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Cementitious composite manufactured by extrusion technique

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Abstract

This paper presents the results of theoretical and experimental studies of short fiber-reinforced composite manufactured by extrusion. The cementitious composite in the extruder is considered a nonlinear viscoelastic fluid. By studying the key parameters of such a fluid, a general nonlinear viscoelastic constitutive model is introduced, in which the effects of the normal stresses are taken into account. The flows in an extruder are assumed to be two-dimensional steady shear flows. The differential equations of a flow motion are solved numerically by a finite difference method. The flow volume rate for a nonlinear viscoelastic fluid is predicted and compared with the experimental data.

Keywords: Composite; Fiber reinforcement; Rheology

Easier processing and lower cost compared with those of long fibers make short fiber-reinforced cementitious composites (SFRCCs) more desirable. It has been verified by experiments that the properties of the SFRCCs depend largely on manufacturing methods. The SFRCCs manufactured by extrusion method show a significant increase in tensile strength and toughness as compared with the traditionally cast ones, due to the improvement of interfacial bonding and fiber direction alignment through high shear and compression forces [1]. Extrusion technique also enables the manufacturers to form intractable materials into desirable shapes.

Since the early 1960s, many researchers have analyzed the non-Newtonian phenomena of polymer flow in an extruder. Weeks and Allen [2] and Rauwendaal [3] used a power expression to fit the empirical relationship between shear rate and polymer viscosity to derive formulas of flow volume rate by only considering one-dimensional velocity in the z axis (Fig. 1) and assuming an infinite extruder channel width. The later one gave out a closed-form solution to this problem. While in a true extruder, the channel flow not only has the z-direction velocity, but x-direction velocity as well. Thus, the actual flow volume rate is affected by this x-direction velocity. Boody [4] and Hami and Pittman [5] calculated this in detail by a numerical scheme with power law assumption and neglecting the effect of extruder flight flanks. However, a major drawback of this power law assumption is that it does not include the effect of normal stress effect on the viscoelastic flows. The authors assume that the cementitious flow in an extruder is incompressible, homogenous, and two-dimensional steady simple shear flow. Based on the facts, the Deborah number is small (De < 1) in the extrusion process of SFRCCs. The general nonlinear viscoelastic model, retarded-motion expansion [6,7], can be introduced into the cementitious extrusion process. For the known stress tensor and the material functions, the output of the cementitious flow in a shallow depth extruder ($H/W < 0.1$, where H is the depth of the channel of an extruder and W is the width of the channel of an extruder) is studied. The nonlinear differential equations are solved numerically by a finite difference method. The output of the extruder with a deep channel ($H/W > 0.1$) is predicted by the modified results of a shallow one with a correct factor derived from the rheology of Newtonian flow. The experimental data are presented and compared with the theoretical results. A general agreement is observed for the comparison.

1. Stress-strain relationship

Because the Deborah number of the SFRCCs in an extrusion process is much <1 [8], the general nonlinear viscoelastic constitutive model of so-called retarded-motion

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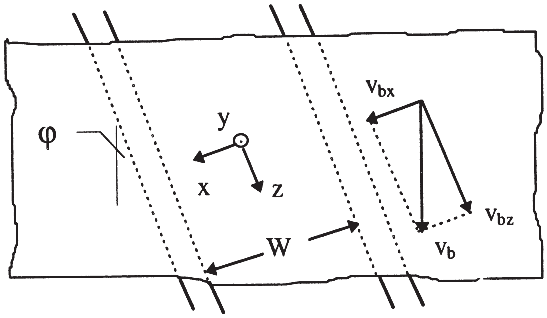

Fig. 1. Unrolled and laid-out screw channel of an extruder.

expansion [6,7] can be reasonably applied here. It assumes that the fluid is incompressible and the stress tensor is symmetric and can be expressed as a polynomial in the rate-of-strain tensors $\gamma_{(n)}$ [Eq. (1)]:

$$\tau = -[b_1\gamma_{(1)} + b_2\gamma_{(2)} + b_{11}\{\gamma_{(1)}\cdot\gamma_{(1)}\} + b_3\gamma_{(3)} + b_{12}\{\gamma_{(1)}\cdot\gamma_{(2)} + \gamma_{(2)}\cdot\gamma_{(1)}\} + b_{1:11}(\gamma_{(1)}:\gamma_{(1)})\gamma_{(1)} + \dots] \quad (1)$$

For higher-order terms in Eq. (1), see reference [7], where b_1, b_2, b_3, b_{11}, b_{12}, $b_{1:11}$, etc. are material parameters and can be determined by a standard rheometer, such as cone-and-plate rheometer or coaxial cylinder rheometer, etc. $\gamma_{(1)}$, $\gamma_{(2)}$, . . . , $\gamma_{(n)}$ are the first, second, . . . , nth rate-of-strain tensor [9] [Eq. (2)].

$$\begin{cases} \gamma_{(1)} = \dot{\gamma} \\ \gamma_{(n+1)} = \dfrac{D}{Dt}\gamma_{(n)} - \{(\nabla v)^T \cdot \gamma_{(n)} + \gamma_{(n)} \cdot (\nabla v)\} \end{cases} \quad (2)$$

where

$$\frac{D}{Dt} = \frac{\partial}{\partial t} + (v \cdot \nabla).$$

In a shallow flight extruder, the shear rates $\dot{\gamma}_{yz}$ and $\dot{\gamma}_{yx}$ are only functions of the y axis. The cementitious flow in the extruder channel is a two-dimensional flow. Thus, the following stress state can be derived [Eq. (3)]:

$$\begin{cases} \tau_{yz} = -\mu\dot{\gamma}_{yz} \\ \tau_{xy} = -\mu\tan\varphi\dot{\gamma}_{yz} \\ \tau_{xz} = -\mu'\dot{\gamma}_{yz} \\ \tau_{zz} - \tau_{yy} = -\psi_1\dot{\gamma}_{yz}^2 \\ \tau_{yy} - \tau_{xx} = -\psi_2\dot{\gamma}_{yz}^2 \end{cases} \quad (3)$$

where

$$\mu = b_1 - 2(b_{12} - b_{1:11})(1 + \tan^2\varphi)\dot{\gamma}_{yz}^2 = b_1 - 2b_{121}\dot{\gamma}_{yz}^2$$
$$\mu' = (-2b_2 + b_{11})\tan\varphi\dot{\gamma}_{yz}$$
$$\psi_1 = -2b_2 - b_{11}\tan^2\varphi$$
$$\psi_2 = b_{11} + b_2\tan^2\varphi.$$

The constants b_1 and b_{121} can be derived from the material parameters of a one-dimensional cementitious flow (cement:sand-1(600–300 μm in diameter):sand-2 (150–90 in diameter):water = 1:0.2:0.15:0.3), which is determined by a

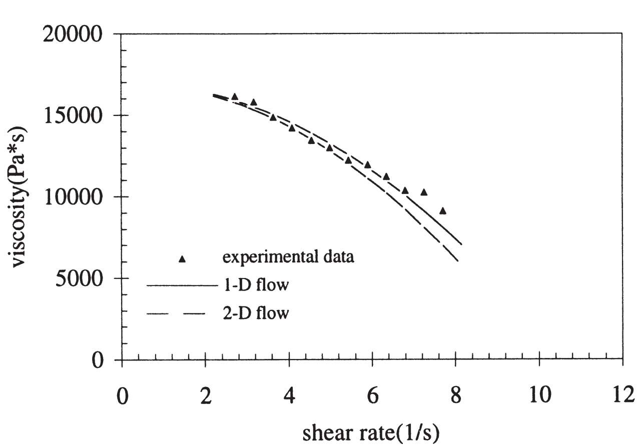

Fig. 2. Relationship between viscosity and shear rate of cementitious flow.

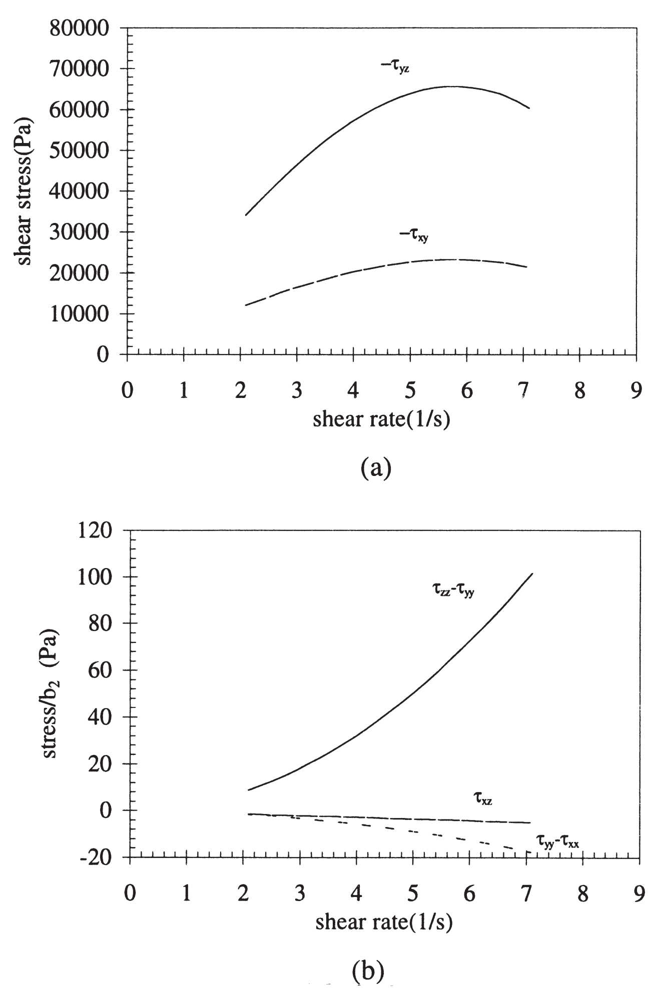

Fig. 3. (*a*, *b*,) Stress state of a cementitious flow.

coaxial cylinder rheometer (Fig. 2). The constants b_{11} and b_2 can be determined by a cone-and-plate rheometer. After obtaining the material parameters of the viscoelastic flow, the stress state can be determined (Fig. 3).

From Fig. 3, it can be seen that in an extruder, shear stress τ_{yz} plays an important role that leads to cementitious flow moving forward as a simple shear flow. The maximum absolute value of this shear stress can reach about 0.07 MPa when shear rate reaches about 6 s^{-1}, which is at least three times larger than the rest shear stresses. It was found that after the shear rate or rotation speed of the screw of an extruder reaches a certain value, the shear stresses τ_{yz} and τ_{xy} decrease with further increase of the shear rate or rotation speed. This can be used to explain the shear thinning phenomenon of the cementitious flow. The shear stress τ_{xz} is the least important stress. It almost maintains zero with the increase of the shear rate. In Fig. 3B, $\tau_{zz} - \tau_{yy}$ positively increases with the increase of shear rate because all three normal stresses, τ_{xx}, τ_{yy}, and τ_{zz}, are positive, i.e., compressive stresses. Then, from the Fig. 3B, it can be seen that τ_{zz} increases much faster than τ_{yy} with the increase of the shear rate and τ_{xx} has almost the same order as the compressive stress τ_{yy}. It is well known that the low shear rate extrusion process can efficiently reduce the swell of the extrudate so that a good product surface can be achieved. However, from this analysis, low shear rate corresponds to low compressive stresses, whereas these compressive stresses are much beneficial to compact the composite paste. Thus, in practical processing, a suitable rotation speed should be set with consideration of the surface finish and the mechanical properties of the extrudate.

2. Cementitious flow volume rate

For flow in a shallow flight extruder, all the variables are a function of only the y axis. By neglecting the body and inertia forces, the equation of motion for an incompressible fluid becomes as given in Eq. (4) [8]:

$$2b_{121}\left(\frac{dv_z}{dy}\right)^3 - b_1\frac{dv_z}{dy} + \frac{P_0 - P_L}{L}y - \text{Const.} = 0 \tag{4}$$

where

$$\text{Const.} \approx 2b_{121}\frac{v_{bz}^3}{H^3} - b_1\frac{v_{bz}}{H} + \frac{P_0 - P_L}{2L}H,$$

and H is the depth of the channel.

After obtaining the velocity profile (finite difference method), the volume rate of the flow in a shallow flight extruder can be predicted as given in Eq. (5):

$$Q \approx \frac{1}{2}\left(v_{bz}\frac{H}{n+1} + v_{z(n)}\frac{2H}{n+1} + v_{z(n-1)}\frac{2H}{n+1} + \cdots + v_{z(1)}\frac{2H}{n+1}\right) \cdot W \tag{5}$$

where n is the number of difference points along the y axis and $v_{z(i)}$ is the corresponding velocity in the z direction.

However, for the extrusion processing of SFRCCs, the channel is not shallow, i.e., $H/W > 0.1$. Thus, all the variables are a function not only of y axis but a function of the x axis as well. Then, analysis of the flow volume rate can reach such a high level of complexity and sophistication that the usefulness to practical processing becomes questionable. In this paper, a correction factor is introduced based on the rheology analysis of Newtonian flow. The correction factor [Eq. (6)] is defined as the ratio of the Newtonian flow volume rate in a deep channel extruder to that in a shallow one (Appendix).

$$C_N = \frac{Q''}{Q'} = \frac{\chi F_d F_{cd}/F_p - 1}{\chi - 1} \tag{6}$$

where

$$\chi = v_{bz}\Big/\left(\frac{H^2}{6\mu}\cdot\frac{P_L - P_0}{L}\right).$$

Thus, the flow volume rate for a viscoelastic flow can be calculated as given in Eq. (7):

$$Q^* \approx C_N \cdot Q. \tag{7}$$

Fig. 4 shows the predicted flow volume rates for a deep flight extruder. The experimental data show that, at low rotation speed (shear rate <5.4 s^{-1}), the theoretical results underestimate the actual output of the cementitious flow by about 11% on average, whereas at shear rate >5.4 s^{-1}, the theoretical results overestimate the actual output by about 8% on average. Here, the correction factor is approximately a function of geometrical shape of an extruder, although from Eq. (6) it is also a function of pressure gradient and viscosity. This is due to the viscosity of cementitious composite, which is so large at these shear rates that the influence of the flow viscosity and die pressure gradient becomes minimal.

3. Conclusions

Based on the general nonlinear viscoelastic constitutive model of "retarded-motion expansion," the equations of the

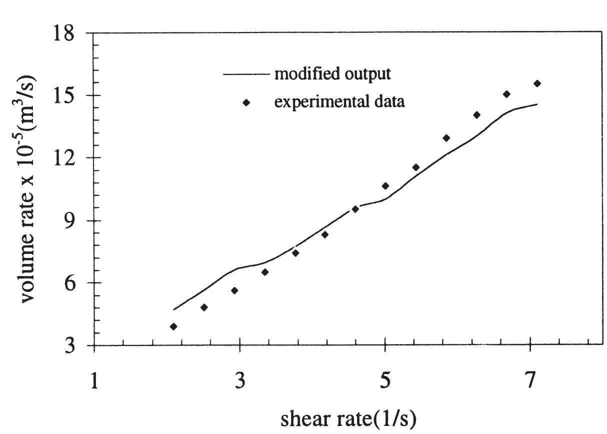

Fig. 4. Prediction of cementitious flow volume rate.

stress state of the cementitious flows in a shallow flight extruder were derived. The viscosity of the cementitious flow is measured by a coaxial cylinder rheometer. After obtaining the viscometric functions from the viscosity curve, the flow volume rate is analyzed. A correction factor is introduced to modify the output of a shallow flight extruder. The experimental data agree reasonably with the theoretical prediction.

Appendix

The flow volume rate of Newtonian fluids in a shallow flight ($H/W < 0.1$) extruder was given by Steven [10] [Eq. (A1)]:

$$Q' = \frac{v_{bz}}{2}WH - \frac{WH^3}{12\mu}\frac{dP}{dz} \tag{A1}$$

where v_{bz} is the barrel line speed in the z direction, dP/dz is the pressure gradient in the z direction, and μ is the viscosity of the flow.

The flow volume rate of Newtonian fluids in a deep flight ($H/W > 0.1$) extruder was given by Rauwendaal [11] [Eq. (A2)]:

$$Q'' = \frac{1}{2}WHv_{bz}F_dF_{cd} - \frac{WH^3}{12\mu}\cdot\frac{\partial P}{\partial z}\cdot F_p \tag{A2}$$

where F_d, F_p, and F_{cd} are shape factors [12,13].

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