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A RECEDING EVAPORATIVE FRONT MODEL FOR THE DRYING CHARACTERISTICS OF A FLAT PLATE II: STRESS AND STRAIN DEVELOPMENT.

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ABSTRACT

An analysis that captures the receding drying front is presented for the stress and strain produced during a three-stage drying process of an elastic flat plate with a fixed base. In tne first stage (saturated stage), the body is fully saturated and pressure-driven flow prevails according to Darcy's Law. During the second stage (partially saturated stage), the evaporative front recedes through the material and divides the material into saturated and unsaturated zones; the equations for saturated flow apply to the saturated region, while moisture transport in the unsaturated region is by diffusion. During the third stage (fully unsaturated stage), the body is entirely unsaturated and moisture is lost by diffusion only. The position of the evaporative front is updated using the maximum capillary tension at the interior of the evaporative front as it recedes through the material. The stress on the solid matrix increases in proportion to the thickness of the plate and the rate of evaporation, and in inverse proportion to the permeability. The maximum stress occurs at the drying surface of the plate.

KEYWORDS: Drying; Stress; Strain; Evaporative front; Flat plate.

INTRODUCTION

In Part I of this series (Puyate, 2005), the theory on the drying characteristics of a flat plate is presented, as well as a proposed three-stage drying process for porous materials. In the first stage (saturated stage), the body is fully saturated and capillary flow prevails. During the second stage (partially saturated stage), the evaporative front recedes into the material and divides it into two regions; the interior of the material remains saturated up to the evaporative front, while the exterior part of the material is unsaturated. During the third stage (fully unsaturated stage), the saturated region of the partially saturated stage is obliterated and the body becomes fully unsaturated; moisture transport within the body during this stage is by diffusion only.

Scherer (1987b) has developed a capillary flow model for calculating the elastic stress and strain produced during drying of a flat plate, through the pressure distribution within the body. Darcy's Law was applied to derive a diffusion equation for the pressure in the liquid, which was solved using a two-stage model. In the first part of the model (the constant-rate period), the evaporation rate is constant and the capillary tension within the liquid rises. A critical point is reached when the capillary tension reaches a maximum value at the free surface, and this marks the end of the first stage. In the second stage of the model (the falling-rate period), the capillary tension at the free surface remains fixed at the maximum value and the drying rate gradually decreases. In this approach, the drying front is effectively pinned at the free surface as the falling-rate period progresses, which is inconsistent with reality.

Since Scherer's model is based on capillary flow, the model is clearly appropriate for the initial stage of drying when the body is saturated. When the drying front recedes into the material, Scherer's model applies only to the saturated region of the partially saturated stage. Within the unsaturated region of the partially saturated stage, and during the fully unsaturated stage, Scherer's model does not apply; yet the model was used to describe the entire drying process of a flat plate from the saturated stage to dryness. There are other inconsistencies in Scherer's analysis which are pointed out in the work by Puyate (2005).

However, in the present paper, when the capillary tension reaches its maximum value at the exterior surface, the evaporative front is drawn into the material and the body is only partially saturated. The equations for saturated flow prevail in the saturated region of the body, and the capillary tension at the evaporative front remains at the maximum value as the evaporative front recedes through the body. Most of the stress build-up and shrinkage occur during the saturated stage, although as will be shown, some stress also occurs during the partially saturated stage.

This paper presents a model for calculating the stress and strain that develop during a three-stage drying process of an elastic flat plate with a fixed base, taking into account the transient evolution of the evaporative front. Like Scherer's analysis (Scherer, 1987a, 1987b, 1990), this work is based on a diffusion equation for the pressure in the liquid, but with a different diffusion coefficient, which is rigorously derived for a flat plate with a fixed base as follows.

Model development

The equation for continuity (conservation of matter) during the saturated stage of drying is given by (Puyate, 2005; Scherer, 1990)

$$\dot{\varepsilon}_{ll} = \frac{\kappa}{\eta_L}\frac{\partial^2 P_L}{\partial x_l^2} \tag{1}$$

where in index notation $i = 1, 2, 3$ and $x_1 = x$, $x_2 = y$, $x_3 = z$; $\dot{\varepsilon}_{ll}$ is the volumetric strain rate and the superscript dot indicates the partial derivative with respect to time, the repeated index (l) indicates summation, $P_L = p_L - p_{atm}$ is the gauge

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pressure in the liquid (where p_L is the pressure in the liquid, and p_{atm} is the atmospheric pressure). κ and η_L are taken to be constant and represent the permeability of the porous medium and viscosity of the liquid respectively. After the *entry point* (Puyate, 2005), the network is no longer able to shrink at a rate equal to the rate of evaporation and the meniscus retreats into the material; then eq. (1) applies only within the saturated zone inside the body.

Just as calculation of thermal stresses requires knowledge of the temperature distribution, prediction of drying stresses depends on calculation of the pore pressure distribution. This involves expressing the volumetric strain rate, $\dot{\varepsilon}_{ll}$, in eq. (1) in terms of the gauge pressure in the liquid using a constitutive equation for the network. Various authors have done this by assuming elastic behaviour of the network with the solid and liquid phases compressible (Biot, 1941) or incompressible (Scherer, 1987b), or allowing the network to be purely viscous (Scherer, 1986) or viscoelastic (Biot, 1954; Scherer, 1988).

In the current work, the network is taken to be compressible and linearly elastic, while the solid and liquid phases are taken to be incompressible, upon which, the total stress borne by the solid phase is obtained as

$$\sigma_{ij}' = -P_L\delta_{ij} + \frac{E_p}{1+\nu_p}\left(\varepsilon_{ij} + \frac{\nu_p}{1-2\nu_p}\varepsilon_{ll}\delta_{ij}\right) \quad (2)$$

where σ_{ij} is the stress (tensor) acting on a saturated porous body, δ_{ij} is the Kronecker delta, E_p and ν_p are the Young's modulus and Poisson's ratio respectively for the porous matrix, ε_{ll} is the volumetric strain, and ε_{ij} is the linear strain tensor given in terms of the displacement vector u_i by

$$\varepsilon_{ij} = \frac{1}{2}\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i}\right) \quad (3)$$

and assumed to be small (Puyate, 2005).

For a one-dimensional drying process with fluid transport in the $z-$direction, P_L is taken to be independent of the *x* and *y* directions in a Cartesian co-ordinate system, and eq. (1) reduces to

$$\dot{\varepsilon}_{ll} = \frac{\kappa}{\eta_L}\frac{\partial^2 P_L}{\partial z^2} \quad (4)$$

Hence ε_{ll} and $\dot{\varepsilon}_{ll}$ are also independent of *x* and *y*. It is further assumed that the displacement of material in the $z-$direction (u_z), and hence the normal strain in the $z-$direction (ε_{zz}) are also independent of *x* and *y*. For a drying material that is homogenous in the plane, the normal strains in the horizontal *x* and *y* directions are taken to be equal; that is, $\varepsilon_{xx} = \varepsilon_{yy} = \varepsilon_H$, and the volumetric strain becomes

$$\varepsilon_{ll}(=\varepsilon_T) = \varepsilon_{xx} + \varepsilon_{yy} + \varepsilon_{zz} = 2\varepsilon_H + \varepsilon_{zz} \quad (5)$$

where ε_T is the 'total' and ε_H is the 'horizontal' strain. Since ε_T and ε_{zz} are independent of *x* and *y*, so is ε_H (Puyate, 1999). Accordingly, the displacements in the *x* and *y* directions can be obtained as

$$u_x = \varepsilon_H x, \qquad u_y = \varepsilon_H y \quad (6)$$

Equations (6) are consistent with the definition for normal strain under the assumed conditions (Shanley, 1957). The normal stresses can be obtained from eq. (2) as

$$\sigma_{xx} = \sigma_{yy} = -P_L + \frac{E_p}{1+\nu_p}\left(\varepsilon_H + \frac{\nu_p}{1-2\nu_p}\varepsilon_T\right) \quad (7)$$

$$\sigma_{zz} = -P_L + \frac{E_p}{1+\nu_p}\left((\varepsilon_T - 2\varepsilon_H) + \frac{\nu_p}{1-2\nu_p}\varepsilon_T\right) \quad (8)$$

Thus σ_{xx} and σ_{yy} are independent of *x* and *y*. The equilibrium equation for isotropic linear elastic saturated porous bodies requires that (Puyate, 1999, 2005)

$$\frac{\partial \sigma_{xz}}{\partial z} = 0 \tag{9}$$

The stress component σ_{xz} can be related to the strain component ε_{xz} using eq. (2) through eqs. (3), (6), and (9), to obtain the component strains

$$\varepsilon_{xz} = \frac{B_H}{2}x, \quad \varepsilon_{yz} = \frac{B_H}{2}y \tag{10}$$

with the corresponding component stresses

$$\sigma_{xz} = \frac{E_p B_H}{2(1+\nu_p)}x, \qquad \sigma_{yz} = \frac{E_p B_H}{2(1+\nu_p)}y \tag{11}$$

and the displacements

$$u_x = (A_H + B_H z)x, \qquad u_y = (A_H + B_H z)y \tag{12}$$

where A_H and B_H are unknown constants. Equations (4)-(12) hold for one-dimensional cases. We now derive the diffusion equation for the pressure in the liquid, and the expressions for the stresses and strains that develop during drying of a flat plate with a fixed base.

Flat plate with a fixed base

Let the saturated porous body be a flat plate of thickness *L* which is homogenous in the *x* and *y* directions. The $x-y$ plane lies at the lower surface of the plate which is fixed at $z = 0$, while the upper surface at $z = L$ is free. The plate is assumed to adhere to a rigid substrate as it dries. This is a reasonable model for the slip casting of a ceramic suspension (Brisçoe et al., 1998; Puyate, 1999). Evaporation occurs at the free surface so that variations of P_L stresses, and strains, occur mainly in the $z-\text{direction}$. Since the plate cannot contract parallel to the $x-y$ plane, $u_x = u_y = 0$ at $z = 0$. There is no external force applied to the surface of the plate (as drying progresses) so $\sigma_{zz} = \sigma_{xz} = \sigma_{yz} = 0$ at $z = L$; this implies $B_H = 0$ in eq. (11). The equilibrium equation for isotropic linear elastic saturated porous bodies also requires that

$$\frac{\partial \sigma_{zz}}{\partial z} = 0 \tag{13}$$

It may be seen from eq. (13) that σ_{zz} is a constant on integration. Since $\sigma_{zz} = 0$ at $z = L$, it means $\sigma_{zz} = 0$ everywhere in the plate. Putting $\sigma_{zz} = 0$ and $\varepsilon_H = 0$ into eq. (8), with $\varepsilon_T = \varepsilon_{II}$ gives

$$P_L = \frac{E_p(1-\nu_p)}{(1+\nu_p)(1-2\nu_p)}\varepsilon_{II} \tag{14}$$

So, in this case, P_L is proportional to ε_{II}. The volumetric strain rate is obtained from eq. (14), which is then used in eq. (4) to give the diffusion equation for P_L in the $z-\text{direction}$ as

$$\frac{\partial P_L}{\partial t} = D\frac{\partial^2 P_L}{\partial z^2} \tag{15}$$

where $D = \kappa E_p(1-\nu_p)/\eta_L(1+\nu_p)(1-2\nu_p)$ as in Puyate (2005)

Pressure distribution

In this section, models for the pressure distributions in the saturated stage and within the saturated region of the partially saturated stage, are presented for the one-dimensional drying of a flat plate whose base is fixed. The receding evaporative front is accounted for in the models, and Darcy's Law is used to describe saturated pressure-driven flow.

Stage 1. Saturated stage

During the saturated stage, the pores are full of liquid so Darcy's Law holds; the governing equation for the pressure distribution is given by eq. (15), which is restated here for the sake of convenience as

$$\frac{\partial P_L}{\partial t} = D\frac{\partial^2 P_L}{\partial z^2} \qquad 0 < z < L \qquad (16)$$

where z is the distance measured in the direction of fluid flow, L is the thickness of the plate, t is time, and P_L and D are as defined before. Initially, the free surface of the plate is covered with a film of liquid (flat surface) so the capillary tension in the liquid is zero, and $P_L = 0$. Since the rate of evaporation is constant during the saturated stage, the evaporative flux must balance the pressure flux at the free surface ($z = L$), while the pressure flux at the unexposed face ($z = 0$) is zero. The initial and boundary conditions of eq. (16) for the saturated stage may then be expressed as

$$t = 0: \qquad P_L = 0 \qquad (17a)$$

$$z = 0: \qquad \frac{\partial P_L}{\partial z} = 0 \qquad (17b)$$

$$z = L: \qquad \frac{\partial P_L}{\partial z} = -\frac{\alpha\eta_L}{\rho_L\kappa} \qquad (17c)$$

where α is the constant rate of evaporation per unit area in the saturated stage, κ is the permeability of the plate, and ρ_L is the density of the liquid. The saturated stage ends when P_L falls to a minimum value $P_{\min}$ at the surface, corresponding to a maximum capillary tension $\varphi_{\max}$. Thereafter, the menisci recede into the pores and the partially saturated stage begins.

Stage 2. Partially saturated stage

Equation (16) applies to the saturated region of this stage, with the initial condition corresponding to the pressure distribution at the end of the saturated stage (Puyate, 2005); the pressure at the interior evaporative front remains at $P_{\min}$ as the evaporative front retreats into the body. The governing equation for the saturated region of the partially saturated stage may then be expressed as

Saturated zone

$$\frac{\partial P_L}{\partial t} = D\frac{\partial^2 P_L}{\partial z^2} \qquad 0 < z < z_i(t) \qquad (18)$$

with the corresponding conditions

$$t = t_E: \qquad P_L = P_E(z, t_E) \qquad (19a)$$

$$z = 0: \qquad \frac{\partial P_L}{\partial z} = 0 \qquad (19b)$$

$$z = z_i(t): \qquad P_L = P_{\min} \qquad (19c)$$

where t_E is the time for the end of the saturated stage (the entry time), $P_E(z, t_E)$ is the pressure distribution at the end of the saturated stage, and $z_i(t)$ is the time-dependent interface (evaporative front) position assumed to be sharp.

The saturated and unsaturated regions of the partially saturated stage may be coupled through a continuity of flux condition at the evaporative front, with which, the motion of the evaporative front can be determined. However, a more useful expression may be obtained from the boundary condition (19c), which may be differentiated with respect to time to give the rate of change of the position of the evaporative front as

$$\dot{z}_i(t) = -\frac{D}{L}\left(\frac{\partial^2 P_L/\partial z^2}{\partial P_L/\partial z}\right)_{z=z_i(t)} \qquad (20)$$

where the superscript dot indicates the derivative with respect to time. The initial condition for the location of the evaporative front is

$$t = t_E : \qquad z_i(t_E) = L \tag{21}$$

Note that at the inception of the partially saturated stage, the extent of the unsaturated zone is infinitesimal, so that the initial condition (21) is appropriate. The partially saturated stage ends when the evaporative front reaches the unexposed face of the plate, where $z_i(t) = 0$, and the saturated region is obliterated.

Stresses and strains

Once P_L has been found, the non-zero components of the stress are given by eq. (7) with $\varepsilon_T = \varepsilon_{II}$ and $\varepsilon_H = 0$ as

$$\sigma_{xx} = \sigma_{yy} = -P_L + \frac{E_p \nu_p}{(1+\nu_p)(1-2\nu_p)} \varepsilon_{II} \tag{22}$$

Using the expression for ε_{II} from eq. (14) in eq. (22) gives this stress as

$$\sigma_{xx} = \sigma_{yy} = -G_1 P_L \tag{23}$$

where $G_1 = (1-2\nu_p)/(1-\nu_p)$. The value of ν_p is expected to be small for a material whose liquid-free porous network is highly compressible, giving $G_1 \approx 1$ in such cases. Thus the stress is proportional to the local pressure in the liquid when the base of a material is fixed and drying occurs from only one exposed face. The stress carried by the solid matrix is

$$\sigma_{Mxx} = \sigma_{xx} + P_L = G_2 P_L \tag{24}$$

where $G_2 = \nu_p/(1-\nu_p)$. Since P_L is negative, this stress is compressive. The only non-zero component of the strain is

$$\varepsilon_{zz} = \varepsilon_{II} = \varepsilon_T = G_3 P_L / E_p \tag{25}$$

where $G_3 = (1+\nu_p)(1-2\nu_p)/(1-\nu_p)$.

3. Solution for the drying equations for the two stages

Using the dimensionless variables

$$F = \frac{P_L}{P_{\min}} \qquad Z = \frac{z}{L} \qquad Z_i(\tau) = \frac{z_i(t)}{L} \qquad \tau = \frac{tD}{L^2} \tag{26}$$

in eqs. (16)-(21) gives a set of dimensionless equations in each of the two stages of drying. In order to fix the size of the saturated region of the partially saturated stage, *Z* is rescaled by $Z_i(\tau)$ in the form

$$\zeta = \frac{Z}{Z_i(\tau)} \tag{27}$$

where ζ is a new dimensionless spatial variable.

Stage 1. Saturated stage

Using ζ from eq. (27) in the dimensionless form of eq. (16) gives the rescaled dimensionless transport equation in the saturated stage as

$$\frac{\partial F}{\partial \tau} = \frac{\partial^2 F}{\partial \zeta^2} \qquad 0 < \zeta < 1 \tag{28}$$

with the corresponding conditions

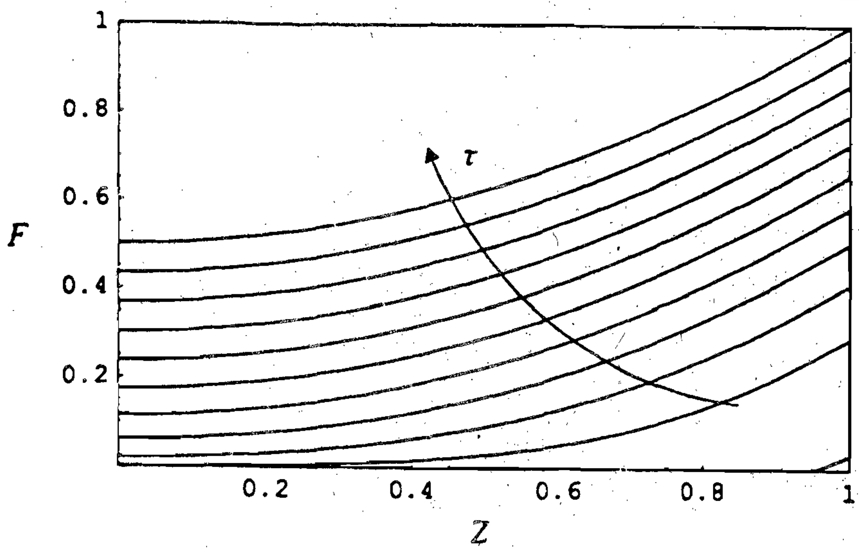

Fig. 1. Pressure distribution in the plate during the saturated stage.

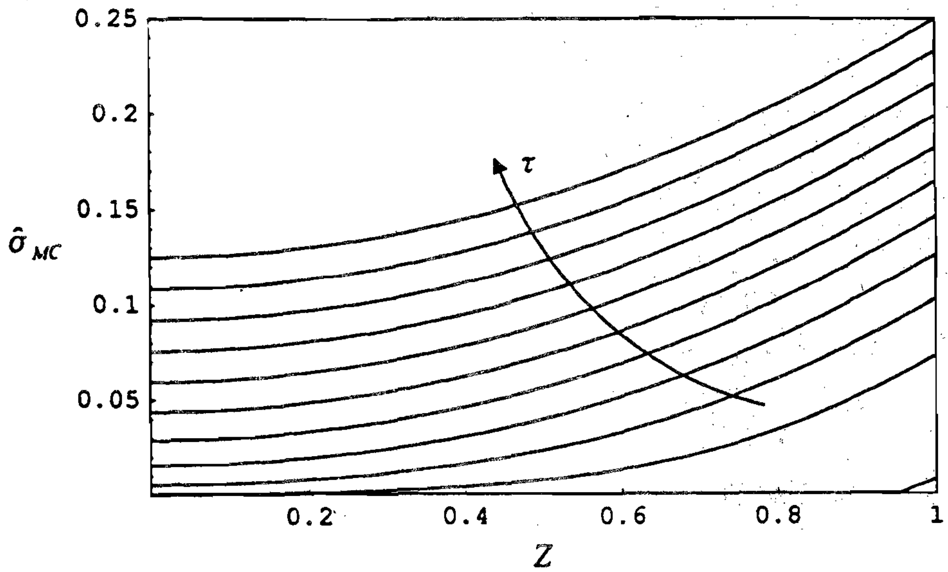

Fig. 2. Stress supported by the solid matrix during the saturated stage.

$$\tau = 0: \qquad F = 0 \tag{29a}$$

$$\zeta = 0: \qquad \frac{\partial F}{\partial \zeta} = 0 \tag{29b}$$

$$\zeta = 1: \qquad \frac{\partial F}{\partial \zeta} = \lambda \tag{29c}$$

where $\lambda = \alpha\eta_L L / |P_{\min}| \rho_L \kappa$ is a dimensionless evaporation rate (or drying intensity) that relates the characteristic times for evaporation and liquid flow. When λ is large, evaporation is fast, large pressure gradients occur, and the saturated stage is short. Conversely, when λ is small, evaporation is slow, the pressure gradients are small, and the saturated stage is long. Note that during the saturated stage, the evaporative front remains at the surface of the plate so that $Z_i(\tau) = 1$ and $\zeta = Z$. The saturated stage ends at $\tau = \tau_E$, when F increases to unity at $Z = 1$.

In order to match the pressure distribution of the saturated stage at τ_E with the initial condition of the saturated zone of the partially saturated stage, eq. (28) has been solved numerically using conditions (29). The numerical solutions have been obtained by converting the governing equations to a system of non-linear ordinary differential equation; the spatial derivatives were approximated using second-order central differences in the partial differential equations, and second-order one-sided differences in the boundary and interface conditions (Puyate, 1999). The resulting system of ordinary differential equations was integrated using Runge-Kutta procedure implemented in *Mathematica*.

Figure 1 shows a plot of F against Z for increasing values of τ, representing the pressure distribution in the plate during the saturated stage. In this and subsequent figures, the parameter value $\lambda = 1$ is used, for which $\tau_L = 0.667$ (determined numerically). The dimensionless variable F represents the tension in the liquid, so the pressure in the liquid will be high in the region of low tension, and vice versa. Thus, the pressure distribution represented in Fig. 1 is uniform, with higher pressure further from the drying surface.

Stresses and strains during the saturated stage

The stress carried by the solid matrix may be expressed using eq. (24) in dimensionless form as

$$\hat{\sigma}_{Mxx} = \frac{\sigma_{Mxx}}{|P_{\min}|} = -G_2 F \qquad (30)$$

where G_2 is as defined before, and the caret indicates the dimensionless variable. The negative sign in eq. (30) simply indicates that the stress on the matrix is compressive; thus the dimensionless compressive stress on the matrix may be represented by $\hat{\sigma}_{MC} = -\hat{\sigma}_{Mxx}$. Figure 2 shows a plot of $\hat{\sigma}_{MC}$ against Z for a range of values of τ for $\lambda = 1$ and $\nu_p = 0.2$. It may be seen from Fig. 2 that the compressive stress at any time in the plane of the plate is always lower at the fixed base than at the surface, and the magnitude of this stress depends on the value of G_2. The stress developed in the plate during the saturated stage is proportional to the rate of evaporation and the thickness of the plate, and is inversely proportional to the permeability; that is, the stress is increased by those factors that steepen the pressure gradient and therefore grows with the intensity of drying. The maximum stress occurs at the surface of the plate when P_L falls to $P_{\min}$ ($F = 1$) and the liquid exerts the maximum possible force; this maximum stress may be seen from eq. (30) to be $G_2|P_{\min}|$. With the stress at the surface of the plate higher than that at the fixed base, permanent deformation due to stressing beyond the elastic limit would be expected to start appearing at the surface.

The volumetric strain comes entirely from the contraction of the plate in the direction (z) normal to the plate, and may be expressed using eq. (25) as

$$\varepsilon_{zz} = \varepsilon_{ll} = -G_3|P_{\min}|F/E_p \qquad (31)$$

where G_3 is as defined before, and the negative sign indicates shrinkage. Clearly, the strain distribution during the saturated stage is similar to the stress distribution.

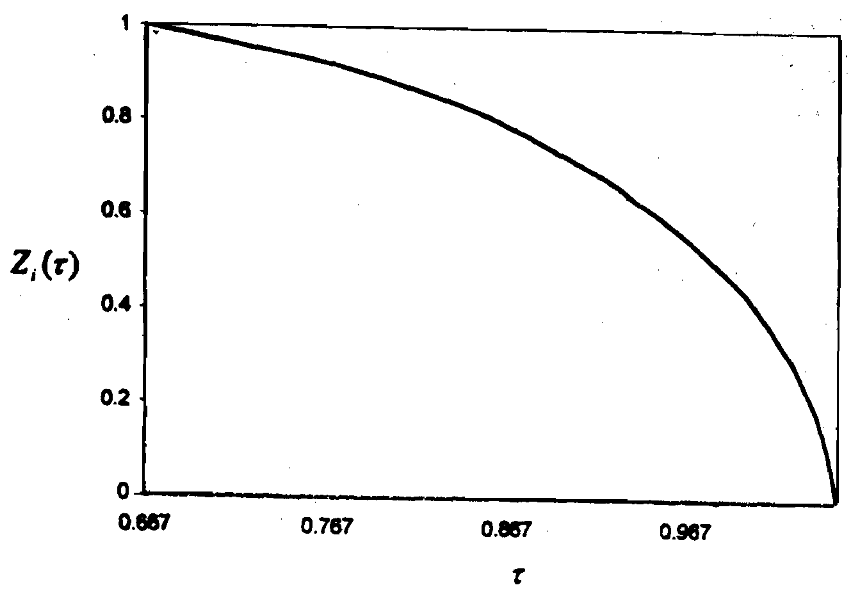

Fig. 3. Evolution of the evaporative front position during the partially saturated stage.

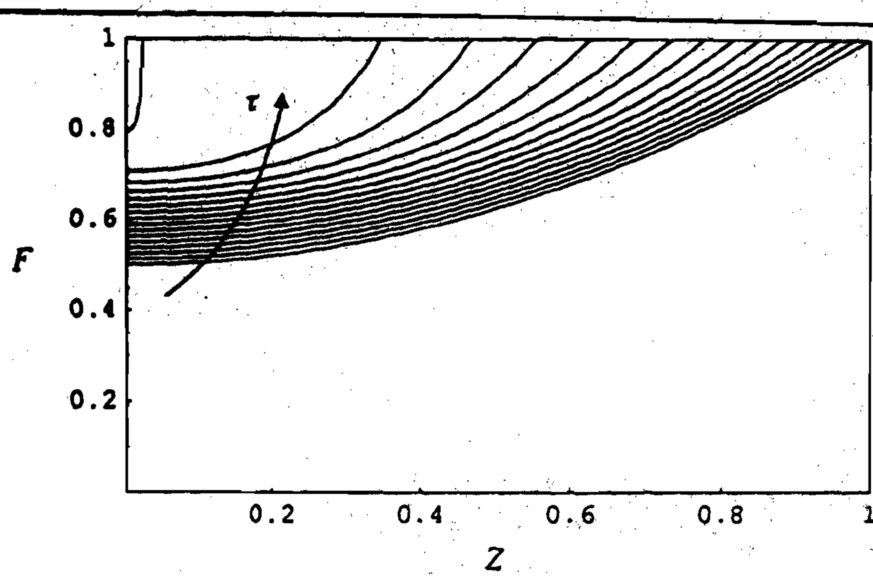

Fig. 4. Pressure distribution in the saturated zone of the partially saturated stage.

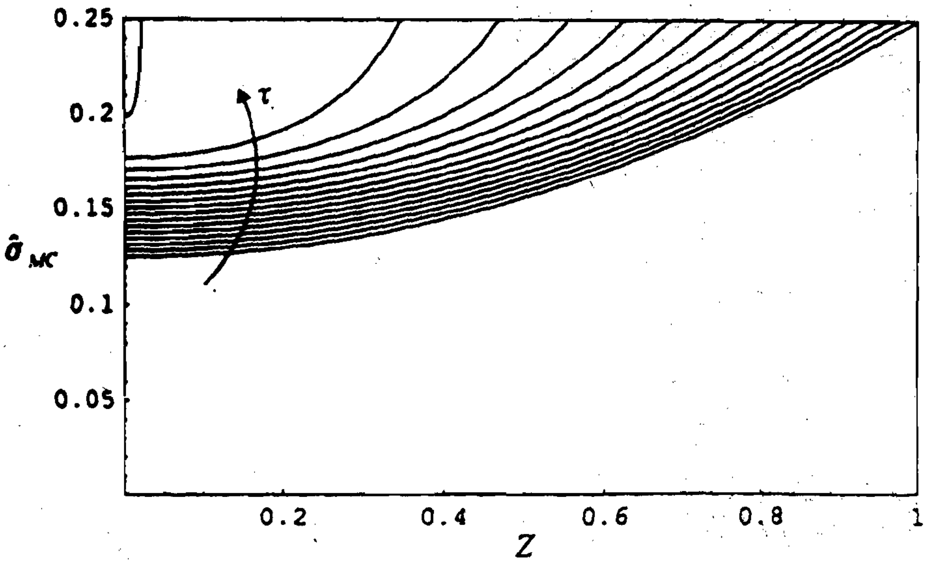

Fig. 5. Stress supported by the solid matrix in the saturated zone of the partially saturated stage.

Stage 2. Partially saturated stage

The rescaled dimensionless transport equation in the saturated zone of this stage can be obtained as

Saturated zone

$$\frac{\partial F}{\partial \tau} - \left(\frac{\dot{Z}_i(\tau)}{Z_i(\tau)} \zeta \right) \frac{\partial F}{\partial \zeta} = \frac{1}{Z_i^2(\tau)} \frac{\partial^2 F}{\partial \zeta^2} \qquad 0 < \zeta < 1 \tag{32}$$

with the corresponding conditions

$$\tau = \tau_E : \qquad F = F_E(\zeta, \tau_E) \tag{33a}$$

$$\zeta = 0 : \qquad \frac{\partial F}{\partial \zeta} = 0 \tag{33b}$$

$$\zeta = 1 : \qquad F = 1 \tag{33c}$$

The rescaled form of eq. (20) which is used to update the position of the evaporative front becomes

$$\dot{Z}_i(\tau) = -\frac{1}{Z_i(\tau)}\left(\frac{\partial^2 F/\partial\zeta^2}{\partial F/\partial\zeta}\right)_{\zeta=1} \tag{34}$$

with the initial condition

$$\tau = \tau_E: \qquad Z_i(\tau_E) = 1 \tag{35}$$

Figure 3 shows the transient evolution of the evaporative front from the end of the saturated stage to the end of the partially saturated stage. It may be seen from Fig. 3 that the partially saturated stage ends when $\tau_{II} \approx 1.05$.

As the evaporative front recedes into the plate after the dimensionless entry time τ_E, the interior of the plate between the unexposed face and the evaporative front remains saturated until the evaporative front reaches $Z = 0$ at $\tau = \tau_{II}$. Equation (32) can then be solved numerically using conditions (33) to obtain he pressure distribution in the saturated zone of the partially saturated stage for the period from τ_E to τ_{II} as shown in Fig. 4.

Stresses and strains during the partially saturated stage

The stress in the partially saturated stage occurs only in the saturated zone where the pores are full of liquid and Darcy's Law applies. Figure 5 shows the compressive stress distribution on the solid matrix of the saturated region of the partially saturated stage for the period $\tau_E \le \tau \le \tau_{II}$ with $\nu_p = 0.2$; the corresponding strain distribution is similar to the stress distribution. As the saturated zone recedes into the plate, an elastic plate expands slightly as the total stress on the network is relieved (Kawaguchi et al., 1986; Simpkins et al., 1989).

CONCLUSION

An analysis has been presented to describe the stress and strain that develop during a three-stage drying process of a flat plate with a fixed base, in which the solid network is assumed to be elastic, with the solid and liquid phases incompressible. Fluid transport through pores of the body is assumed to obey Darcy's Law in the saturated region. Although the means of calculating drying stresses and strains through the pressure distribution have been developed relatively recently, the present model which captures the receding drying front offers a more qualitative description of drying stresses and strains.

The stress results from a gradient in pressure in the liquid in the pores of the drying body. The stress increases with the drying rate and the thickness of the body, and is inversely related to the permeability of the body. The compressive stress on the network is greater at the drying surface, and reaches a maximum value at the entry point. At the end of the partially saturated stage, the body will recover its original shape if it is truly elastic because the stress on the matrix will have been released. If the material is plastic and the yield stress is exceeded or the material is hypoelastic, it remains permanently deformed.

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