

CHAPTER II

COMPUTER SIMULATION OF WOOD-FLAKE COMPOSITE MAT STRUCTURES*

Abstract

Based on the mathematical model developed by Dai and Steiner (1993, 1994a and 1994b) and structural characteristics defined in this thesis, a Monte Carlo simulation program was written to run in a Microsoft Windows environment. Several kinds of simulations and calculations can be performed using the program. In this study, simulated mats that were randomly generated by a computer were analyzed in terms of the following structural characteristics: flake deposition, flake area coverage, free flake length and its distribution, flake crossings, location and distribution of void size, and density and overlap distributions. The simulation program can also determine the effect of sampling zone size on the maximum, minimum and mean density, standard deviation and mean deviation of density distribution. A similar analysis could also be performed on experimental designed mats. This chapter demonstrates the use of the simulation program as a tool to improve the understanding of internal mat structures and the related properties.

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2.1. Introduction

The physical and mechanical properties of flake-based wood composites depend on the properties of the constituents and the manufacturing process. A better understanding of its internal structure is needed to improve the characterization of material properties and efficiency in the utilization of wood-based composites.

A two-dimensional mathematical model was developed to describe the structural characteristics of flakeboards, assuming uniform flake size and random process (Dai 1993, Dai and Steiner 1993, 1994a and 1994b). In relating to wood-flake composite mat formation, the most noticeable structural feature of a random mat is the non-uniform wood element coverage, *i.e.*, the varying number of elements overlapping at different positions within the mat. This non-uniform wood element coverage affects heat and mass transfer in the mat during hot pressing and horizontal density distribution in the final panel.

Steiner and Dai (1993) discussed some other important features in the spatial structure of wood-based composites 1) the strong influence of flake geometry on the relative void volume in a mat; 2) the important role of element orientation on optimizing directional strength properties; and 3) the reduction of variation of horizontal density distribution by improving packing behavior and board alignment. Although the mathematical model (Dai 1993) shows that the flake deposition and area coverage follow Poisson process, a closed form solution to describe the real mat formation process was not developed. Furthermore, a purely empirical approach to this problem can be extremely expensive and time-consuming because of the large number of interacting variables.

In this study, an MS-Window-based simulation program was written. In addition to the simulation and calculation of the structural characteristics of the mat, a robotic control system was also developed, where flake placements can be exactly controlled for experimental study. The simulation program linked with the robot allows verification of the theory and random generation of new databases of mats with various input parameters and mat structures. The objective of the current study is to demonstrate the use of the simulation program as a tool to improve the understanding of internal mat structures and the related properties.

2.2. Monte Carlo Simulation

A two dimensional model of a wood flake composite mat is considered as multi-layers of flakes deposited in a predefined area (length (L) (mm) \times width (W) (mm)) with each flake having a definite position in the horizontal plane of the mat. It is termed as a "two-dimensional" model because the model outputs are referenced only to the horizontal domain. The flake centroid location can be described by x and y coordinates ($0 \leq x < L$, $0 \leq y < W$) and flake orientation can be described by angle \mathbf{q} ($-90^\circ \leq \mathbf{q} < 90^\circ$), which is defined as the angle between the x axis and the longitudinal axis of the flake (**Figure 2.1**). If P is the location in the mat area where the flake is placed, then the coordinates (x , y) for P and flake orientation angle \mathbf{q} can be numerically simulated by computer or the results from experimental measurements.

As we define the flake centers in a mat area ($L \times W$), inevitably some flakes will protrude beyond the defined mat area despite having their centers restricted to lie within the mat area, causing "side effects" (Dai 1993). To solve this problem, the "torus conversion" concept (Hall 1988) was

employed in the program. The part of a flake that protrudes from one side of the mat area was considered to re-enter again from the opposite side. This concept becomes more logical and meaningful when the present mat is part of a much larger network in which flakes protruding out of one unit inevitably enter another or vice-versa. In cases where an experimental designed mat is analyzed, side effects do exist and the torus conversion is no longer suitable for this situation. Therefore a maximum of half of the flake length from every edge of the mat must be removed before any test specimens are made unless side effects were explicitly considered during the experimental design by using more flakes around the edges than in the middle.

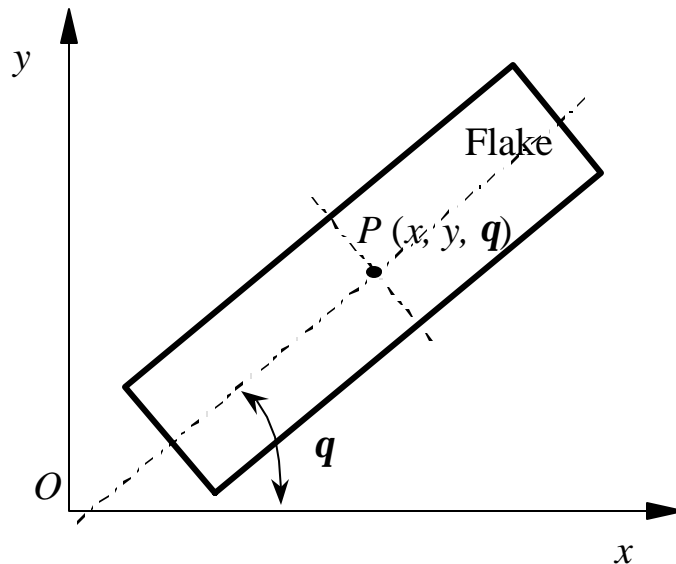


Figure 2.1 Position and orientation of the flake in a mat

2.3. Program Input and Output

The composite mat simulation program can randomly generate data to represent the structural characteristics of flakeboards. A simulated mat can be analyzed by the program to obtain information, such as flake coverage, free flake length and void size. The horizontal density distribution of these mats can also be graphically presented. A robotic control system, which is a link between the computer simulation and a robot controller, was also developed. Such a robotic mat formation system can be used to build experimental mats with predefined structures. Such experimental mats can also be analyzed using the program to obtain similar types of information.

The inputs to the simulation program include: mat size (length, width and thickness in mm), flake geometry (length, width and thickness in mm), flake density (g/cm^3), flake orientation angles ($-90^\circ \leq \alpha < 90^\circ$), flake centroid locations, and final panel density (g/cm^3). The flake geometry (length and width), orientation, and centroid location can be considered as random parameters defined by various probability distribution functions. A complete randomized flakeboard mat would have: 1) the flake orientation angle specified within a range of -90° to $+90^\circ$ under a uniform probability distribution; and 2) the flake centroid location specified within the range of the horizontal domain under a Poisson probability distribution (Dai and Steiner 1994a and 1994b). In cases of partially randomized flakeboard composite mats, a reduced range of flake orientation angles can be specified (for example, -5 to $+5$ degrees) under a uniform distribution and/or the centroid location of each flake can be directly specified as desired. The length and width of each "flake" can be simulated independently from normal distribution (specified mean and standard deviation of the mean) with upper and lower bounds within the mean \pm three times the standard deviation. Alternatively, a mixed

flake geometry with a predefined proportion of flake sizes can be used.

2.4. Robot Control System

The developed robotic controlling system links the computer simulation and experimental mat. Data such as the orientation and centroid location of each flake can be generated from the simulation program and stored in a file. The robotic mat-forming system can access the file and the information can be transferred into the robot controller in the format of robot commands (**Figure 2.2**). Experimental mats can be made flake by flake using the robot to verify the simulation procedures and build a test database on mats with high repeatability. This type of work is beyond the scope of this thesis and can be found in a publication by Wang and Lam (1998).

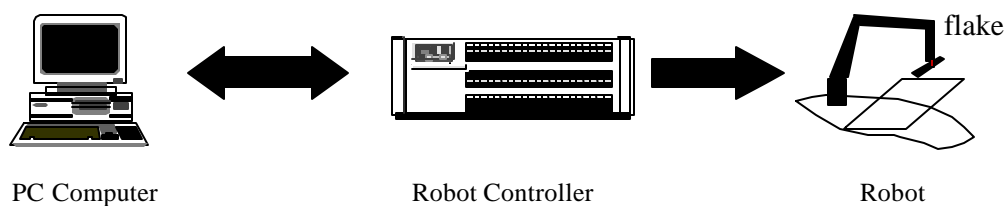


Figure 2.2 Robot control system

2.5. Results and Discussions

2.5.1. Density and overlap distributions

By using the constant mass in a given volume, we are able to obtain the relationship between the overlaps (O) which is the number of flake layers measured at any local area (a) and the local densities (\mathbf{r}), as follows:

$$O \mathbf{t}_f \mathbf{r}_f = \mathbf{t} \mathbf{r} \quad (2.1)$$

$$O = \frac{\mathbf{t}}{\mathbf{t}_f} \frac{\mathbf{r}}{\mathbf{r}_f} = R_t R_r \quad (2.2)$$

where \mathbf{t} = panel thickness,

\mathbf{r} = panel local density,

\mathbf{t}_f = flake thickness,

\mathbf{r}_f = flake density,

R_t = thickness ratio between panel and flake, and

R_r = density ratio between panel and flake.

The assumptions are that the flake thickness, flake density and panel thickness are fixed for a given mat. Under these assumptions, the overall overlap distribution is linearly proportional to the panel local density distribution. In this study, a flake thickness of 1 mm, a flake density of 0.4 g/cm³, a panel thickness of 11 mm, and a target panel density of 0.6 g/cm³ were chosen for simulation. Generally, the flake overlap is a function of thickness ratio and density ratio between panels and flakes as shown in **Equation 2.2**.

In this study, three classes of flake sizes are considered, uniform, mixed and distributed. Uniform refers to a mat generated from flakes of uniform size (80mm × 20mm × 1mm). Mixed means a mat made of five different sizes of flakes with the same ratio of weight (100mm × 22mm × 1mm, 80mm × 20mm × 1mm, 70mm × 18mm × 1mm, 60mm × 16mm × 1mm, and 50mm × 14mm × 1mm). Distributed indicates a mat made of the average flake size of 80mm × 20mm × 1mm where the flake length and width follow a normal distribution and the standard deviations of length and width are 8mm and 2mm, respectively.

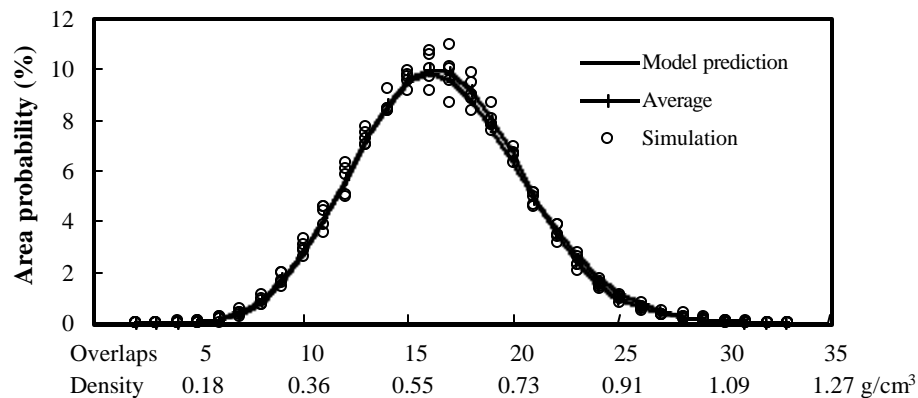


Figure 2.3 Flake overlap and density distributions in the composite mat.

(Simulated mat geometry: 250mm × 250mm × 11mm, target board density: 0.6g/cm³, flake geometry: 80mm × 20mm × 1mm, flake density: 0.4 g/cm³, and resolution: 1mm × 1mm.)

The typical density and overlap distributions obtained using uniform flake size are plotted in **Figure**

2.3. These distributions are obtained by first digitizing the 250mm × 250mm domain into squares with 1mm × 1mm resolution. Within each 1mm × 1mm square, the number of flakes through the depth of the "simulated" panel is obtained. Based on this information the overlaps and density with a 1mm × 1mm zone can be estimated. The average point density, maximum density, minimum density, and standard deviation of density from the simulated mat are 0.600, 1.108, 0.188, and 0.143 g/cm³, respectively. As shown in **Figure 2.3**, the computer-simulated data are in good agreement with mathematical model predictions defined by Poisson distribution (Dai and Steiner 1994a). The horizontal density variation for the simulated mat is plotted as shown in **Figures 2.4a** and 2.4b.

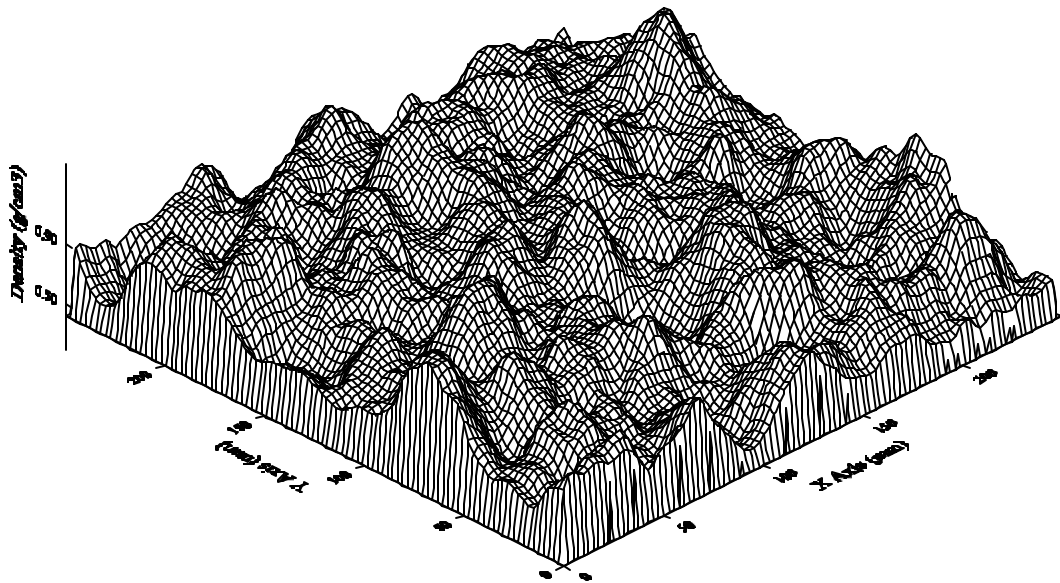


Figure 2.4a Graphical representation of horizontal density distribution by surface map (conditions the same as **Figure 2.3**).

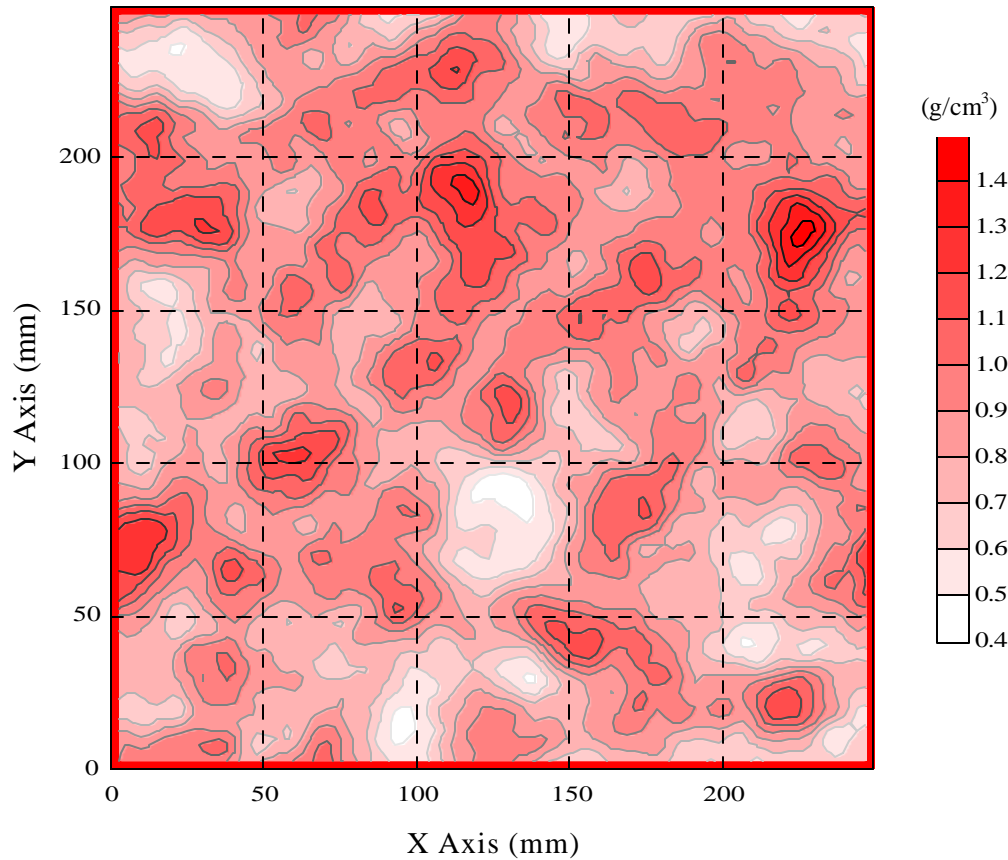


Figure 2.4b Graphical representation of horizontal density distribution by contour map (conditions the same as **Figure 2.3**).

2.5.2. Free flake length and its distribution

Free flake length is defined as the distance between two adjacent crossings of flakes. So if there is only one crossing or all the flakes are parallel to each other, no free flake length can be calculated. The distribution of free flake length (average of 5 layers) is illustrated in **Figure 2.5** for a flake length of 100 mm, and a flake width of 10mm and 20mm. Flake width is an important factor that

influences the free flake length distribution. Thus the original model (Dai and Steiner 1994a) needs to be modified to incorporate this factor. From **Figure 2.5**, it is clear that model prediction and program simulation results fit better at higher aspect ratios (the ratio of flake length to width). At higher aspect ratios, the result agrees well with the free fiber length distribution studies in paper structure (Kallmes and Bernier 1963).

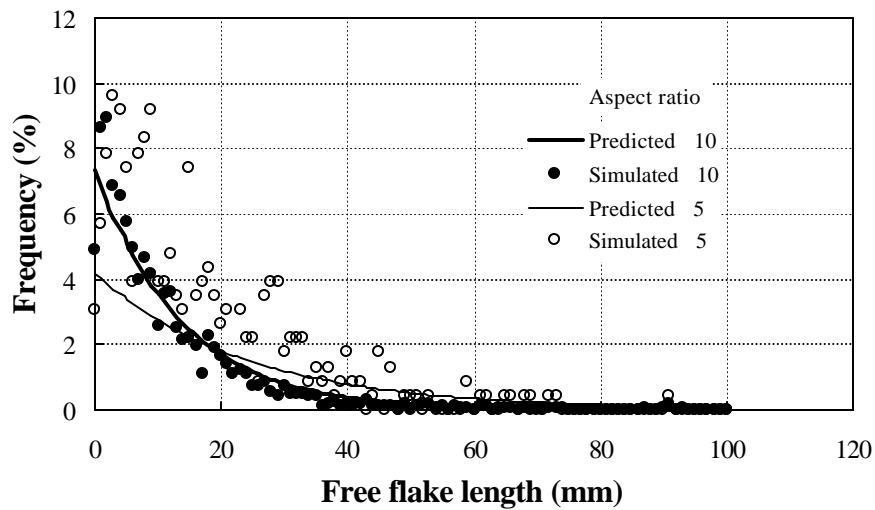


Figure 2.5 The free flake length distributions with the data predicted by Dai's mathematical model and the current simulation study. (flake length is 100 mm, width 10 mm and 20 mm, other conditions are the same as **Figure 2.3**)

2.5.3. Void size and its distribution

By definition, a layer is one flake deep. If a given number of flakes (N_f) are perfectly aligned one by one in the plane of one layer with $N_f I w = A$ (mat area), there is no void at all. All the area in that layer, whether it is big or small, will be covered by only one flake thickness. However, if the centers of flakes and their orientation angles are randomly distributed or partially randomly predefined in the experimental design, some areas will not be covered and some areas will be covered by more than one flake. Therefore, voids inevitably exist in the layer, causing the horizontal density distribution and the variation of the panel properties. **Table 2.1** lists the void areas in the first 10 layers of the simulated mat. The data indicate that in a randomly formed mat the void area in any layer in a mat is between 33 to 40 percent of the total layer area.

Table 2.1 Void sizes in the area of each layer

Layer No.	No. of voids	Total void area (mm ²)	Average void area (mm ²)	Proportion of voids (%)
1	40	23401	585	37
2	29	23514	811	38
3	35	20905	597	33
4	30	21778	726	35
5	32	21540	673	34
6	29	24729	853	40
7	23	24000	1043	38
8	27	24069	891	39
9	26	20545	790	33
10	42	20836	496	33

2.5.4. Effect of sampling zone size

A sampling zone is defined here as a rectangle of certain length and width, where the local board density is evaluated. The effects of various parameters of the sampling zones on the standard deviation of density of the simulated mats are illustrated in **Figures 2.6a** through **2.6d**, where **Figure 2.6a** represents the mat made of flakes with uniform size and **Figures 2.6b, 2.6c, and 2.6d** represent mat made of three different types of flakes (uniform, mixed and distributed). The average density remains the same in all combinations of different lengths and widths of sampling zones (**Table 2.2**). The maximum density, mean deviation and standard deviation of density decrease as the area of the sampling zone increases. The minimum density increases as the area of sampling zone increases. **Figures 2.6a** through **2.6d** also show that the standard deviation of density for mats of uniform flakes is higher than that of the mixed or distributed flakes in any combination of sampling zone length, width or area; this is because more small size flakes are deposited on mats with the selection of mixed or distributed flakes. The standard deviations of density for the mats of the mixed and distributed flakes are quite similar to each other.

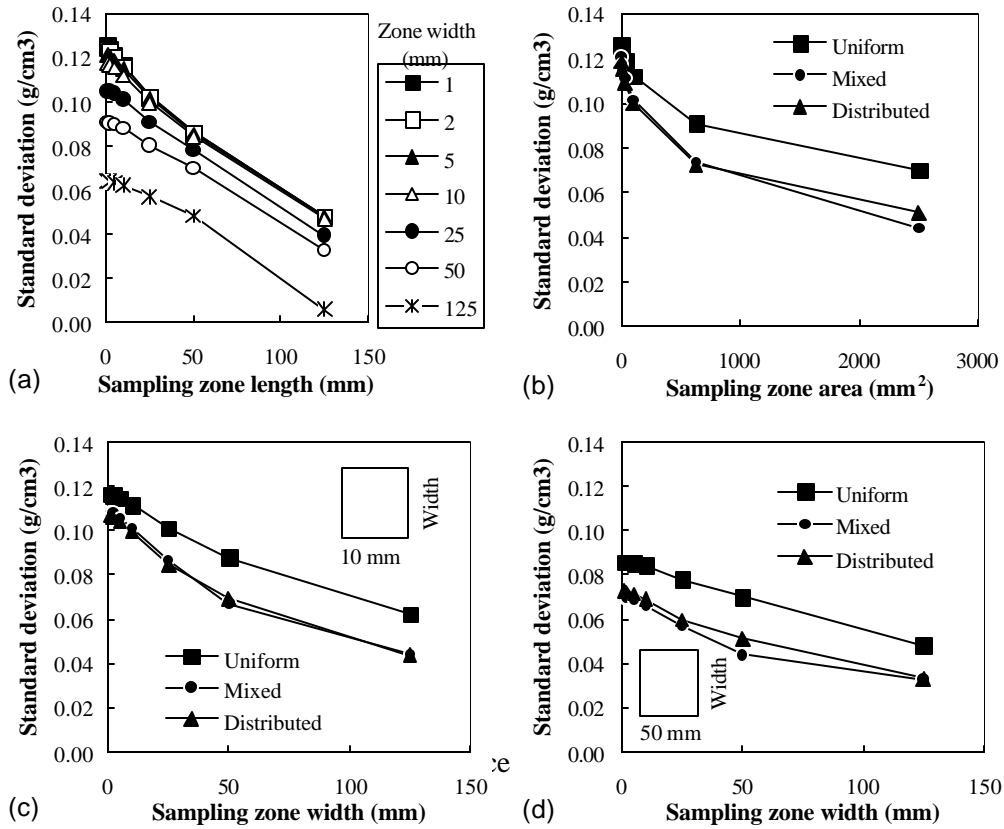


Figure 2.6 The effect of sampling zone sizes on the standard deviation of density of flakeboard mat. a) the effect of sampling zone length and width on the standard deviation of density for a uniform flake mat; b) the effect of sampling zone area on the standard deviation of density for three different types of mats; the effect of sampling zone width on the standard deviation of density for three different types of mats in the case of sampling zone length is 10mm (c) and 50mm (d).

Table 2.2 Effect of sampling zone size on the density distribution (g/cm³)

<i>Zone Size</i> (<i>x</i> × <i>y</i> mm ²)	<i>Maximum</i>	<i>Minimum</i>	<i>Average</i>	<i>Std. dev.</i>	<i>Cov (%)</i>
1×1	1.11	0.19	0.6	0.14	23.95
2×2	1.07	0.21	0.6	0.14	23.43
5×5	0.98	0.27	0.6	0.13	21.67
10×10	0.88	0.32	0.6	0.11	18.78
25×25	0.76	0.41	0.6	0.08	13.51
50×50	0.69	0.52	0.6	0.05	8.00
125×125	0.67	0.55	0.6	0.04	7.23

2.5.5. Comparison between different flake types

The uniform flake type is an ideal model available only for research purposes. Different flake sizes are used in commercial products. This simulation, therefore, includes the more useful mixed or distributed flake sizes. The results indicate that there is little difference of density distribution in the panels between the three types of flakes (**Figure 2.7**). Although different numbers of flakes were used (2652 for uniform flakes, 3689 for mixed flakes and 2703 for distributed flakes), the total flake coverage remained the same because there was the same volume of flakes in each mat. However, **Figures 2.6b** through **2.6d** show that the standard deviation of density for the uniform

flake size is quite different from those of the mixed and distributed flake types. This phenomenon is because the sampling zones used in **Figure 2.6** are much larger than the 1×1 mm resolution used to obtain the information shown in **Figure 2.7**.

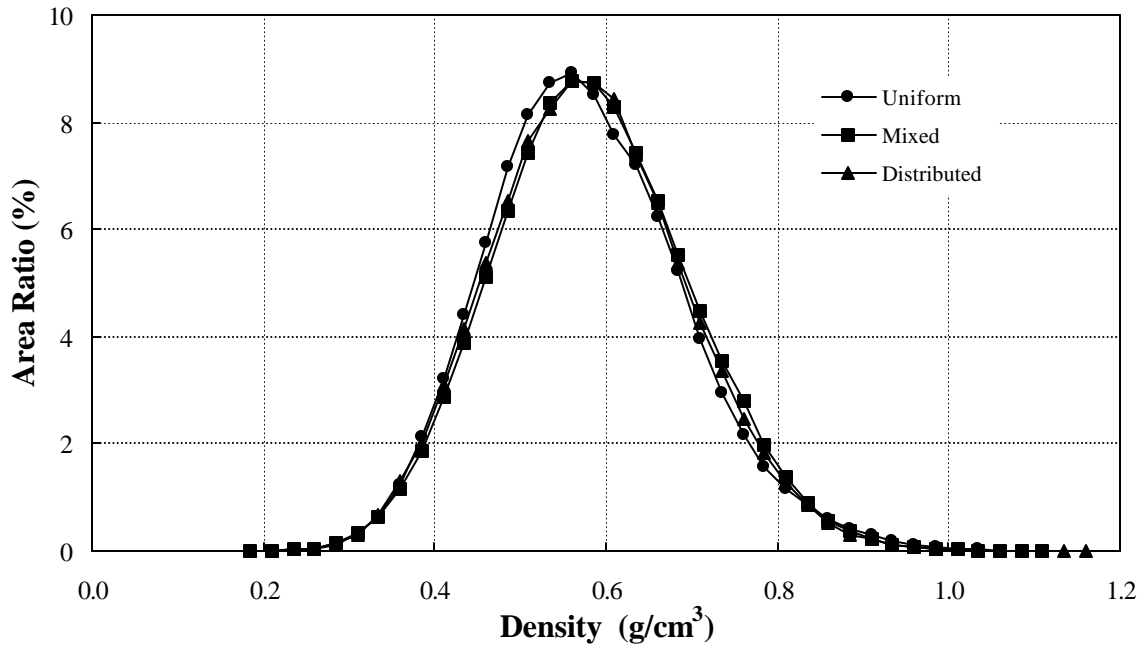


Figure 2.7 Comparison of area ratio of density obtained from three different flake types (Mat size: 500×500 mm \times 20mm).

2.6. Conclusions

With the developed simulation program, one can easily edit the input parameters, generate flake deposition information, calculate flake area coverage in any layer of a mat or the entire mat, analyze

distribution of flake overlaps and densities, and provide statistical information concerning density distribution under different sampling zones. Free flake length and void size, and their distributions can also be calculated.

The flake coverage distribution matches the mathematical model developed by Dai and Steiner (1994a and 1994b) quite well. However, their model, which describes the free flake length distribution, should be modified to consider flake width (or the aspect ratio of flake length to width). The mixed and distributed flake sizes show a lower standard deviation of density than that of uniform flake size. The total void area in any layer in a mat takes more than 1/3 of the total mat area for random formation. The standard deviation of density variation decreases dramatically as sampling zone size increases (zone length, width or area).

2.7. References

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