

FIG. 3. MOR vs. SG for wood fiber/polymer fluff composites processed at different press temperatures.

Unlike the analysis of covariance method, the adjusted MOR values by the specific strength method are lower for the lower temperature boards (17.02 MPa for 110°C and 20.50 MPa for 130°C) and higher for the higher temperature boards (25.94 MPa for 170°C and 27.90 MPa for 190°C) compared to that of the indicator variable method (21.64 MPa for 110°C, 21.67 MPa for 130°C, 24.65 MPa for 170°C, and 26.40 MPa for 190°C). As it is shown in Fig. 3, the intercepts for all the actual regression lines are negative because the composites will not have strength until a certain SG is obtained. However, the specific strength method assumes that the regression lines are through the zero coordinate. Therefore, the slopes (specific strength) obtained assuming the intercept is zero will be smaller than the actual slopes of the regression function. For the lower SG boards (lower temperatures) where the MOR should be adjusted up, the adjusted MOR value by the specific strength method should be lower than that by the actual regression function. On the other hand, for the higher SG boards (higher temperatures) where the MOR should be adjusted down, the adjusted MOR value by the specific strength method should be higher than that by the actual regression function.

A significant effect resulting from press temperature on the MOR of the composites has been shown from the results of all four data analysis methods employed in this research. From the results of the multiple comparisons using the different analysis methods are shown in Table 2, all the analysis methods show that there are no significant differences in MOR among the temperatures of 150°C, 170°C, and 190°C. However, discrepancies were found between the indicator variable method and the other methods for the comparison of temperatures of 110°C and 130°C. The results from the average, analysis of covariance, and specific strength methods show that there are no differences between the temperatures of 110°C and 130°C, and 130°C and 150°C. However, the significant differences between these temperatures (110 to 150°C) were detected by the indicator variable method. For the specific strength method, even though a significant difference between the 130°C and 190°C was detected, the differences between the temperatures 130°C and 150°C, and 130°C and 170°C were not. For the analysis of covariance method, the conclusion from the experiment is that temperature does not effect MOR in the range of 130–190°C; however, the indicator variable method indicates no effect within the narrower range of 150–190°C. The results of the indicator variable method should be more reliable because it has compared the regression lines based on the data in the whole specific gravity range of the test specimens.

The above experiment only uses the MOR as an example for the evaluation of the different statistical methods. The other properties of the composites such as modulus of elasticity, internal bond, thickness swelling, and water absorption, can also be assumed to have a linear relationship with the specific gravity within a short density range. The indicator variable method can also be applied to the comparison of these properties. However, it should be pointed out that the statistical adjustment for the specific gravity is based on the assumption that a linear relationship exists between the property and specific gravity. For the cases when a relationship between the property and the specific gravity cannot be established using the test specimens, the effect of density variation is minor and does not need to be eliminated because no systematic error is found in the properties of different specimens. Therefore, the average method should be sufficient to conduct the statistical comparison.

This study was conducted to eliminate the errors caused by bulk density variation among the specimens of the same board type. The variation on the micro-level characteristics of wood composites, such as the vertical density profile (VDP), was not considered in this paper. It is known that the VDP affects certain board properties, e.g., stiffness. Because of the variation in inherent material density, mat forming, temperature, and mat moisture content within the panel, for the same board type, the VDP of specimens selected from different places may be different. The VDP variation among the specimens could also be eliminated statistically if a specific relationship was found between the properties and quantitative VDP. However, further study is needed to investigate how significant the effect of this micro-level variation is on the board properties.

CONCLUSIONS

The results from this study indicate that specific strength, analysis of covariance, and the indicator variable method can all be applied to data analysis for wood composites to eliminate the effect of density differences. The specific strength method can be applied only to the comparison of strength properties and may not be suitable to the analysis of low density composites since the linear regression line of strength vs. SG does not go through the zero coordinate. The analysis of covariance method is more reliable compared to the specific strength because it can be applied to all the property adjustments for the specific gravity and is suitable to either high and low density composites. However, this method neglects the difference in the slope of the regression lines for the different composites. Because the indicator variable method can be used to compare the linear regression lines of property vs. SG for the different composites considering both the intercept and the slope, it is a very good alternative to the analysis of covariance method when the behaviors of the regression lines are different. The conclusion from the indicator variable method will be more reliable than the specific strength and analysis of covariance methods because it has considered the whole specific gravity range of the test specimens.

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