APPLICATION OF MICROCOMPUTERS IN ROOFING MATERIALS RESEARCH

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Characterization of the constitutive equation of roofing materials with rheological models is a useful method for describing rheological response of the materials and assessing their functional performance. Under conditions of different temperature, composition, structure, etc., the rheological behavior of roofing materials is very complicated. Substantial effort is required to measure rheological properties, establish a suitable mechanical model, and determine the best set of model constants. Because of the difficulty of manual data acquisition and traditional methods of fitting model constants, most roofing materials have not yet been comprehensively and systematically studied to determine rheological models and constitutive equations. This paper introduces some new advances related to rheological testing and model fitting for roofing materials used in China.

The mechanical behavior of roofing materials is complex, so it is hardly sufficient to simply rely on analytical methods to set up constitutive equations. Many mathematical models can only be based on data observed and measured. Therefore, system identification theory was adopted as the theoretical basis for establishing rheological models.

SYSTEM FOR REAL-TIME DATA COLLECTION AND CONTROL DURING THE CREEP PROCESS OF A MATERIAL

A system was developed, with automated data acquisition, to measure creep of roofing materials. The system is shown in Figure 1.

The system was controlled with a microcomputer. Test specimens were placed in a test cup and loaded and unloaded automatically. The creep curve was plotted and creep data were printed, thus providing complete and automatic measurement of the creep process for each roofing material tested.

The testing system has the following characteristics.

Rapid Sampling and High Accuracy

Sampling cycles ranged from 0.1 to 10 seconds, with an interval of 0.1 second. One hundred different sampling cycles were available, with a maximum loading time of 1,000 seconds. One thousand data points for the creep curve can be collected during a single experiment. For some low viscosity materials, measurement of the creep process can be completed in two seconds. Experimental data and the creep curve from a typical experiment are shown in Figure 2. This experiment was completed in two seconds.

The resolution of the system reaches 0.0025mm within its 0 to 5mm range. An interpolation subroutine was installed in the microcomputer to rectify non-linear errors from the transducer and the analog-to-digital converter. The system provides high accuracy.

Good Repeatability

Since sampling is synchronous, the impact of loading and unloading is eliminated, and the experiment operates automatically. Man-made errors are excluded, experimental repeatability enhanced, and the real case of initial instantaneous deformation during the creep process can be accurately observed. The results shown in Figure 3 for two experiments printed on the same diagram indicate good experimental repeatability.

Fast Experimental Process

In a short time, the system can measure the creep process of many materials under different conditions.

Multiple Functions and Convenient Operation

The system simultaneously has the functions of extreme limit warning, loading, unloading, sample mark demonstration and automatic adjustment to the zero state. During the experiment, readjustment to the original work-ready state is unnecessary, making the system convenient to operate.

The system has already been applied to test the creep process of many roofing materials under different conditions.

PROGRAM LIBRARY FOR FITTING RHEOLOGICAL MODELS TO ROOFING MATERIALS

Data obtained by the system for real-time collection and control during the creep process can be used to establish a rheological model and constitutive equation for the material. However, model fitting for creep data and model validation require tedious calculation and can hardly be accomplished manually. Therefore, a special program library, RHELIB, was developed to catalog selected rheological models of materials. The mathematical theory used for this program library was the system identification theory[1]. The general procedure and process for system identification consists of four steps: (1) experiment design; (2) model structure selection; (3) parameter estimation; (4) model testing. These steps are expressed as a block diagram in Figure 4.

The problem of experiment design was covered in the first part of this paper. Now, the problem is to select the model structure, estimate the rheological parameters and test the model. It is clear from Figure 4 that this is a cyclic and repeating process. A model structure is selected according to the identification purpose, the knowledge before the test and the experimental data. The system identification theory is then applied to estimate the parameters of the model and to test the model. If the model does not meet the requirement, alternative models are selected and fitted automatically until a final model is obtained which best represents the data. Using RHELIB, the cyclic model fitting process was completed automatically on the computer.

The program library RHELIB included model-fitting programs for many proposed models which are well known and of practical value. It also included some application programs. All the model setting-up programs have the function of digital simulation as well. RHELIB has interactive facilities, drawing demonstration and print out and then prompts the user to enter additional commands. Therefore, the iterative process of model structure selection, parameter estimation and model testing can be conveniently dealt with on a personal microcomputer. A single cycle takes about two minutes.

Put the creep process data obtained from the experiment into the computer; set up a data file on the magnetic disk. With the experimental data and curve shown on the screen, study the characteristic of the creep curve and select the model structure. There are more than 20 rheological model programs in RHELIB; the name for each program is the structural formula for its model. Some models and their structures are shown in Table 1.

We can select any one of the model setting-up programs to deal with experimental data. During the process of running the program, several simple questions are raised by the computer. When they are answered through the keyboard, the model setting-up process can be completed within seconds. Simultaneously, the experimental creep curve and the model simulation curve are displayed on the screen. The degree of fit between the experimental data and the model determines if the model meets the requirement. If the result is poor, select and set-up again. If the result is satisfactory, the printer types out the original data and curve, the simulation data and curve, the model structural formula, the model parameters, the fitting error and the experimental statement.

Thus, a complicated problem of modeling roofing materials becomes a simple operation. RHELIB is available to all engineers and technicians.

Figure 5(a) is an example of model fitting by the computer. The diagram clearly indicates that the experimental curve and the simulation curve do not fit well, and require another try. Figure 5(b) is a diagram of the experimental curve and the simulation curve after reselecting and resetting-up the model.

Figure 6 is the printed result of a model fit.

PARAMETER IDENTIFICATION METHOD OF THE RHEOLOGICAL MODEL

The parameter identification method based on the system identification theory is expounded as follows.

The general formula of the constitutive equation[3] can be written as:

$$f(\sigma, \sigma, \sigma, \ldots\ldots, \sigma^{(n)}, \epsilon, \epsilon, \epsilon, \ldots\ldots, \epsilon^{(n)}, t) = 0 \qquad (1)$$

Where σ is stress, ϵ is strain.

The rheological model corresponding to it has m parameters[3] as $P_1, P_2, P_3, \ldots\ldots P_m$. ($P_i$, i = 1, 2, 3, ... m, coefficients of springs or dashpots.)

Let $P = [P_1\ P_2\ P_3 \ldots\ldots P_m]^T$

θ* is m-order, column vector. The functional relation of P and θ can be defined as

$$P = F[\theta] \qquad (2)$$

The creep curve data obtained from the experiment are E(1), E(2), ϵ(L), and stress σ is known.

Let $Y = [\epsilon(1), \epsilon(2), \ldots\ldots \epsilon(L)]^T$

While W is a m × m matrix composed of elements $\epsilon(1)$, $\epsilon(2)$, ... $\epsilon(L)$ and σ.

According to the system identification theory[1] the optimum estimation for θ is

$$\theta = (W^TW)^{-1}W^TY \qquad (3)$$

Putting θ into the equation (2), P can be evaluated.

Since P is known, the constitutive equation (1) can be deduced.

The rheological model in Figure 7 has been analyzed as an example.

In Figure 7, μ_1 is the spring constant of the first Kelvin Body, η_1 the viscosity coefficient of the first Kelvin Body, μ_1 the spring constant of the second Kelvin Body, η_2 the viscosity coefficient of the second Kelvin Body.

Find θ by the experimental data. Where $\theta = (e_0\ e_1\ f_0\ f_1)$, $P = (\mu_1\ \mu_2\ \eta_1\ \eta_2)$.

The relation between P and θ, $P = F(\theta)$, is as shown in the following formulas*

$$\begin{aligned} B &= (-e_1 + \sqrt{e^2_1 - 4e_1})/2 \\ A &= e_1 / A \\ \mu_1 &= (1-A)\cdot(A-B)/(f_0 + f_1 A) \\ \mu_2 &= (1-B)\cdot(B-A)/(f_0 + f_1 A) \\ \eta_1 &= -\mu_1 T/(\mathrm{Ln}\ A) \\ \eta_2 &= -\mu_2 T/(\mathrm{Ln}\ B) \end{aligned} \qquad (4)$$

In formulas (4), T is the sampling cycle in the experiment, Ln is the symbol of natural logarithm.

When the model parameter vector P is evaluated, the constitutive equation may then be determined.

Other models can be treated as analagous to the above.

ACTUAL TEST RESULTS—THE RHEOLOGICAL MODEL FOR RESIDUAL OIL MODIFIED WITH BUTADIENE RUBBER[4]

Residual oil modified with butadiene rubber is a well-mixed solvent. After butadiene rubber is added, liquid state residual oil exhibits a certain degree of solid behavior. The addition of butadiene rubber causes residual oil to have notable instantaneous elasticity and retarded elasticity, and gives it excellent mechanical properties. To reveal the technological property of rubber bitumen and the mechanism of property modification, the creep process was measured for residual oil modified with butadiene rubber by applying the real-time data collection and control system. A rheological model was established with the special program library RHELIB.

Under the condition of indoor temperature 8C, the experiment was done five times continually, with the constant shear stress 233.333 dynes/cm², 466.666 dynes/cm², 700 dynes/cm², 933.333 dynes/cm², and 1166.66 dynes/cm². The sampling cycle is one second, the loading time is 35

* θ is to be described in details in other papers.

* The formula (4) is to be described in details in other papers.

seconds. Specimens were unloaded at 35 seconds. The recovery process is 36 seconds. seventy-two creep values were collected in each experiment. See Figure 8 for the creep curves.

The result of model fitting with the program library RHELIB indicated that residual oil modified with butadiene rubber is a typical Burgers Body. The model of Burgers Body is shown in Figure 9.

Model parameters are listed in Table 2. Lines 1 through 5 give parameters from five experiments. The sixth line gives average values, and the seventh the coefficients of variation. In the table P1 is μ_1, P2 is η_2, P3 is ν_3 and P4 is η_2.

With the rheological model, further study could be made of the rheological mechanical properties of residual oil modified with butadiene rubber. This is beyond the scope of this paper. For detailed information please refer to the original article mentioned in the references.[4]

SUMMARY

A system was developed to enable real-time data collection and control of the creep process. Rheological models were fitted to data with the aid of a special program library, RHELIB, and rheological properties of numerous roofing materials were measured. The computer was shown to be a useful tool for selecting and fitting rheological models for roofing materials. Adoption of advanced technical methods combined with the system identification theory provides the advantages of speed, accuracy, reliability and material characterization which could hardly be obtained with other methods. Therefore, we suggest that computers be used in the study of roofing materials.

REFERENCES

[1]Robert C.K. Lee, Optimal Estimation, Identification and Control, The M.I.T. Press, 1964

[2]*(In Chinese)*

[3]*(Also in Chinese)*

[4]Zhang De Fu, Jin Shu Xin and Xu Zhao Dong, Viscocity and Elasticity of Residual Oil Modified with Butadiene Rubber, China Building Waterproofing Material, 2nd Issue in 1984

[5]T.L. Booth, Yi-Tzuu Chien, Computing: Fundamentals and Applications

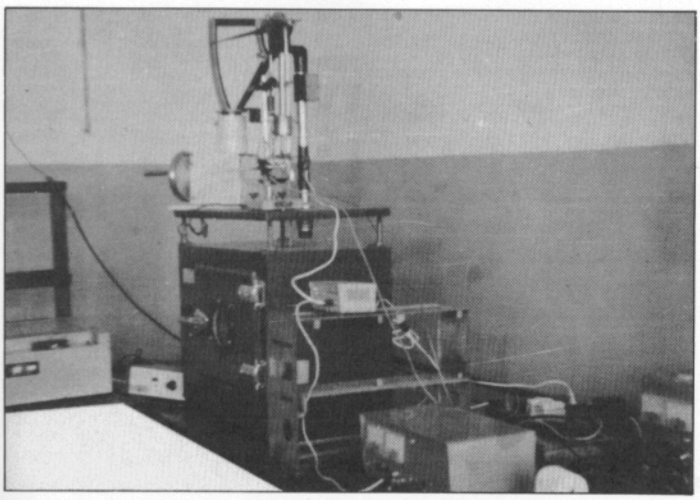


Figure 1 A system for real-time data collection and control during the creep process of a material

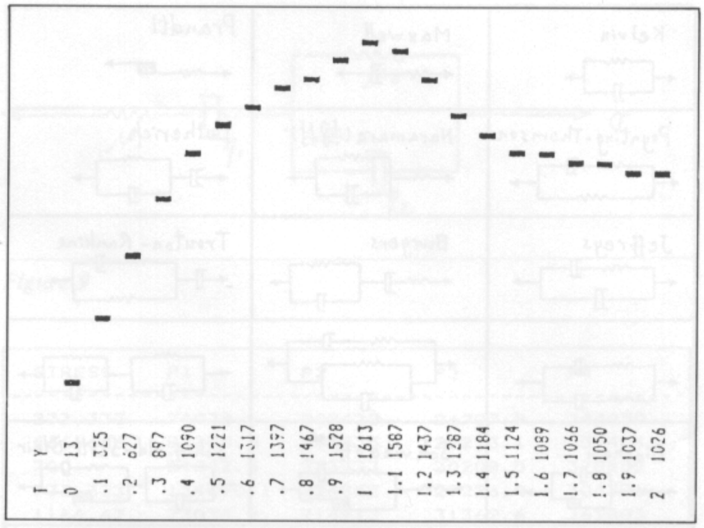


Figure 2 Computer output from a typical creep experiment

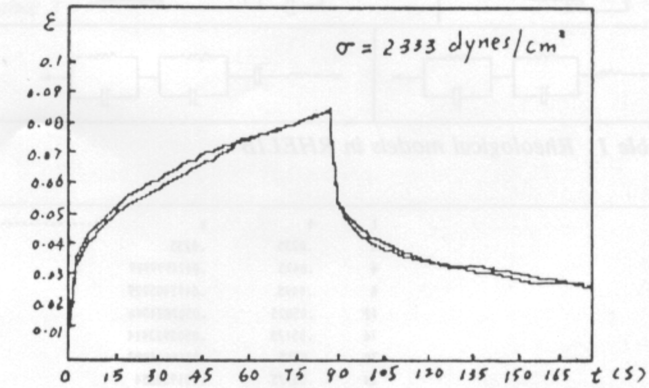


Figure 3 Two experiments printed on the same diagram indicate the good property of experiment repeating

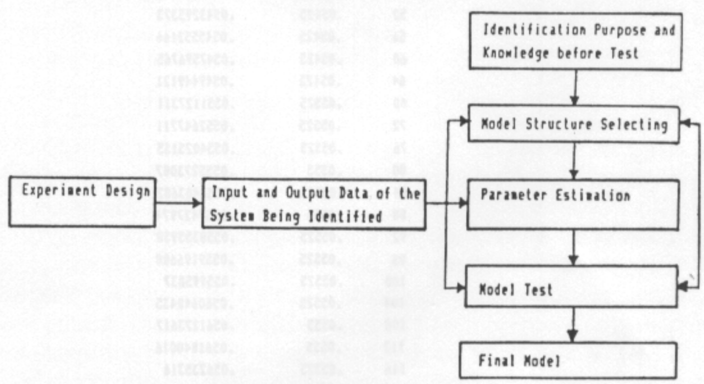


Figure 4 Steps used in system identification theory

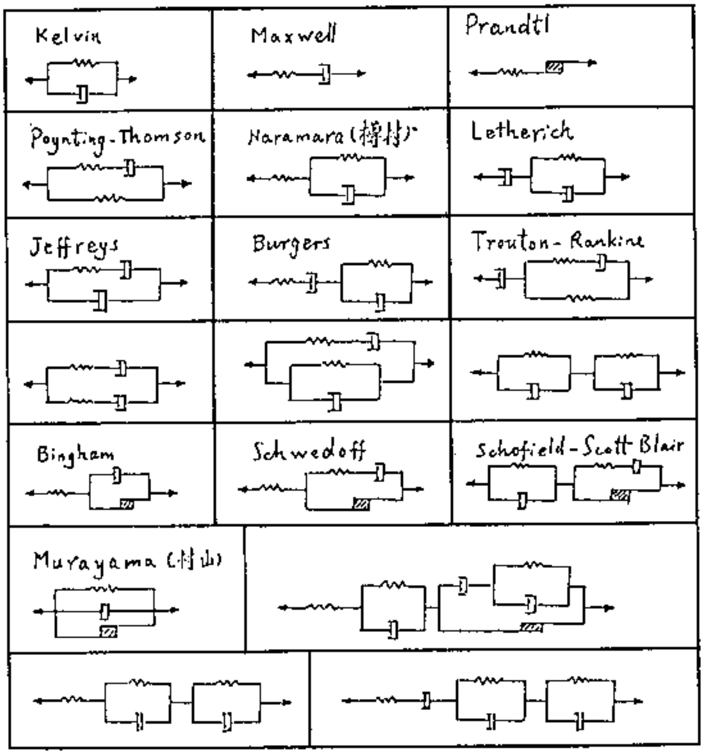


Table 1 Rheological models in RHELIB

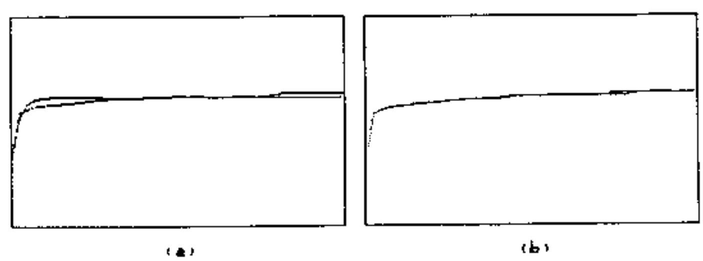
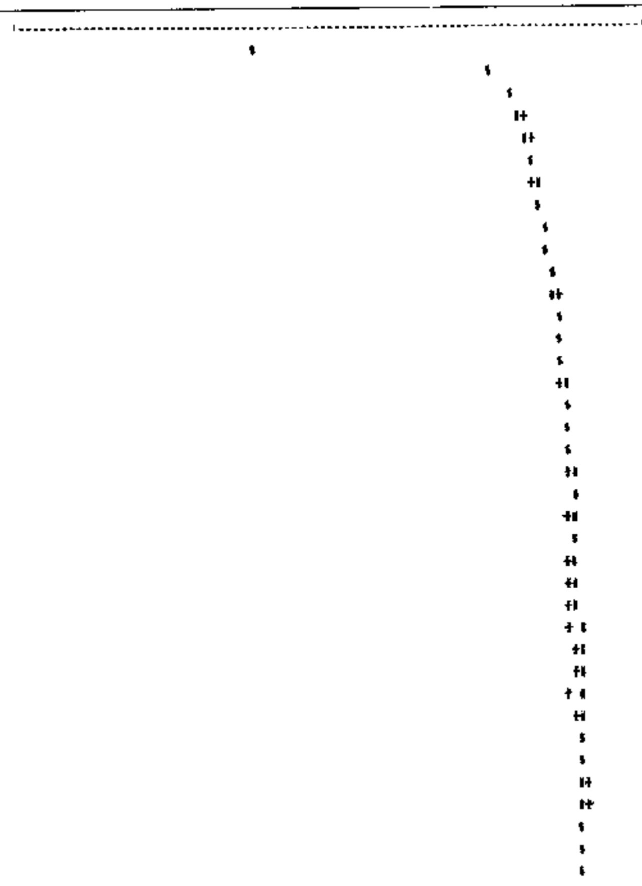


Figure 5 An example of model fitting by the computer

T	*	#
0	.0235	.0235
4	.0475	.0474999999
8	.0495	.0495405929
12	.05075	.0507824346
16	.05125	.0503923414
20	.0515	.0514414087
24	.05175	.051938654
28	.05225	.0523891351
32	.0525	.0527972595
36	.053	.0531670101
40	.0535	.0535019952
44	.054	.0538054835
48	.05425	.0540804366
52	.05425	.0543295373
56	.05425	.0545552166
60	.05425	.0547596765
64	.05475	.0549449121
68	.05525	.0551127311
72	.05525	.0552647711
76	.05525	.0554025155
80	.0555	.0555273087
84	.05525	.0556403682
88	.0555	.0557427974
92	.05525	.0558355958
96	.05525	.0559196688
100	.05525	.055995837
104	.05525	.0560648435
108	.0555	.0561273617
112	.0555	.0561840016
116	.05525	.056235316
120	.0555	.0562818057
124	.05625	.0563239241
128	.0565	.0563620824
132	.057	.0563966529
136	.057	.0564279729
140	.05675	.0564563481
144	.05675	.0564820553
148	.05675	.0565053455
152	.05675	.0565264457



65 60 0C T=4 L0=50 C0=27.222

P1=2127.65958 P2=2035.38311 P3=2827.69518 P4=5770.76774 P5=233769.542 Q=3.19188861E-04

CONSTRUCTION EQUATION IS H-(H/N)-(H/N)

*Figure 6 The printed result of a model fit T:Time (second) *:Shear strain of experiment #:Shear strain of simulation*

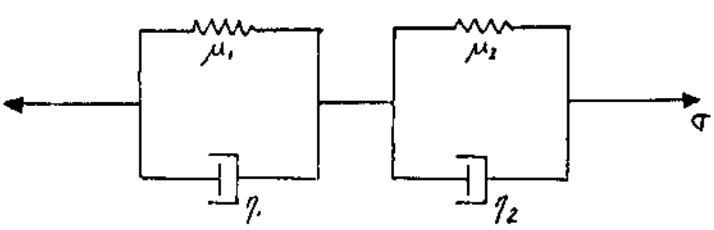


Figure 7 An example of rheological model

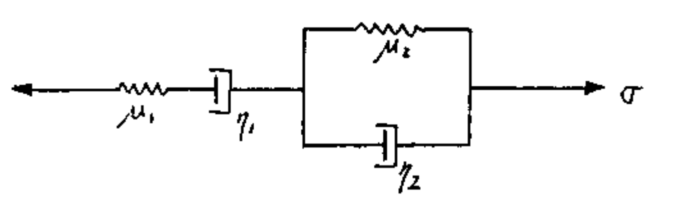


Figure 9

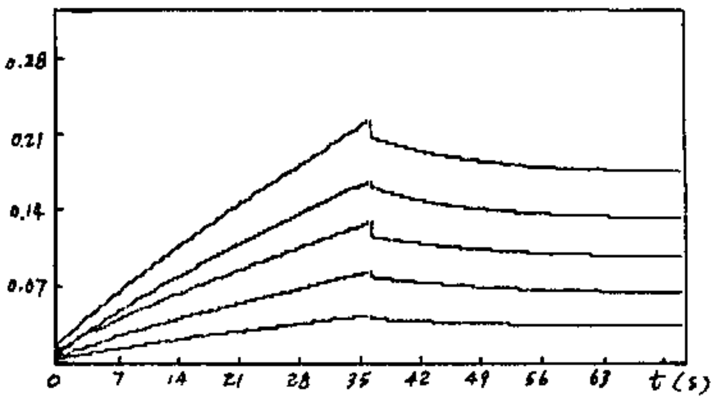


Figure 8

STRESS	P1	P2	P3	P4
233.333	74038	228438	26707.9	344050
466.666	93288.5	233333	27213.1	339464
700	54842.6	233333	30208.5	378802
933.333	134890.1	226852	29226.4	304391
1166.67	73034.2	214912	31362.6	362883
E	86018.7	227373.6	28943.7	345918
V	31 %	7.6 %	6.08 %	7.24

Table 2