Characterization of Thermosetting Polymer Mortars

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Synopsis

The behavior of epoxy and polyester mortars were studied under various curing conditions, temperatures, and strain rates. The effect of curing temperatures on the compressive stress–strain relationships of polymers and polymer mortars were also investigated. The properties of interest of the two polymer mortars cured under optimum conditions are the compressive strength, splitting tensile strength, compressive modulus, and compressive stress–strain relationship. The compressive strength of polymer mortars are related to the testing temperature and logarithmic strain rate. The compressive modulus and splitting tensile strength of polymer mortars are related to their compressive strength. A new nonlinear constitutive model is proposed to predict the complete compressive stress–strain behavior of epoxy and polyester polymer mortars.

INTRODUCTION

Among the various polymer composites, polymer mortar is increasingly used in construction and repair of highways, structures, and in the manufacture of precast articles of various kinds.[1-3] During the past two decades, practical use of polymer mortar has preceded without the full knowledge of its engineering properties. Rapid-setting organic polymers are used in polymer mortar as binders, and the most popular binders currently in use are epoxy, polyester, and methylmethacrylate.[3] Studies on epoxy and polyester polymers have shown that the strength, failure strain, failure mode, and stress–strain relationships are influenced by curing method, temperature, and strain rate.[4,5] Haddad et al.[6] studied the strength of methylmethacrylate mortar and concluded that initiator-to-promoter ratio, initiator and promoter levels, casting temperature, testing temperature, aggregate type, and gradation had varying effects on the strength. Information on the performance epoxy mortar and polyester mortar are rather limited.[7-11] Also, there is increasing interest in the deformation characteristics and stress–strain relationship of polymer mortar under working conditions. As a structural and repair material, polymer mortar, which is invariably brittle, must withstand higher stresses under extreme service conditions. Hence understanding the mechanical properties of polymer mortars is important in aiding their efficient utilization.

In this study the compressive and tensile properties of epoxy mortar and polyester mortar are investigated under various curing conditions, temperatures, and strain rates. Both room temperature and high-temperature curing were investigated. The strain rate was varied between 0.01 and 6% strain per minute and the temperature between 22 and 120°C. The strengths of the mortars are related to the testing temperature and logrithmic strain rate. Compressive

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strength of mortars are related to their splitting tensile strength and compressive modulus. A new nonlinear stress–strain model has been developed to predict the complete compressive stress–strain behavior of the polymer mortars.

EXPERIMENTAL PROGRAM

In order to verify the influence of polymer matrices on the behavior of polymer mortar, epoxy and polyester were selected as binders. The epoxy resin had a viscosity between 110 and 150 P at 20°C and a specific gravity of 1.1. The polyester resin had a viscosity between 40 and 50 P at room temperature and a specific gravity of 1.07. The composition of polymer mortar systems used in this study are summarized in Table I. The Ottawa 20-30 sand (spherical particles) was composed mainly of quartz and had a specific gravity of 2.65. Studies have shown that for the polymers and the fine aggregate under investigation, polymer mortars with 15% polymer content (by weight) gives the maximum compressive strength and/or modulus.[5,10,11] Since curing conditions will also affect the property development in the polymer mortar, both room temperature and high-temperature curing conditions were investigated. All specimens were first cured at room temperature (RT) for a day and then cured at 22, 40, 60, and 80°C to determine the optimum curing condition after a total of two days of curing. Specimens first cured at room temperature and then cured at 60°C will be referenced as 2-RT-60°C where the first number refers to the number of days of curing before testing.

In preparing mortar specimens, a preselected amount of sand and polymer were mixed in quantities of not more than 1000 g. For compression and splitting tension tests, 38-mm-diameter cylindrical specimens were cast in Teflon molds and compacted in two lifts. In order to ensure parallel loading faces during compressive tests, 38-mm-diameter cylindrical specimens were trimmed using a diamond saw. For most of the monotonic loading tests a closed-loop servo controlled hydraulic testing machine with a capacity of 400 kips was used. An external LVDT (linear voltage differential transformer) was used as a feedback

TABLE I
Compositions of Polymer Mortars

Constituents	By weight (%)
Polymeric matrix	
Epoxy	
Resin: Epon 828 (Shell Chemical Co., Houston, TX)	15
Initiator: Versamide 140[a]	35
Polyester	
Resin: Polyester, Dion Iso-6315 (Kopper Co., Pittsburgh, PA)	15
Initiator: Methyl ethyl ketone peroxide (MEKPO)[a]	2
Promoter: Cobalt napthenate[a]	0.2
Aggregate	
Sand: Ottawa 20–30	85

[a] By weight of resin.

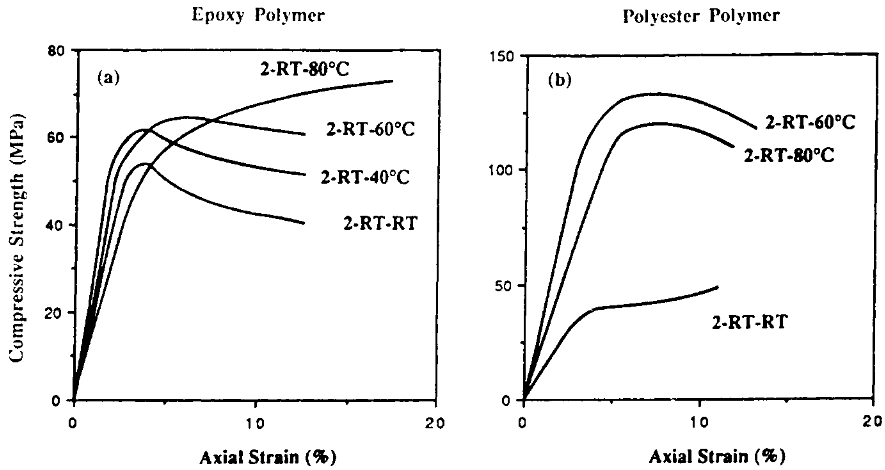

Fig. 1. Compressive stress–strain relationships for polymers cured at various temperatures.

control for the testing machine. Load–deformation curves were obtained using a X-Y recorder. Figure 1 shows the stress–strain relationships for the two polymers under various curing conditions with 2-RT-60°C being the best based on the compressive strength. For epoxy polymer, 2-RT-40°C curing resulted in a stiffer material. For the elevated temperature tests the specimens were equilibrated at the testing temperature for at least 24 h before testing, and the testing temperature was varied up to 120°C. In the displacement controlled tests on mortar the strain rate was varied between 0.01 and 6% strain per minute.

Since mortars with 15% polymer content resulted in optimum properties, these were used for in-depth study. The 15% mortar had a mean density of

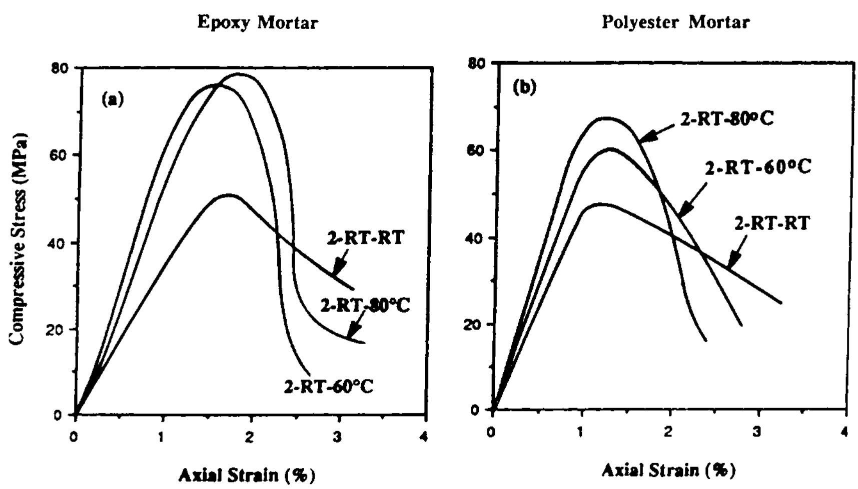

Fig. 2. Compressive stress–strain relationships for polymer mortars cured at various temperatures.

1.98 Mg/m^3. Figure 2 shows the influence of curing conditions on the stress–strain relationships of epoxy mortar and polyester mortar. The results show that the compressive strength of epoxy mortar and polyester mortar increases with curing temperature and reaches a maximum for 2-RT-80°C curing. The compressive modulus of epoxy mortar and polyester mortar reach their peak values for 2-RT-40°C and 2-RT-80°C curing, respectively. The splitting tensile strength of epoxy mortar remain almost unchanged with curing temperature. But, the splitting tensile strength of polyester mortar increased with curing temperature of up to 80°C.[5] Hence, the optimum curing condition (based on compressive strength) for the polymers and the 15% mortars are different, with the mortar systems requiring about 20°C higher temperature. Polymer mortars cured at 2-RT-80°C were used for strain rate and temperature studies.

ANALYSIS OF TEST RESULTS

Influence of loading strain rate on the compressive stress–strain relationships are shown in Figure 3 for both epoxy mortar and polyester mortar at room temperature. The compressive strength and modulus of both epoxy mortar and polyester mortar increases with increasing strain rate. Figure 4 compares the effect of temperature on the compressive stress–strain response of epoxy and polyester polymer and mortar, and it also clearly demonstrates the ductile and brittle nature of polymers and mortar, respectively. There is a greater percentage reduction in polymer compressive strength and modulus with an increase in temperature than mortar. The compressive yield strain of polymer (yield point is defined as the point where there is excessive strain in the materials for a small increase in stress) and failure strain of mortar also change with increase in temperature.[5]

The influence of each test variable [temperature (t°C) and strain rate ($\dot{\epsilon}$% strain/min)] on the compressive and splitting tensile strengths and compressive stress–strain relationship was studied separately to obtain the functional relationships. The strength properties are considered to be linear combination of the functional relationships of the test variables and represented as follows:

$$\sigma_c = A \log \dot{\epsilon} + Bt + C \tag{1}$$

where σ_c is the unconfined compressive strength and A, B, and C are material parameters and are obtained from least-square fit of the test data. Table II summarizes the strength parameters for both epoxy mortar and polyester mortar. The measured and predicted variation in compressive strength with the strain rate and temperature are compared in Figure 5. The relationship between splitting tensile strength (σ_{st}) and temperature can be represented as

$$\sigma_{st} = Mt + N \tag{2}$$

where M and N are material parameters and are obtained from least-square fit of the data. M and N for epoxy mortar are −0.0429 MPa/°C and 12.1 MPa,

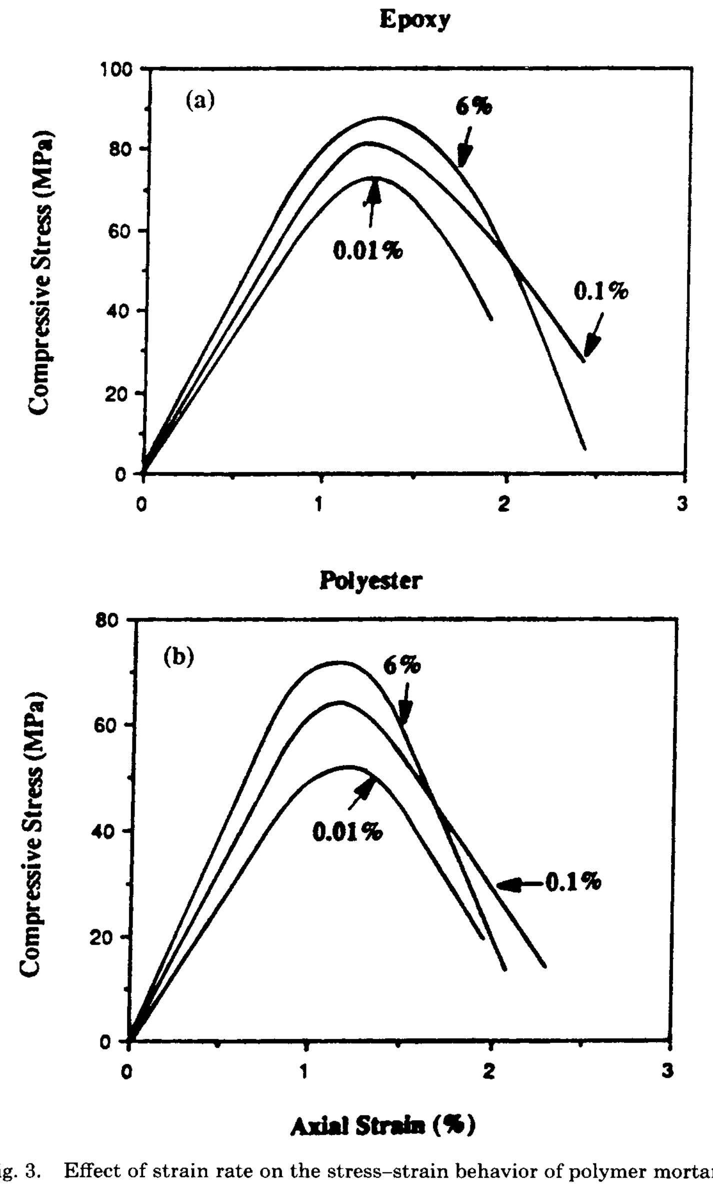

Fig. 3. Effect of strain rate on the stress–strain behavior of polymer mortars.

and for polyester mortar are −0.0593 MPa/°C and 10.4 MPa, respectively, and the predictions are compared to the measured values in Figure 6.

The variation of compressive strength ratios for the 15% mortars with temperature are shown in Figure 7. The strength ratios were obtained by normalizing the mortar properties with the properties of polymer at the testing temperature but cured at 2RT-60°C and tested at 5% strain rate. The compressive strength ratios increase with increasing temperature, and this can be represented as $\phi^{PC}/\phi^{P} = f(t)$ for the optimum mortar systems under investigation. Where ϕ^{PC} and ϕ^{P} are representing the compressive strength of mortar and polymer, respectively, and function $f(t)$ is determined from the best-fit curve for the

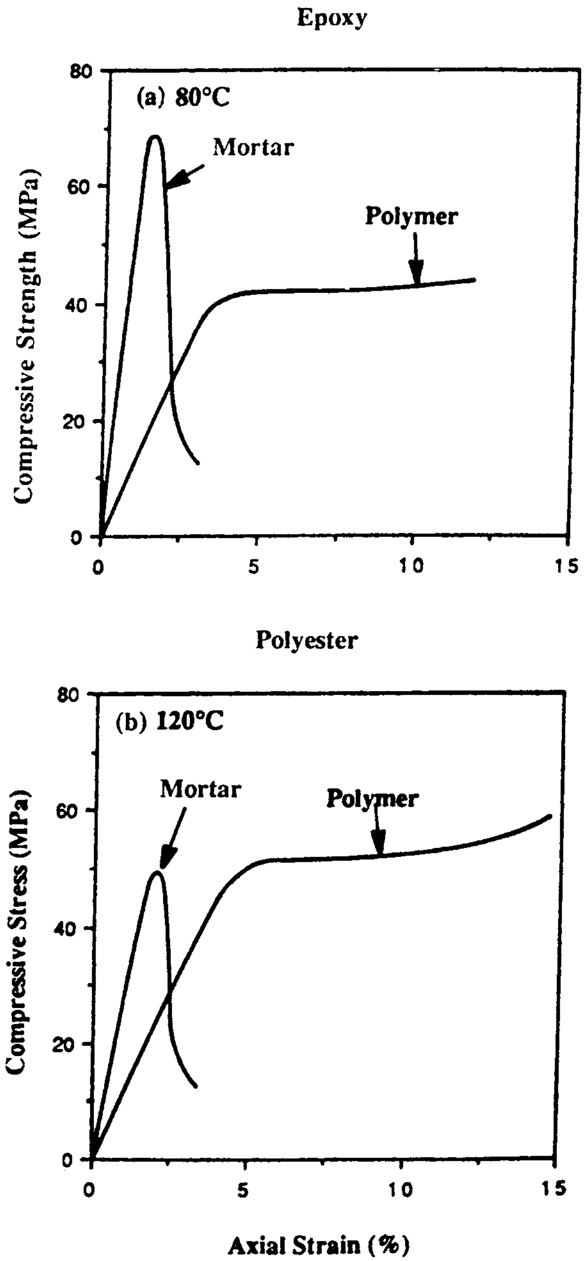

Fig. 4. Effect of temperature on the stress-strain behavior of polymers and polymer mortars.

test data. The function $f(t)$ for epoxy mortar and polyester mortar are $0.90 + 0.009t$ and $0.49 + 0.0038t$, respectively, for the range of temperatures investigated.

Property Relationships

The relationships between the properties of epoxy mortar and polyester mortar systems are investigated. There are several relationships including

TABLE II
Compressive Strength Parameters for Polymer Mortars

Parameters	Epoxy mortar	Polyester mortar
A (MPa-min)	4.378	3.472
B (MPa/°C)	−0.026	−0.139
C (MPa)	90.80	79.32

American Concrete Institute (ACI) code recommendations for cement concrete relating its compressive strength to compressive modulus, flexural strength, and splitting tensile strength.[12] The property relationships for cement concrete and cement mortar vary from linear to nonlinear to power law. Figure 8(a) compares the compressive modulus of mortars to the compressive strength.

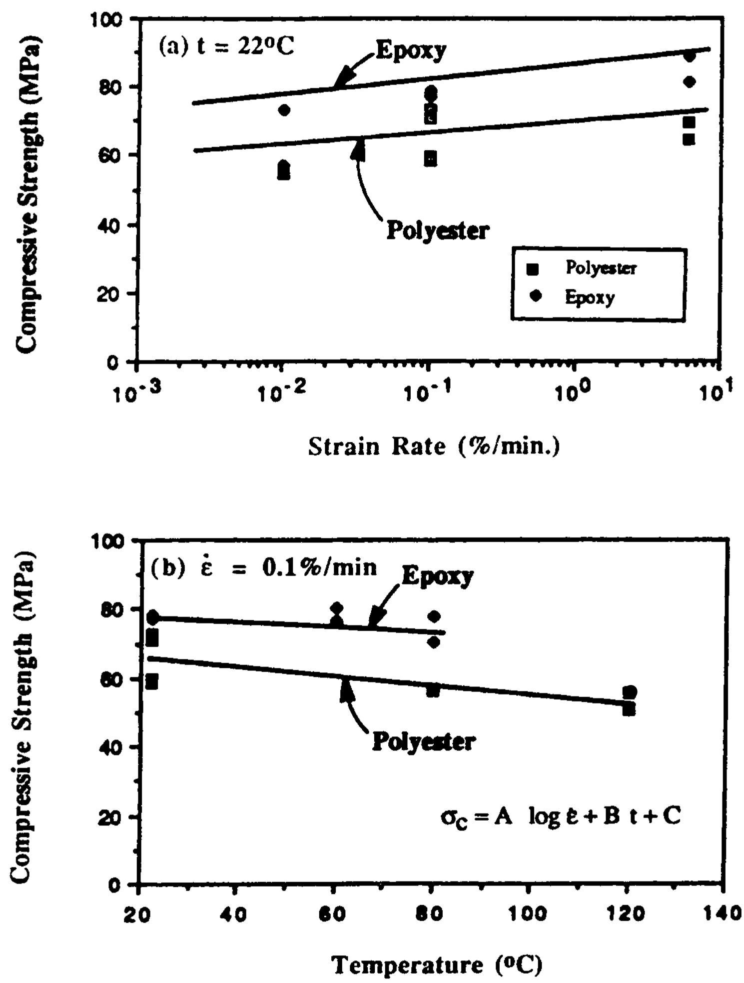

Fig. 5. Predicted and measured variation in compressive strength of polymer mortar at different strain rates and temperatures.

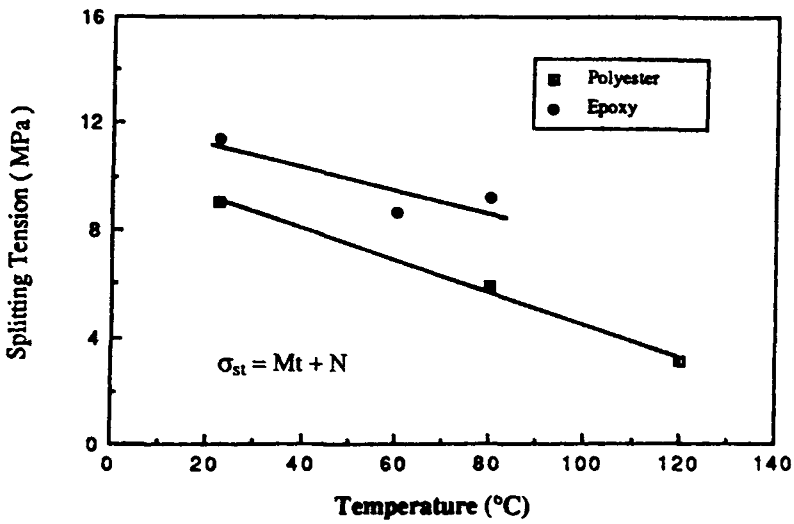

Fig. 6. Variation of splitting tensile strength of polymer mortar with temperature.

The data on mortar modulus and compressive strength can be best fitted with the following relationship (also recommended in ACI code for cement concrete):

$$E_c = \beta_E(\sigma_c)^{0.5} \tag{3}$$

where E_c (GPa) and σ_c (MPa) are the mortar compressive modulus and strength, respectively. While the least-square fit of the data gives a value of 0.676 and 0.846 for epoxy mortar and polyester mortar, respectively, for β_E with an average value of 0.785 for the mortar systems investigated. It should be noted that the

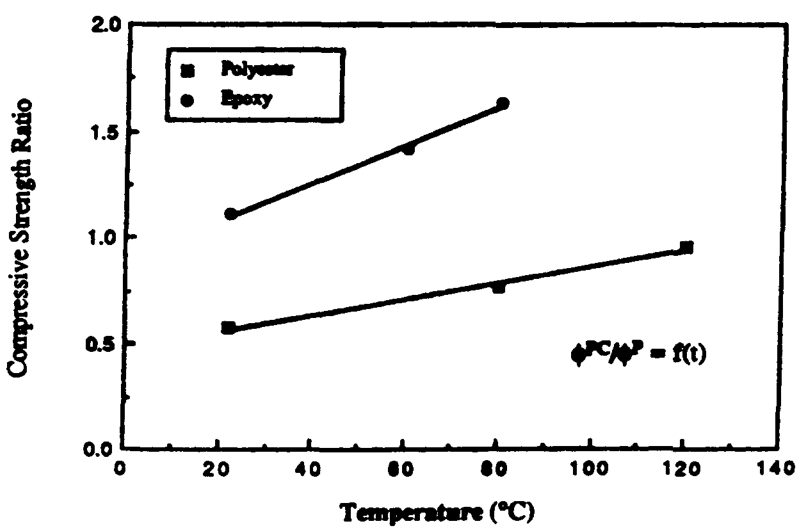

Fig. 7. Predicted and measured compressive strength ratio versus temperature.

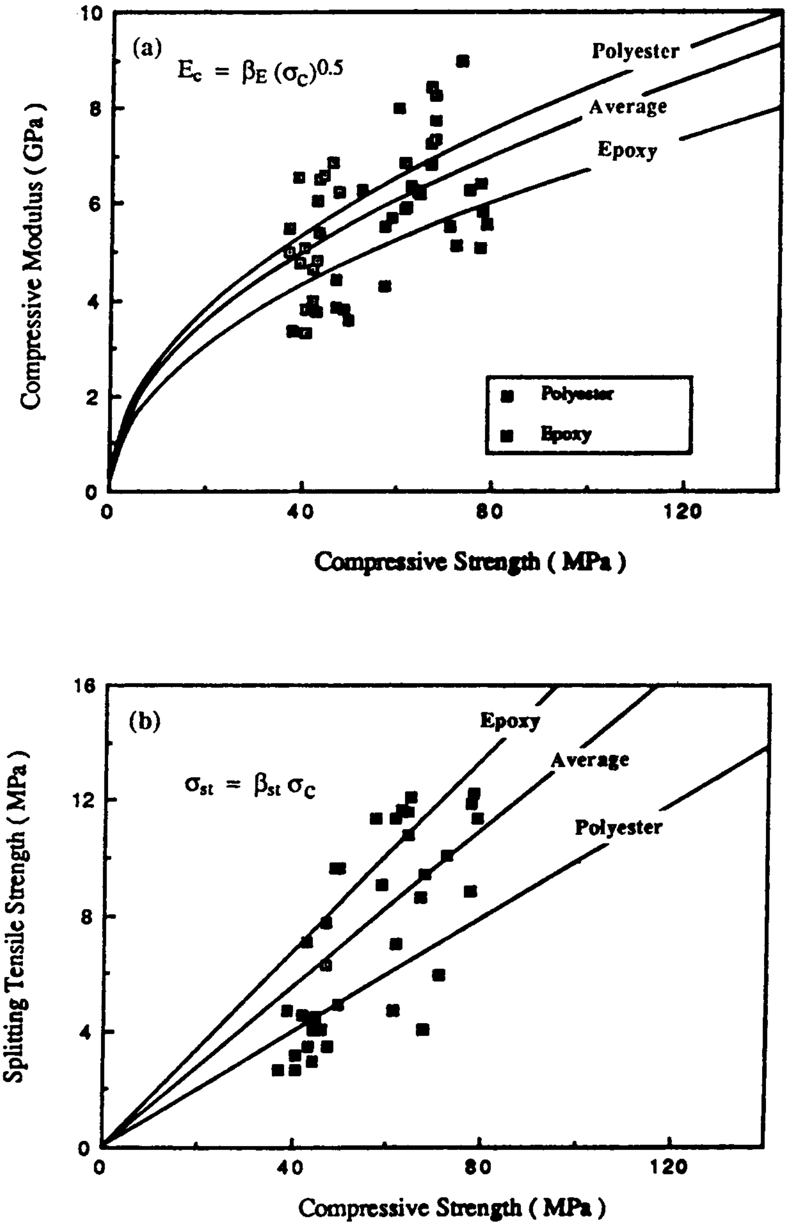

Fig. 8. Relation between compressive modulus, splitting tensile strength and compressive strength of polymer mortars.

compressive modulus reported in this study are somewhat lower than the values reported by other researchers for polymer mortars.[6,7,9]

Although there is a scatter in the test data, the relationship between splitting tensile strength (σ_{st}) and compressive strength of mortar can be best represented as

$$\sigma_{st} = \beta_{st}\sigma_c \tag{4}$$

Least-square fit of the data from all the experiments, including various methods of curing, gives a β_{st} of 0.168 and 0.098 for epoxy mortar and polyester mortar, respectively. The average value of β_{st} for the two mortar systems is 0.137.

Stress–Strain Relationship

The stress–strain response of epoxy mortar and polyester mortar was investigated at various temperatures and strain rates. There is continuing interest in developing analytical models for predicting the short-term rate-independent stress–strain behavior of polymer mortar.[4] A new model is being proposed to predict the complete compressive stress–strain behavior of mortars.

The proposed equation is

$$\sigma = \frac{\epsilon/\epsilon_c}{(1-p-q) + q(\epsilon/\epsilon_c) + p(\epsilon/\epsilon_c)^{(1-q)/p}}\,\sigma_c \tag{5}$$

where p and q are the material parameters to be determined, ϵ_c is the strain at failure stress, and σ and ϵ are the stress and strain, respectively. The proposed model is more general when compared to the relationship suggested by Saenz[13,14] for cement concrete.

Several additional conditions have to be satisfied by Eq. (5) to predict an acceptable strain softening stress–strain curve. These conditions are as follows:

1. At $\epsilon = 0$, the initial tangent modulus $E_{ci} = (d\sigma/d\epsilon)_{\epsilon=0}$,

$$E_{ci} = \frac{E_0}{1-p-q}, \tag{6}$$

2. $d\sigma/d\epsilon > 0$ when $\epsilon < \epsilon_c$,
3. $d\sigma/d\epsilon = 0$ at $\epsilon = \epsilon_c$,
4. $d\sigma/d\epsilon < 0$ when $\epsilon > \epsilon_c$,

where E_0 is the secant modulus at peak stress and is equal to σ_c/ϵ_c. By solving all these conditions, the following constrains are applied to the values of p and q:

$$p + q > 0 \tag{7a}$$

$$p + q < 1 \tag{7b}$$

$$(1-q)/p > 0 \tag{7c}$$

The admissible values for the material parameters p and q are shown in Figure 9. The material parameters p and q are also represented in terms of the test variables in the following general form as

$$p(t, \dot{\epsilon}) = \alpha_1 + \alpha_2 t + \alpha_3 \log \dot{\epsilon} \tag{8a}$$

$$q(t, \dot{\epsilon}) = \beta_1 + \beta_2 t + \beta_3 \log \dot{\epsilon} \tag{8b}$$

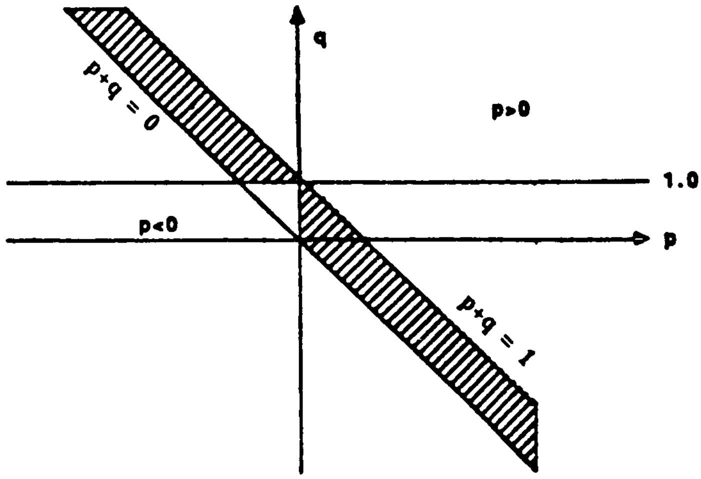

Fig. 9. Admissible values for the stress–strain parameters p and q (shaded area).

where α_1, α_2 (in./°C), α_3, β_1, β_2 (in./°C), and β_3 are material parameters to be determined using experimental data and the least-square method. The α's and β's for polyester mortar and epoxy mortar are summarized in Table III. The predicted stress-strain curves are shown in Figure 10. The model predictions for epoxy mortar and polyester mortar compare very well with the experimental data.

CONCLUSIONS

Behavior of epoxy mortar and polyester mortar was studied under various curing conditions, strain rates, and temperatures. Based on the complementary experimental and analytical study, the following conclusions can be advanced:

1. For the various curing conditions investigated, the optimum curing condition (based on compressive strength) for the polymers and 15% polymer mortars are different with mortars requiring about 20°C higher temperature.
2. The behavior of thermosetting mortars are very much influenced by the

TABLE III
Stress–Strain Relationship Parameters for Polymer Mortars

Parameter	Epoxy mortar	Polyester mortar
α_1	0.221	0.149
α_2	−0.001	−0.001
α_3	0.003	−0.012
β_1	0.085	0.075
β_2	0.000	−0.001
β_3	0.014	−0.017

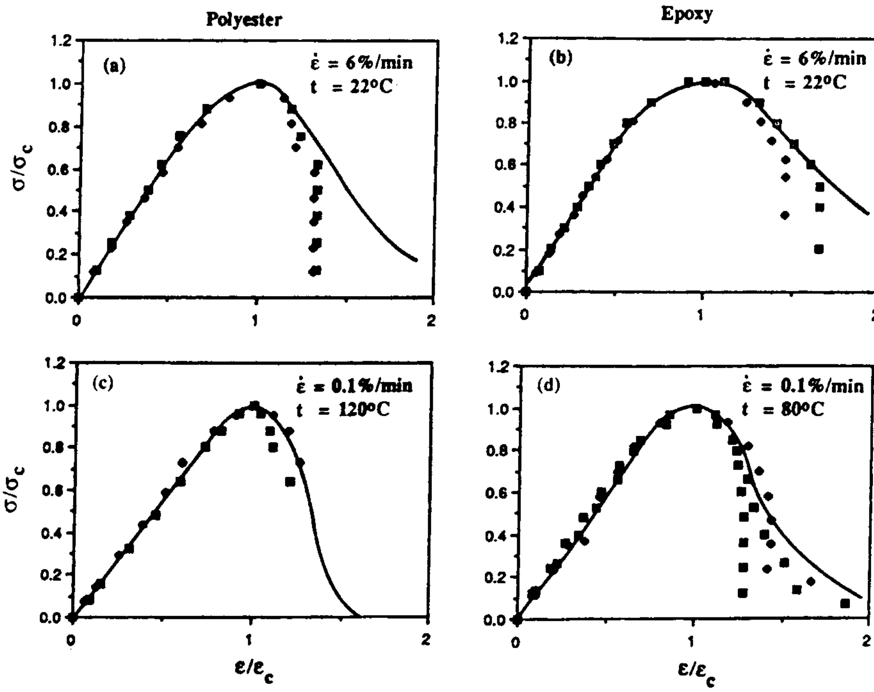

Fig. 10. Predicted and measured stress–strain relationships for polymer mortar.

curing method and temperature, strain rate, and testing temperature. Properties of polymer mortar systems are related to testing temperature and logarithmic strain rate.

3. The splitting tensile strength and compressive modulus of the polymer mortars have been related to their compressive strengths by linear and power relationships, respectively. The polymer mortar to polymer compressive strength ratios increases with increase in temperature.
4. A new constitutive model, capable of modeling strain softening, has been used to predict the stress–strain relationships of epoxy mortar and polyester mortar. The prediction compares very well with the experimental data.

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