FLOW AND COMPACTION DURING THE ISOTHERMAL CONSOLIDATION OF A CO-MINGLED THERMOPLASTIC COMPOSITE

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In this study, the consolidation phase of the processing of a co-mingled glass/polypropylene material has been addressed. Sectional micrographs of co-mingled material at various states of consolidation have been obtained, and material has been compacted at differing rates to determine the effect of rate upon generated moulding pressure. A 1-D model of the isothermal consolidation of co-mingled material has been developed in order to validate observed consolidation processes. This model is based on fibre bed compaction and matrix flow in fibre bundles. In addition to prediction of developed moulding pressure, the model predicts fibre volume fraction and void content at each stage of consolidation. The paper concludes with a brief discussion of the use of such a model in predicting processing parameters for more complex 3-D mouldings.

INTRODUCTION

Co-mingled fabrics allow production of parts containing aligned glass fibres at higher volume fractions using lower moulding pressures than are attainable using flow moulded materials. This makes them particularly attractive to the automotive industry with the potential to permit cost and weight benefits over established material systems. Several manufacturing routes exist for processing of co-mingled materials including press moulding, vacuum bagging and autoclave moulding [1]. In order to produce high quality laminates using any of these processes economically, it is important to have an understanding of the effect of the processing parameters upon the finished laminate. Several workers, notably Klinkmuller [2], Ye [3] and Van West [4], have investigated the impregnation and consolidation mechanisms occurring during the isothermal compaction of co-mingled materials. Van West has developed a 1-D consolidation model based on a worst-case state of fibre interspersion, with the glass and matrix filaments located in two adjacent but completely separate regions. In this paper, staged compaction of a new co-mingled material is used to obtain micrographs of the fibre interspersion and matrix impregnation at states of consolidation ranging from unconsolidated to completely consolidated. Observations from these micrographs suggested a modification to the Van West consolidation model which allows improved simulation of the fibre dispersions observed for the material under study.

EXPERIMENTAL DETAILS

Materials

A balanced twill weave fabric of superficial density 650g/m^2 consisting of a yarn of 60%

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by mass co-mingled E-glass and carbon black pigmented polypropylene supplied by Vetrotex SA International under the trade name "Twintex™" was used throughout the studies. Figure 1 shows an optical micrograph of the material in the uncompacted state, in which the glass fibres and the polypropylene filaments had nominal diameters of 17 and 20 - 25 microns respectively. Because of the fibres' differing radii it is possible to qualitatively assess the relative distribution of the two components. This sample contains distinct areas of polymer and glass fibre rather than the ideal uniform intermingling of polymer and reinforcing fibres.

Specimens consisting solely of the glass reinforcement which is incorporated in Twintex were required in order to determine the compressive response of the fibre constituent. Samples of material were treated in a furnace at 400° Celsius for 300 seconds to remove the polypropylene filaments without disturbing the glass fibre architecture.

Partial compaction trials.

In these trials, the consolidation mechanism exhibited by the material was investigated by isothermally compacting material samples to differing states of consolidation. An Instron Universal Mechanical Testing Machine model 1195 with a 100 kN load cell and model 3111 hot air oven was used to compact 100 x 100 mm squares of fabric between steel platens. The temperature between the platens and of the material stack was monitored using K type thermocouples. Four layers of fabric were placed into the platens at 180 - 185° Celsius with a thermocouple inserted into the centre of the fabric. When the temperature of the material reached 180° Celsius the fabric was compacted at 1mm/min. The laminate was cooled to 100° Celsius, the load removed and the plaque extracted.

4 samples were prepared, with compaction to 25%, 50%, 75% and 100% of the cross-head displacement required to produce full consolidation. The theoretical laminate height of 0.46mm/layer was calculated on the basis of the material superficial density, the constituent densities and fibre volume fraction. At 25% consolidation (Figure 2(a)) the reinforcement bundles are distinct and separate, with some matrix material interspersed within the bundle. At 50% consolidation (Figure 2(b)) the matrix has almost coalesced, but large voids remain within and around the bundles and dispersion of fibres within the matrix is uneven. At 75% consolidation (Figure 2(c))the laminate still contains significant voidage, but matrix and reinforcement are well interspersed, and the longitudinal bundles are increasing in aspect ratio as they are compressed. At 100% consolidation (Figure 2 (d)), the fibre distribution is improved still further, and little voidage remains.

Compaction rate study

This study was conducted in order to examine the effect of compaction rate upon the consolidation of the material. The arrangement shown in Figure 3 was used to compact 100 x 100 mm samples of co-mingled material between the integrally heated steel platens. Each platen contained two electric cartridge heaters and a K-type thermocouple, which allowed independent control of the individual platens via two self-tuning PID controllers. A K-type thermocouple embedded within each platen provided the temperature feedback required by the PID controllers. The compaction force was applied by means of a servo-hydraulic system, and the platen displacement was measured by a ±5mm LVDT. The platen controllers were set to 190° Celsius,

and the platen temperature allowed to stabilise. Four layers of material with a thermocouple inserted into the centre of the stack were sandwiched between two layers of aluminium foil , and placed between the platens. When the temperature of the material reached 180° Celsius, the thermocouple was withdrawn and the material compacted at the required rate.

Samples were compacted at several rates with the lowest rate being 1mm/minute, and the highest rate being 30mm/s. Specimen data obtained during compaction of the material at 30mm/minute is shown in Figure 5. Data obtained during compaction of the material at other rates is being analysed.

CONSOLIDATION MODEL

A 1-D isothermal consolidation model for co-mingled has been developed, which is based on the work of Van West [4], but differs from the original in several of the modelling assumptions which are applied. The model assumes a constant rate of compaction is applied to the material, and the matrix material may be non-Newtonian. The material resistance to compaction is assumed to be the sum of the fibre bed compressive response and the matrix pressure. The impregnation portion of the model uses an 'effective bundle radius' which is determined as the distance the matrix must flow to wet out the fibres, and is based on observations of cross-sectional micrographs of the unconsolidated material. For the purposes of the work described in this section, an effective bundle radius of 100μm is assumed to be representative of the material.

This model is composed of four sub-models:

Fibre compaction

Modelling of the elastic response of the reinforcement is based on experimental data. Compaction tests were performed upon reinforcement only, which was obtained as described previously. The reinforcement was lubricated with an automotive 20/50 oil ("Century" supplied by Chemac Ltd) after Gutowski [5], in order to allow for the lubricating effect of the molten matrix material. A single layer of reinforcement was compacted at 1mm/minute using an Instron model 1195 testing machine. It was found that the behaviour of the fibre bed could be represented by a power-law relationship:

$$P_{fb} = A \cdot \left(\frac{h}{h_0} \right)^b \qquad (1)$$

The constants A and b were calculated to be 0.0355 and 10.0 respectively. Figure 4 shows a good correspondence between the experimental data for compaction of lubricated reinforcement and the power-law representation.

Permeability

A modified Kozeny-Carman equation as proposed by Gutowski [5] is used to predict the fibre bundle permeability coefficient:

$$K = \frac{r_i^2}{4k'} \frac{\left(\sqrt{\frac{v_a}{v_f}} - 1 \right)^3}{\left(\frac{v_a}{v_f} + 1 \right)} \tag{2}$$

The value of v_a, fibre volume fraction at zero permeability, was calculated to be 0.91 assuming hexagonal close packing of fibres. The value of k', the modified Kozeny constant is chosen to fit experimental data and uses a value of 0.9.

Impregnation

Re-arranging Van West's impregnation expression to isolate the pressure terms gives:

$$(P_r - P_v) = -\frac{\mu}{K}.\left[\frac{r_i - R_i}{\Delta t}.r_i^2.\ln\left(\frac{r_0}{r_i}\right) + \frac{U_0}{r_0}.\left(r_i^2.\ln\left(\frac{r_0}{r_i}\right).\alpha - \frac{(1+\alpha)}{2}.(r_0^2 - r_i^2) \right) \right] \tag{3}$$

The matrix pressure P_r can be derived from (3), as the void pressure P_v is governed by the ideal gas law: All other terms can be evaluated using subsidiary expressions described in [4], while the matrix flow-front radius r_i can be determined geometrically at each time step.

Matrix shear thinning

It is proposed that at ultimate compaction the reinforcing fibres will assume a hexagonal close packed structure, and at each intermediate stage of compaction the fibres will lie in a proportionately packed hexagonal array. The mean inter-fibre spacing x, can then be determined from the instantaneous volume fraction v_f by solving (4).

$$\left(\frac{x}{r_f}\right)^2 + 4\left(\frac{x}{r_f}\right) + 4 = \frac{1}{\left(Cos\frac{\pi}{6}.v_f \right)} \tag{4}$$

If the flow path between the f ibres is idealised as a rectangular channel, then the shear-strain rate attributable to flow between the fibres is given by (5), where V is the matrix flow velocity and n is the matrix power-law index.

$$\gamma_a = \frac{2n+1}{n}\left(\frac{2V}{x}\right) \tag{5}$$

$$V = \frac{r_i - R_i}{\Delta t} \tag{6}$$

The viscosity of the matrix is then determined from the manufacturer's power-law description of the matrix material shear/viscosity relationship at the required temperature (7). For example, at 180° Celsius, $B = 3971.9$ and $n = 0.37$.

$$\mu_a = B.(\gamma_a)^{(n-1)} \tag{7}$$

RESULTS

Specimen model output is displayed in Figure 5, which shows developed pressure vs. rational laminate height for compaction at 30mm/minute. The general form of the curves show an increase in developed pressure with increasing state of consolidation (that is, as the instantaneous height h tends to h_f, the ultimate laminate height). As the areas of dry fibre are incrementally impregnated, and the radius of dry fibre decreases, the radial flow rate into the remaining dry area increases.

A reasonable correspondence with the experimental data is obtained, with the ultimate predicted value of developed moulding pressure being slightly lower than the measured value.

DISCUSSION

The model shows a reasonable agreement with measured behaviour. However, areas of concern include difficulties inherent in acquiring reliable permeability data, as well as the dangers of applying a model based on a mean flow path distance to a material of varying consistency. Accuracy in determination of the flow path length could be improved by use of image analysis techniques, as estimates based on visual observations provide only a partially satisfactory basis for establishing model parameters.

Industrial applications of co-mingled materials will probably involve non-isothermal processing conditions, and will exploit the drapeability of the fabric to form 3-D components. Further work is aimed at accommodating these conditions by integrating consolidation modelling with heat transfer and deformation models.

CONCLUSIONS

A consolidation mechanism has been identified for a co-mingled glass/polypropylene material. A model based on a previous worker's analysis has been adapted and applied to this material, giving a reasonable agreement withe experimental compaction data.

This model, if combined with a material forming model, should provide the basis for modelling the processing complex 3-D components, giving manufacturers a rational method for process design for these materials.

Nomenclature

A	=	Power-law constant	r_1	=	Flow front rad. in equiv. circular bundle
b	=	Fibre bed compaction exponent	r_0	=	Equivalent circular bundle outer radius
B	=	Power-law constant	R_1	=	Flow front radius, previous time step
h	=	Laminate instantaneous height	Δt	=	Duration of a time step
h_f	=	Laminate ultimate height	U_0	=	Fibre velocity at bundle outer radius
h_0	=	Laminate initial height	v_a	=	Fibre v/f at zero permeability
H	=	Laminate thickness, previous time step	v_f	=	Instantaneous fibre to non-fibre v/f
k'	=	Modified Kozeny constant	V	=	Matrix flow velocity
K	=	Permeability coefficient	x	=	'Average' fibre spacing within a bundle
n	=	Matrix power-law index	α	=	Solid to liquid volume ratio
P_{fb}	=	Fibre bed pressure	γ_a	=	Apparent matrix shear strain rate
P_r	=	Matrix pressure	μ	=	Matrix viscosity
P_v	=	Void pressure	μ_a	=	Apparent matrix viscosity (= μ)
r_f	=	Radius of a reinforcing fibre			

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Figures

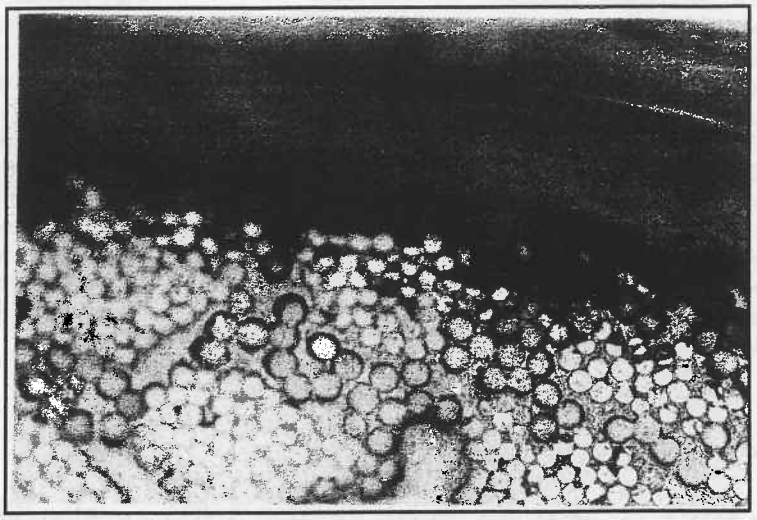

Figure 1: Unconsolidated Co-mingled Material.

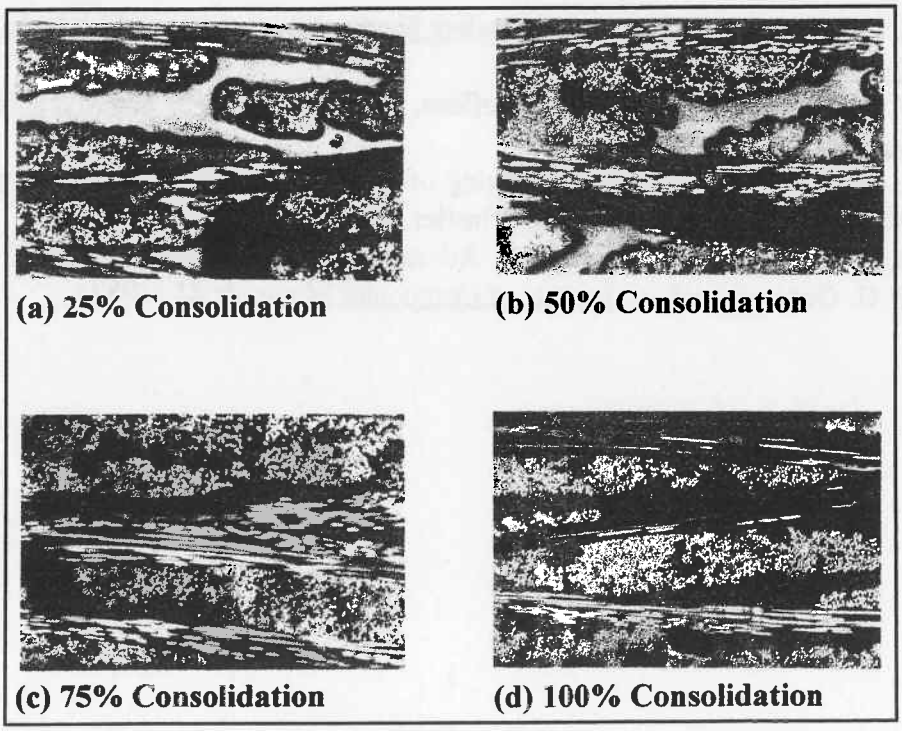

Figure 2: Co-mingled Material, States of Consolidation.

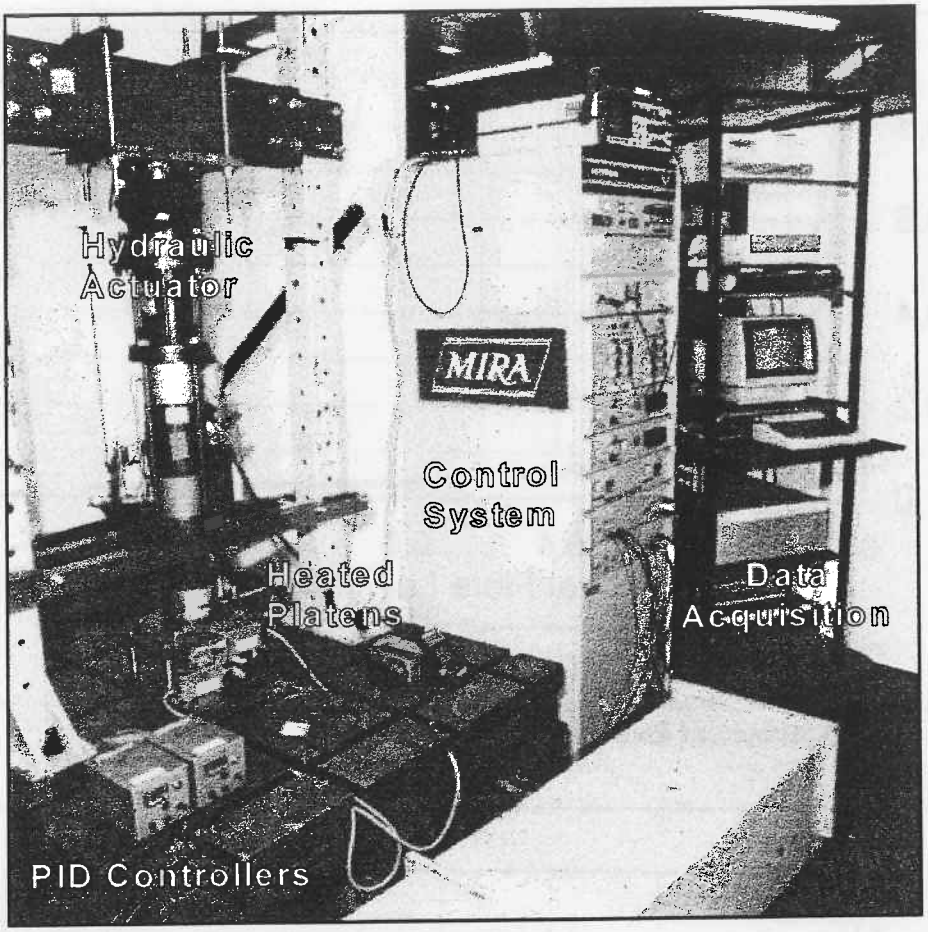

Figure 3a: Experimental Arrangement

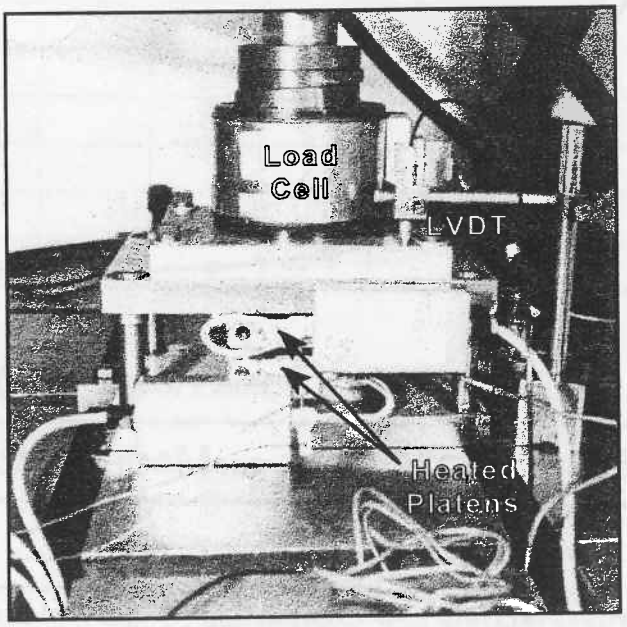

Figure 3b: Experimental Arrangement - Detail View

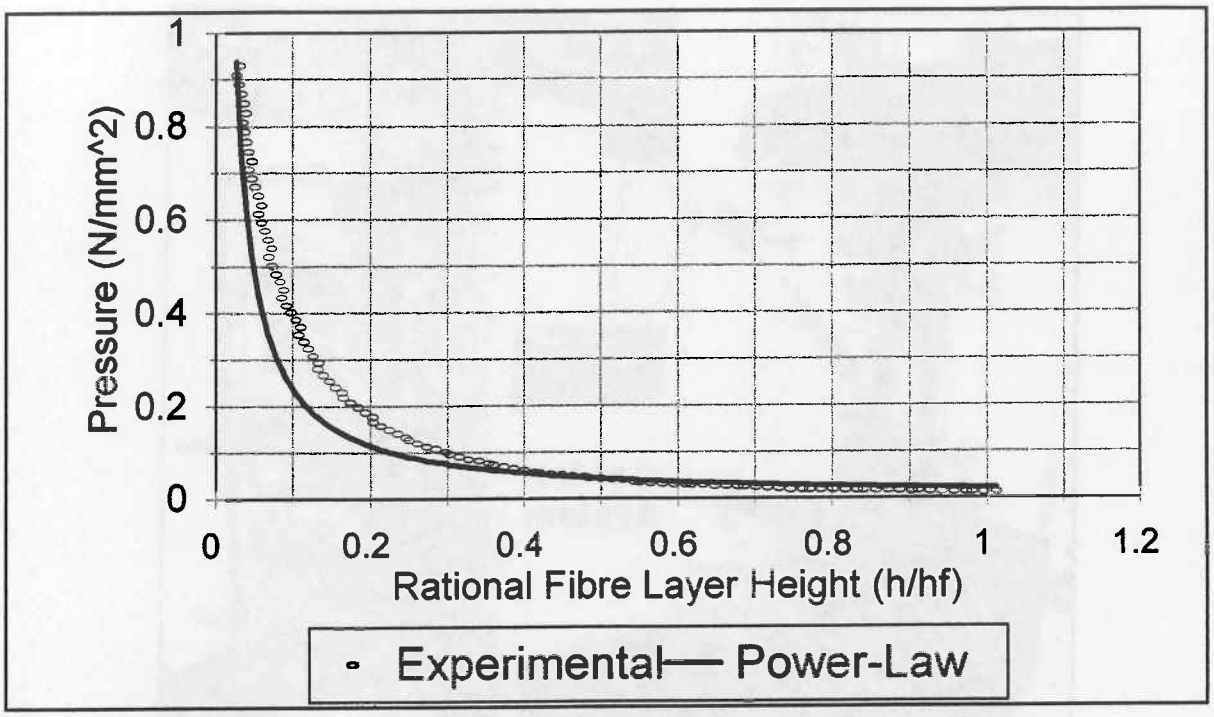

Figure 4: **Reinforcement Lubricated Compaction.**

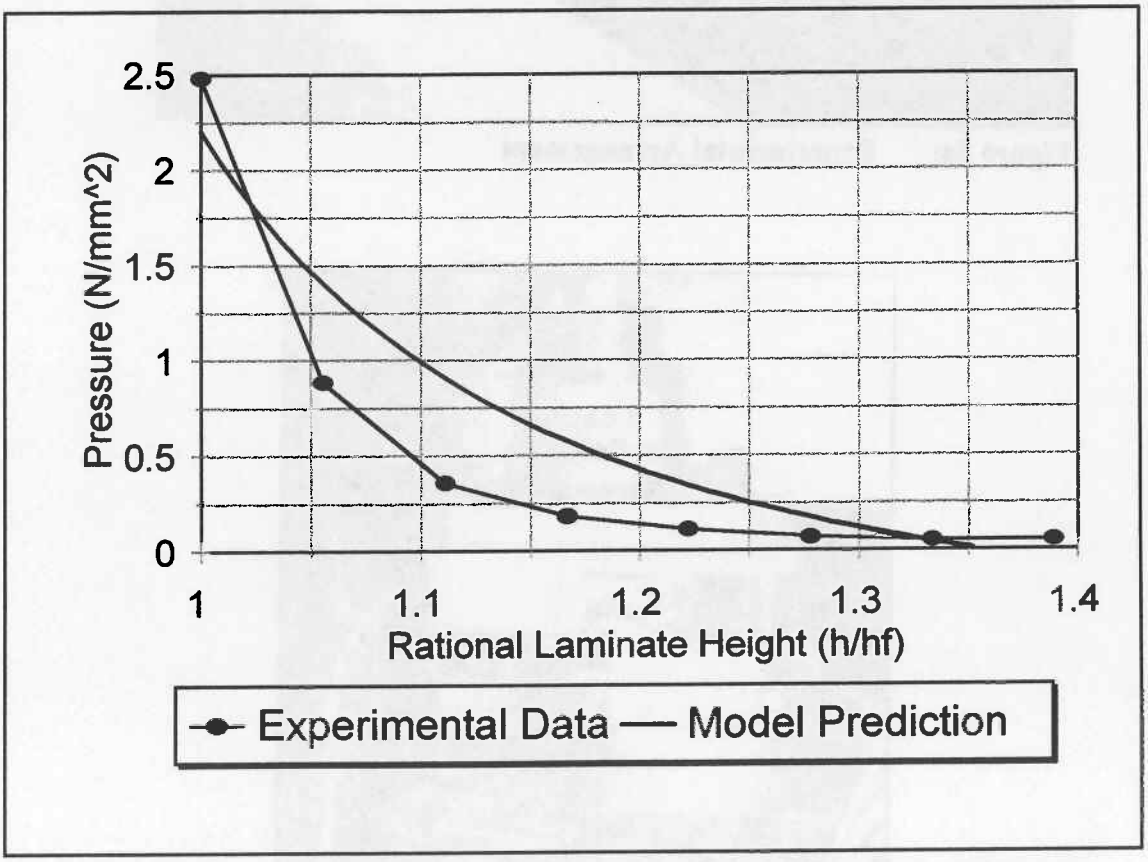

Figure 5: **Experimental Data and Compaction Model Output at 30mm/min.**