

1973

Stress-strain behavior of polymer-impregnated concrete, paper prepared for Sym. on Polymer-Impregnated Solids, Amer. Chemical Soc., Chicago, August 30, 1973

J. A. Manson

W. F. Chen

J. W. Vanderhoff

Y. N. Liu

Follow this and additional works at: <http://preserve.lehigh.edu/engr-civil-environmental-fritz-lab-reports>

Recommended Citation

Manson, J. A.; Chen, W. F.; Vanderhoff, J. W.; and Liu, Y. N., "Stress-strain behavior of polymer-impregnated concrete, paper prepared for Sym. on Polymer-Impregnated Solids, Amer. Chemical Soc., Chicago, August 30, 1973" (1973). *Fritz Laboratory Reports*. Paper 2087.

<http://preserve.lehigh.edu/engr-civil-environmental-fritz-lab-reports/2087>

This Technical Report is brought to you for free and open access by the Civil and Environmental Engineering at Lehigh Preserve. It has been accepted for inclusion in Fritz Laboratory Reports by an authorized administrator of Lehigh Preserve. For more information, please contact preserve@lehigh.edu.

STRESS-STRAIN BEHAVIOR OF POLYMER-IMPREGNATED CONCRETE (1)

J. A. Manson*, W. F. Chen**, J. W. Vanderhoff***,
Y.-N. Liu*, E. Dahl-Jorgenson**, and H. Mehta**

College of Engineering
Lehigh University
Bethlehem, Pennsylvania 18015

FRITZ ENGINEERING
LABORATORY LIBRARY

INTRODUCTION

The polymerization of monomers within the pore structure of previously-cured concrete yields a new composite, POLYMER-IMPREGNATED CONCRETE (PIC), which has an unusual combination of mechanical properties and corrosion resistance. Steinberg et al. (2-5) have demonstrated that PIC composites containing relatively small proportions of polymers (e.g., poly(methyl methacrylate)) show several-fold increases in Young's modulus, tensile strength, and compressive strength compared with those of the control. Similar observations were made by other investigators, not only with cement and concrete (6-12), but also with ceramic substrates (13-15).

In order to properly use PIC in the design of structures, its entire stress-strain relationship and mode of failure must be known as a function of loading conditions. Auskern and Horn (16) showed that the compressive stress-strain curves for cement and concrete specimens impregnated with poly(methyl methacrylate) were dramatically different from those of the unimpregnated control specimens. The PIC specimens responded in a linear (Hookean) elastic manner over most of the experimental range, whereas the control specimens yielded and began to fail progressively at relatively low strains (behavior typical of concrete). Flajsman et al. (12) incorporated various fibers in PIC specimens and determined their stress-strain curves. The combination of fibers and polymer appeared to have a synergistic effect in increasing the strength properties; however, the incorporation of fibers changed the response towards the more progressive mode of failure typical of unmodified concrete. These observations are important because they point out the way to arrive at the optimum compromise between increased mechanical properties and mode of failure for a given application, e.g., to gain in ductility with some sacrifice in ultimate strength.

The mechanism by which the polymer strengthens the concrete is of great fundamental interest. One suggestion (16) is that the polymer simply fills the void spaces of the concrete so that the strength of the composite begins to approach the idealized strength of pore-free cement. Other suggestions (7, 8, 16-18) attribute the improved strength of PIC to such specific factors as enhanced interphase bonding and better resistance to crack growth.

At the same time, there is evidence for the polymer functioning in an unequivocal mechanical reinforcement role. Auskern and Horn have used a modified additivity relationship (17) to interpret improvements in the modulus (18). Also, Gebauer et al. (14) have shown that the strength of polymer-impregnated tile passes through a transition at the second-order transition temperature T_g of the polymer, and Haselman and Penty (17) have shown that impregnation with polymer of a substrate should result in a significant redistribution of stress concentrations between a pore and the matrix, even if the modulus of the polymer is low.

In order to resolve some of the foregoing points, a study was begun to determine the

*Materials Research Center

**Fritz Engineering Laboratory

***Center for Surface and Coatings Research

effect of polymer state (i. e., glassy or rubbery) on the stress-strain behavior and fracture morphology of PIC and the extent to which the mode of failure can be controlled. Various mixtures of methyl methacrylate (MMA) and butyl acrylate (BA) were polymerized in porous mortar and concrete substrates, to give examples of polymer behavior ranging from glass to rubbery, and the stress-strain behavior of the PIC specimens was determined.

EXPERIMENTAL DETAILS

Portland cement mortar cylinders (1 in. diameter; 2 in. height) were prepared using a 12:24:64 water-Type II Portland cement-Ottawa silica sand (ASTM C-109) mix and cured under water for 28 days at room temperature. These cylinders were dried in an air oven for 3 hours at 150°C, placed in a vacuum chamber, and subjected to vacuum for 15 minutes, then immersed in monomer (various mixtures of MMA and BA) containing 0.5% azobisisobutyronitrile for 3 hours at atmospheric pressure. These monomer-impregnated cylinders were immersed in a 70°C water bath for 4 hours, to polymerize the monomer. The conditions of drying, impregnating, and polymerization were sufficient to ensure practically complete filling of the specimen void space. The polymer loadings were 5-7% based on dried weight.

Compression tests were run on these polymer-impregnated mortar cylinders using an Instron tester operated at a constant strain of 0.01 in./min. To ensure reproducible results, the circular ends of the cylinders were ground flat before testing. It was also necessary to preload the specimens to 1000-2000 lb. and unload, before loading to failure. Each series of tests used 4-6 specimens.

Concrete cylinders (3 in. diameter; 6 in. height) were prepared using water, Type I portland cement, sand, and gravel (3/8 in.) according to ASTM C33-67. After one day at room conditions, the cylinders were cured for 28 days in a moist room (90-100% RH), then stored for 14 days at room conditions. They were then dried, impregnated with monomer, and polymerized in a manner similar to that of the smaller mortar cylinders. The polymer loadings were about 6% based on dried weight.

Compression (ASTM C39-66) and split-tensile (ASTM C496-66) tests were run on these polymer-impregnated concrete cylinders using a Baldwin hydraulic tester (300,000 lb. capacity). The tester was operated at constant hydraulic flow rate, and hence at an approximately constant load rate (40-50 lb./sec.), during the loading phase. Thus, the crosshead speed was not constant throughout the test, but increased after rupture of the specimen began. The strain was plotted as a function of stress, using the output from strain gauges attached to various parts of the specimen.

EXPERIMENTAL RESULTS AND DISCUSSION

Mortar Specimens

Figures 1-3 show typical results of the stress-strain measurements. It is obvious that the modulus, strength, ultimate strain, and energy-to-break of the portland cement mortar are increased and dramatically by impregnation with poly(methyl methacrylate) (PMMA), as was reported previously (2-6). Although the absolute values and relative improvement of these properties are smaller than those reported by Auskern and Horn (18), the polymer loading is also proportionately lower. Also, as reported earlier (16), the stress-strain curves show a high degree of linearity, with only a slight tendency to yield at very high strains. Thus, the impregnation of portland cement mortar with PMMA gives a dramatic increase in strength, stiffness, and overall toughness, accompanied by a corresponding decrease in ductility due to progressive yielding (this ductility is not obvious in the control specimen of Figure 1, probably because of the small specimen size). It is interesting to note that a high level of elastic and brittle behavior is achieved by impregnation of the mortar, with

PMMA, which by itself is normally ductile in compression.

As the proportion of BA in the monomer impregnation mixture is increased past 25%, the tensile properties show a corresponding decrease. The value of the modulus for the 75:25 MMA-BA sample may be anomalous; however, the apparent increase over the modulus of the PMMA sample (also noted by Tazawa and Kobayashi (8) for the case of a plasticized polymer) may reflect a more complete impregnation and a more controlled polymerization of the 75:25 MMA-BA sample. In any event, in contrast to the predictions of a simple pore-filling model (16), the modulus (and probably other properties) of the polymer must play a significant role in whatever relationship is used to predict behavior of the polymer-impregnated composite. This observation is consistent with the findings of Gebauer et al. (14), namely, that the strength of a polymer-impregnated ceramic depends upon whether the measurements are made at a temperature above or below the second-order transition temperature of the polymer. Possible implications are discussed below.

Because of the small specimen size, which results in catastrophic failure once cracking begins, caution must be exercised in interpreting the variation of stress as a function of strain. Thus, the decrease in ultimate strain at high proportions of BA may reflect the test method as much as the properties of the specimen, at least at the strain-rate used. The stress concentration in the cementitious matrix will be higher, the lower the modulus of the polymer, so that failure will occur first in the BA-rich samples as long as the specimen must follow the crosshead motion without relaxation. Even so, the incorporation of BA in the monomer mixture confers a significant degree of yielding prior to failure, and a peak stress is observed for compositions containing 50% or more BA. Thus, ductility is conferred by the BA, although under these testing conditions, it is not reflected in the breaking strain. This is consistent with the observation that only those specimens containing 75% or more MMA broke with sharp audible cracks.

Concrete Specimens

Figures 4 and 5 show that the improvement in tensile and compressive properties observed for PMMA-impregnated mortar is also observed for PMMA-impregnated concrete. These curves confirm those reported earlier for compressive tests (16). Not surprisingly, the values of the strength and modulus decrease with increasing proportion of BA in the monomer mixture. However, in contrast to the results for polymer-impregnated mortar, the increase in ductility due to the increasing proportion of BA in the monomer mixture is strikingly evident. In effect, the short ductile region of the curves of Figure 1 is expanded on the strain scale of Figure 4 for the larger specimens tested at constant loading rate, so that progressive failure was observed even in the concrete control specimens. Indeed, for the 25:75 MMA-BA and poly(butyl acrylate)(PBA) samples, complete disintegration was not observed over the test period.

These results show that it is possible to obtain a variety of combinations of stress-strain properties and thus in principle tailor the properties of the PIC composite to particular service requirements. They also show that the stress-strain behavior is dependent on the nature of the test method used. Further experiments are in progress to elucidate the fracture behavior as a function of loading rates and pattern and to correlate these results with the specimen morphology.

The Role of the Polymer

The foregoing results show that the polymer in PIC plays an active role in the reinforcement of the cementitious matrix and not merely a passive pore-filling role. Unfortunately, several expressions proposed for the quantitative prediction of composite properties in terms of constituent properties do not work well with PIC. Although the present study has not progressed far enough to permit rigorous evaluation

of these expressions, the preliminary results indicate that neither the porosity model of Auskern and Horn (16) nor the model of Hobbs (18, 19) can account for the observed effect of polymer modulus. The variations in PIC modulus as a function of polymer modulus predicted by these models are less than 10%, compared with the observed variation of 36%. The flat-shaped model proposed by Hasselman et al. (15) does predict a more significant variation (about 27%) for a probably-not-unrealistic length to width ratio of 5.

Nevertheless, it is interesting to consider the effects of polymer modulus on stress concentrations both in the cementitious matrix and in the polymer phase (17). For inclusions of PMMA, the stress concentration in the matrix is reduced almost 3-fold for a flat-shaped pore with a length to width ratio of 5; on the other hand, the stress concentration in the polymer is increased significantly. These effects are almost (but not quite) negligible for inclusions of the lower-modulus PBA. Thus, even if the modulus of PIC cannot yet be predicted accurately, and even though the polymer does not fill the pores completely, the higher-modulus polymer must not only reduce the stress concentration in the matrix, but must also transfer load to the polymer-filled pore. This conclusion complements the findings of Isenburg and Vanderhoff (20), i. e., that a latex polymer incorporated in the mix plays an active role in minimizing stresses when microcracks form during curing, and the conclusion of Tazawa and Kobayashi (8), i. e., the inclusion of polymer in PIC increases the fracture energy significantly. Further studies of the role of the polymer are in progress.

CONCLUSIONS

1. The compressive modulus, strength, and ultimate strain (Instron; 0.01 in./min.) of portland cement mortar are increased significantly by impregnation with PMMA or MMA-BA copolymers, according to the proportion of MMA.
2. PIC specimens show ductility to different degrees, according to the mode of testing used. In constant strain-rate tests, the substitution of BA for all or part of the MMA results in a measure of ductility and yielding, according to the proportion of BA. In constant-load-rate tests, this ductility or progressive yielding is much more evident; unloading takes place over a much wider range of strain than with unmodified concrete; however, the compressive strength is still greater than that of unmodified concrete. Thus, it appears possible to obtain both improved strength and ductility by judicious selection of the monomer mixture used for impregnation.
3. Although quantitative prediction of composite behavior is not yet possible, polymer-impregnation does reinforce the porous cementitious matrix mechanically.

ACKNOWLEDGMENTS

The authors acknowledge gratefully the assistance of Dr. J. D. Hoffman for preparation of the mortar specimens and Dr. D. P. H. Hasselman for many helpful discussions.

REFERENCES

1. This work was sponsored by: 1) the Pennsylvania Science and Engineering Foundation; 2) the Undergraduate Research Program, National Science Foundation; 3) the American Association of State Highway Officials, in cooperation with the Federal Highway Administration, conducted in the National Cooperative Highway Research Program, which is administered by the Highway Research Board of the National Academy of Sciences - National Research Council. (The opinions and conclusions expressed or implied in this paper are those of the research contractor (21). They are not necessarily those of the Highway Research Board, the National

of Sciences, the Federal Highway Administration, the American Association of State Highway Officials, or of the individual states participating in the National Cooperative Highway Research Program.)

2. M. Steinberg, J. T. Dikeou, L. E. Kukacka, J. E. Backstrom, P. Colombo, S. Rubenstein, J. J. Kelsch, & B. Manowitz, "Concrete-Polymer Materials, First Topical Report," BNL 50134 (T-509) & USBR General Report No. 41, Dec. 1968.
3. M. Steinberg, J. T. Dikeou, L. E. Kukacka, J. E. Backstrom, P. Colombo, K. B. Hickey, A. Auskern, S. Rubenstein, B. Manowitz, & C. W. Jones, "Concrete-polymer Materials, Second Topical Report," USBR REC-OCE-70-1 & BNL 50218 (T-560), Dec. 1969.
4. J. T. Dikeou, M. Steinberg, W. C. Cowan, L. E. Kukacka, G. W. DePuy, A. Auskern, W. G. Smoak, P. Colombo, G. B. Wallace, J. M. Hendrie, & B. Manowitz, "Concrete-Polymer Materials, Third Topical Report," USBR REC-ERC-71-6 & BNL (T-602), Jan. 1971.
5. J. T. Dikeou, W. C. Cowan, G. W. DePuy, W. G. Smoak, G. B. Wallace, M. Steinberg, L. E. Kukacka, A. Auskern, P. Colombo, J. M. Hendrie, & B. Manowitz, "Concrete-Polymer Materials, Fourth Topical Report," USBR REC-ERC-72-10 & BNL 50328, Jan. 1972.
6. J. Gebauer & R. W. Coughlin, *Cement & Concrete Res.* 1, 187 (1971).
7. D. G. Manning & B. B. Hope, *Cement & Concrete Res.* 1, 631 (1971).
8. E. Tazawa & S. Kobayashi, paper presented at the fall meeting, American Concrete Inst., Hollywood, Fla., Oct. 1972.
9. D. W. Fowler, J. T. Houston, & D. R. Paul, paper presented at symposium on Polymers in Concrete, American Concrete Inst., Atlantic City, Mar. 1973.
10. B. Sople, A. E. Fiorato, & R. Lenschow, paper presented at the fall meeting, American Concrete Inst., Hollywood, Fla., Oct. 1972.
11. D. Whiting, D. Kline, & P. R. Blankenhorn, paper to be presented in this symposium, Aug. 1973.
12. F. Flajsman, D. S. Cahn, & J. C. Phillips, *J. Am. Ceram. Soc.* 54, 129 (1971).
13. J. Gebauer, D. P. H. Hasselman, & R. E. Long, *Am. Ceram. Soc. Bull.* 51, 471 (1972).
14. J. Gebauer, D. P. H. Hasselman, & D. A. Thomas, *J. Am. Ceram. Soc.* 55, 175 (1972).
15. D. P. H. Hasselman, J. Gebauer, & J. A. Manson, *J. Am. Ceram. Soc.* 12, 588 (1972).
16. A. Auskern & W. Horn, *J. Am. Ceram. Soc.* 54, 282 (1971).
17. D. P. H. Hasselman & R. A. Penty, *J. Am. Ceram. Soc.* 56, (1973).
18. A. Auskern & W. Horn, "The Role of Polymer in Polymer Impregnated Concrete," BNL-17572, Jan. 1973.
19. D. W. Hobbs, "The Dependence of the Bulk Modulus, Young's Modulus, Shrinkage, and Thermal Expansion of Concrete Upon Aggregate Volume Concentration," TRA 437, Cement and Concrete Assocn., London, Dec. 1969.
20. J. E. Isenburg & J. W. Vanderhoff, paper to be presented in this symposium, Aug. 1973.
21. Project 18-2, National Cooperative Highway Research Program, Highway Research Board, National Academy of Sciences. Investigators: J. A. Manson, W. F. Chen, J. W. Vanderhoff (Lehigh); P. D. Cady, D. E. Kline (Penn. State Un.), 1972.

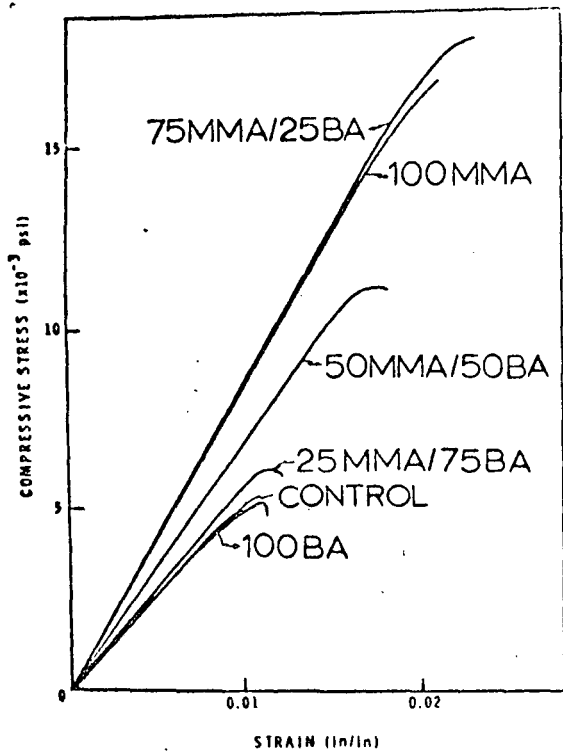


Fig. 1. Polymer-Impregnated Mortar: Typical compressive stress-strain curves (Instron).

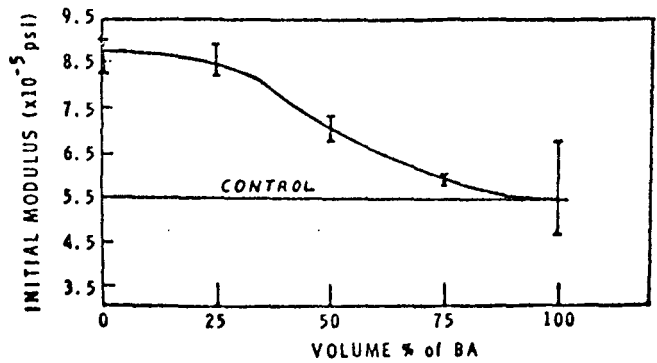


Fig. 2. Polymer-Impregnated Mortar: Variation of compressive modulus with strain rate as a function of polymer composition (Instron).

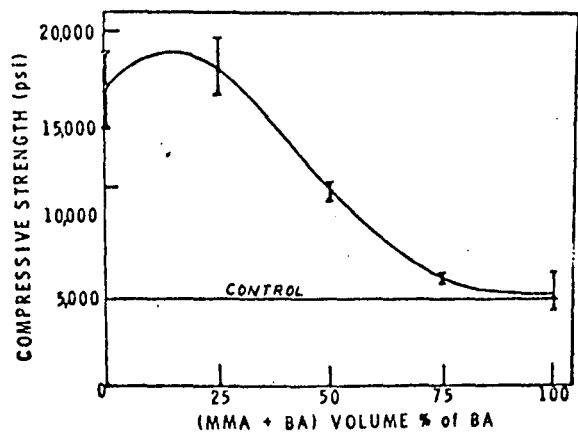


Fig. 3. Polymer-Impregnated Mortar: Variation of compressive strength with strain rate as a function of polymer composition (Instron).

MMA = Methyl Methacrylate
BA = Butyl Acrylate

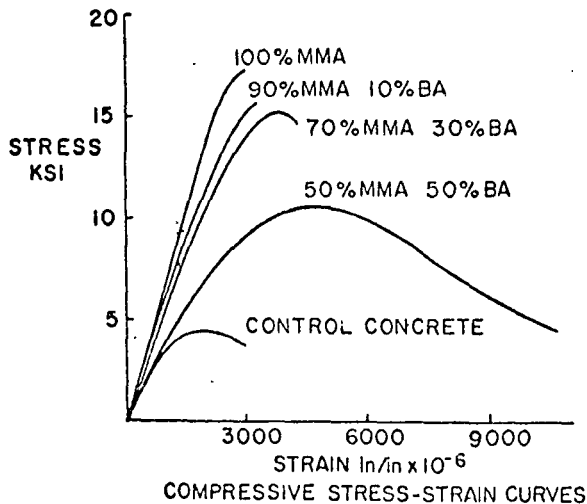


Fig. 4. Polymer-Impregnated Concrete: Tensile stress-strain curves as a function of polymer composition (hydraulic tester).

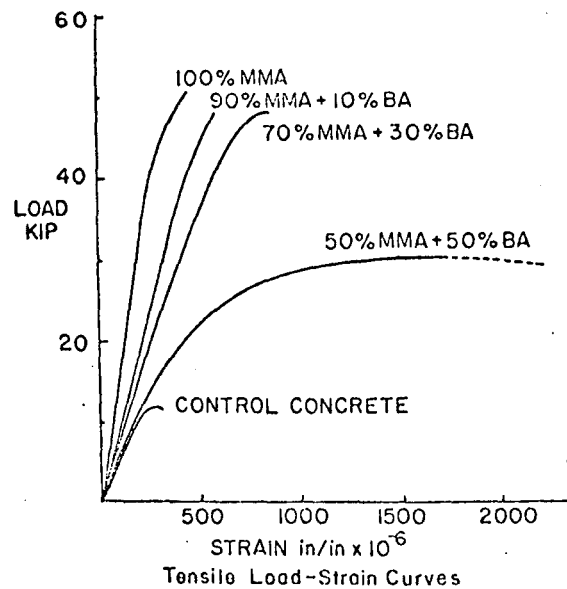


Fig. 5. Polymer-Impregnated Concrete: Tensile stress-strain curves as a function of polymer composition (hydraulic tester).