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Engineering Properties of Fiber-Reinforced and Polymer-Impregnated Shotcrete

UNITED STATES DEPARTMENT OF THE INTERIOR

Report of Investigations 8001

Engineering Properties of Fiber-Reinforced and Polymer-Impregnated Shotcrete

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ENGINEERING PROPERTIES OF FIBER-REINFORCED AND POLYMER-IMPREGNATED SHOTCRETE

by

M. E. Poad,[1] M. O. Serbousek,[2] and J. Goris[3]

ABSTRACT

Structural properties of steel-fiber-reinforced shotcrete and polymer-impregnated shotcrete, both plain and fiber-reinforced, were investigated by the Federal Bureau of Mines, Spokane Mining Research Center. The research center has found that flexural strengths can be increased by as much as 106 percent, and splitting-tensile strength by 50 percent, by introducing randomly oriented steel fibers. A slight decrease of compressive strength was found in the fiber-reinforced shotcrete. Polymer-impregnated shotcrete exhibited a threefold to fourfold increase in compressive and splitting-tensile strength.

The techniques of preparing shotcrete with the dry process, using both fast-set agents and regulated-set cement, are described, along with the results of physical-property testing. Physical properties include compressive and splitting-tensile strengths, tangent and secant moduli, and stress-strain curves for plain shotcrete, fiber-reinforced shotcrete, and polymer-impregnated plain and fiber-reinforced shotcrete. Flexural strengths for plain and fiber-reinforced shotcrete are also reported.

Steel-fiber shotcrete is the more promising of the new structural materials for ground support, and additional research is recommended.

INTRODUCTION

Shotcrete, a form of sprayed concrete, is immediately self-supporting when used with fast-setting agents. Although shotcrete has been used extensively for tunnel support, it has not gained ready acceptance in the mining industry because there is little information on its basic characteristics, such as material properties and rock interaction.

This study concerns needed information on engineering properties of plain, fiber-reinforced (fibrous), and polymer-impregnated shotcrete. These properties include compressive, splitting-tensile, and flexural strengths; tangent

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[1]Research civil engineer.
[2]Structural engineer.
[3]Civil engineer.

and secant moduli; and density. (ASTM Test Standards were used where applicable.) The laboratory techniques for preparing shotcrete, and results of physical-property testing, are described. Shotcrete panels and specimens were prepared at the research center's Auxiliary Lab, 35 miles west of Spokane; physical-property testing was done in the Spokane office. The modified shotcretes (fibrous and polymer-impregnated) were compared with plain shotcrete (used as control samples) for direct evaluations.

ACKNOWLEDGMENTS

The authors are indebted to C. H. Henager of Battelle Pacific Northwest Laboratories, Richland, Wash., for supplying the fibers, and for technical assistance in mix design and batching procedures. Larry Kukacka, Brookhaven National Laboratory, and W. Glen Smoak, Bureau of Reclamation, helped with the treatment of polymer-impregnated shotcrete specimens.

BACKGROUND

In 1969, the Spokane Mining Research Center began to investigate new and improved methods of using concrete as an underground support. Initial results indicated that shotcrete was the most promising, so active research, both in-house and contract, has been underway since 1970.

Shotcrete is defined by the American Concrete Institute (ACI) (2)[4] as "mortar or concrete conveyed through a hose and pneumatically projected at high velocity onto a surface." Two basic processes can be used--wet mix or dry mix. In the wet process, all the ingredients, including the water, are mixed before introduction into the delivery hose, and conveyed either pneumatically or by displacement. In the dry process, all of the mixing water is added at the nozzle as the mix is pneumatically conveyed.

One of the first successful shotcrete applications for rock-surface stabilization was in the Lodaro-Mosagro tunnel of the Moggic hydroelectric project in Switzerland between 1951 and 1955 (6). However, use of large-aggregate shotcrete in North America was sporadic until the Canadian National Railroad tunnel was constructed at Vancouver, British Columbia (5). Since then, it has been used in numerous tunneling and mining projects in Canada and the United States.

An advantage of shotcrete is that a thickness sufficient for effective structural support can be built up rapidly. A thin layer of shotcrete applied immediately after the blast (with or without rock bolts, depending on rock conditions) prevents or reduces loosening, and thus aids in transforming the rock into a self-supporting arch (6). It also protects shalelike rock against slaking upon exposure to air, and helps control water percolation. The use of large-size aggregate increases shotcrete strength, and requires less cement, which in turn reduces shrinkage and resultant cracking, as well as cutting costs.

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[4]Underlined numbers in parentheses refer to items in the list of references at the end of this report.

All shotcrete has benefited from development of fast-set agents. Shotcrete can now be used for support immediately upon application and, in a short time, can be layered to almost any thickness. Fast-set agents also help control percolating water, and thus protect the rock. Until recently, fast-set agents were limited to dry-process shotcrete. A wet gun and additive feed system for the powder have been developed, and a laboratory study has investigated the material properties (4). The equipment is presently undergoing field evaluation.

Although fast-set agents possess definite advantages, caution must be exercised. The compatibility of fast-set agents and the cement must be assured. In some cases, the chemical composition of the fast-set agents can be modified to react favorably with available cement. In other instances, it may be necessary to change the type or brand of cement. Because the additives are caustic, safety precautions must be taken.

Work at SMRC and IIT Research Institute has demonstrated the feasibility of using regulated-set cements in dry-process shotcrete. Preliminary results indicate that high early strengths, and comparable ultimate strength, can be obtained (4).

Shotcrete promises to be an excellent underground-support system. However, it is not a "cure-all." Detailed geologic comparisons should be made with conditions under which shotcrete has proven successful. It can be used alone or with rock bolts, wire mesh, or steel sets. Although shotcrete with fast-set agents can reduce or seal off water, drainage should be provided if there is a hydrostatic head. Also, as with any concrete job, laboratory investigation into cement types, aggregates, and water/optimum-mix designs is of paramount importance for good results. Of particular value is a field-test section, if possible. This is time-consuming and costly, but until technology can actually design a support system, it is extremely important. Opinion differs as to whether rock should be cleaned (sand or water blasted) before application. Because of the difference in rock types and conditions, only cored samples and bond tests will determine if this is needed. All preliminary testing and investigations will be useless unless a qualified nozzle man and experienced crew can be employed, since shotcrete is still more of an art than a science.

Shotcrete has tremendous potential for support in rapid excavation. Shotcrete could be applied by remote control, thus eliminating exposure of personnel to unsupported rock. Application could be synchronized to varying rates of advance through the use of multiple nozzles. Thickness could be varied, depending upon rock conditions. New cements, fast-set agents, and reinforcement materials are continually being developed to make the product more adaptable to solving support problems.

LABORATORY INVESTIGATIONS

Fibrous Shotcrete

Battelle Development Corp. has developed a fiber-reinforced concrete called Wirand,[5] consisting of randomly placed steel fibers in a mortar mix. A typical parts-by-weight mix is 2.4 sand, 1.0 cement, 0.45 water, and 0.25 (2 volume-percent) steel fibers (10 to 16 mils in diameter, 1/2 to 1 inch long). Flexural strengths (first crack) of 1,800 psi and compressive strength of 12,000 psi have been reported. In addition, the material exhibits high-impact strength and improved resistance to abrasion (3).

A shotcrete with flexural strengths of this magnitude would be an extremely versatile material for underground support. The Spokane Mining Research Center began investigating such a possibility in 1970. Working with Battelle Pacific Northwest Laboratories, three different fibrous shotcretes were shot with a dry-process shotcrete machine. These fibers were (1) 16 mils in diameter, 3/4 inch long; (2) 16 mils in diameter, 1 inch long; and (3) 10 mils in diameter, 3/4 inch long. The shotcrete mix design (table 1) closely followed that used for Wirand to correlate work done on cast, in-place material.

TABLE 1. - Mix design for fiber-reinforced shotcrete

Material	Weight, lb	Volume, ft^3
Cement	940	4.80
Blended sand	2,375	14.30
Steel fibers	265	.54
Additive	9	-

A high early (Type III) cement and Tricosal as a fast-set agent were used with the 16-mil-diameter, 3/4-inch- and 1-inch-long fibers. In another mix, a regulated-set cement with 1-percent soda ash as an accelerator was used with the 10-mil, 3/4-inch fibers.

The shotcrete machine (fig. 1) is capable of shooting up to 3/4-inch aggregate. An air regulator, mounted on the machine, allows monitoring and control of pressure. In addition, a centrifugal water pump with regulator and volume meter controls and records pressure and quantity. This insures a uniform flow, either in the lab or field. A cumflow pan mixer disperses the fibers in the mix--a time-consuming process because fibers must be handled manually from boxes. For each fiber test, two transit mixers transported the material to the laboratory. One truck carried a control batch (no fibers); the other carried the fibrous mix.

The mix was discharged into a hopper mounted on the end of the shotcrete machine, then fed to the gun by screw feed. The fast-set additive was introduced to the mix as it was conveyed by the screw. Pneumatic placement was

[5]Reference to specific products is made for identification only and does not imply endorsement by the Bureau of Mines.

made onto four standard plywood panels mounted vertically on a concrete wall to prevent vibration (fig. 2). Two of the panels were shot with the fibrous mix, two with the control mix. (The bottom of one panel was used to adjust the mix, and was discarded later.) Once adjusted, the panel was built up in two layers to a depth of +7 inches (fig. 3). Safety precautions were necessary during placement and handling of the shotcrete, because the fiber will penetrate ordinary clothing, and even the completed panel has fibers protruding from the finished surface like a brush. The panels were allowed to stand for 1 day, after which they were stripped, cut into sections, and placed in a curing room. Sections were removed and cored or cut into specimens, as required (figs. 4-5).

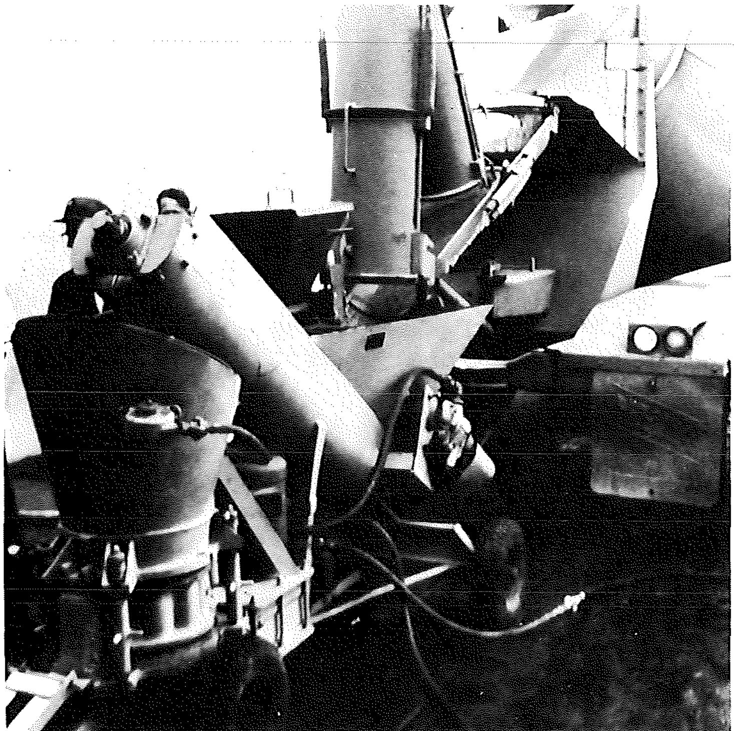

FIGURE 1. - Shotcrete machine.

Compression and splitting-tensile specimens were 3 inches in diameter and 6 inches long. Compression cylinders were weighed, capped, and tested in a 400,000-pound testing machine. Stress-strain data were obtained from a mechanical strain gage, consisting of two aluminum rings with set screw connected through a linear transducer (fig. 6). Information from the transducer was fed into a data acquisition system that produced a punched tape for direct use by a computer for data reduction and plotting.

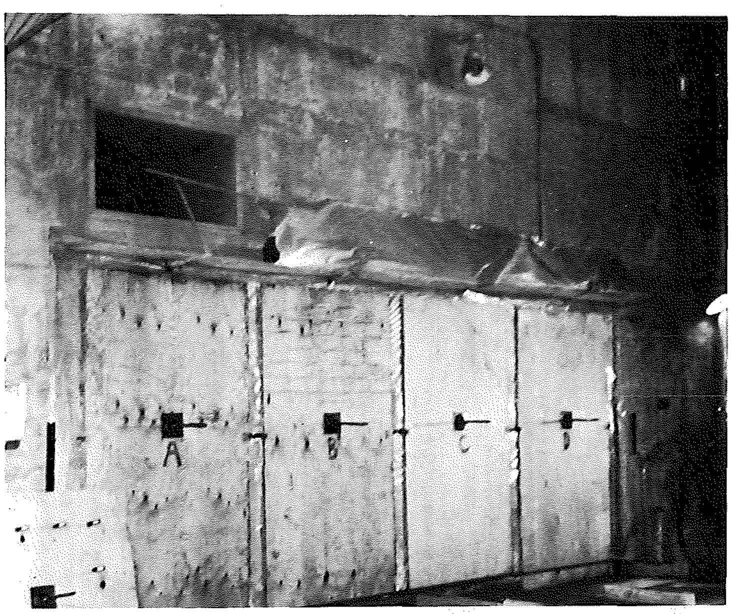

FIGURE 2. - Mounted plywood panels.

The splitting-tensile test followed the procedure outlined in the ASTM Test C496-64T (fig. 7).

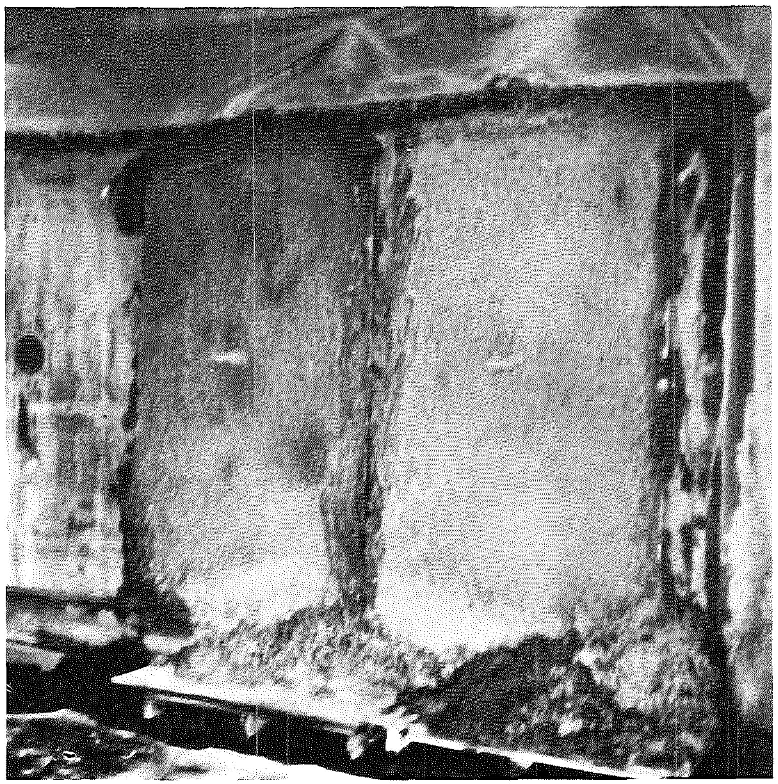

FIGURE 3. - Completed shotcrete panels.

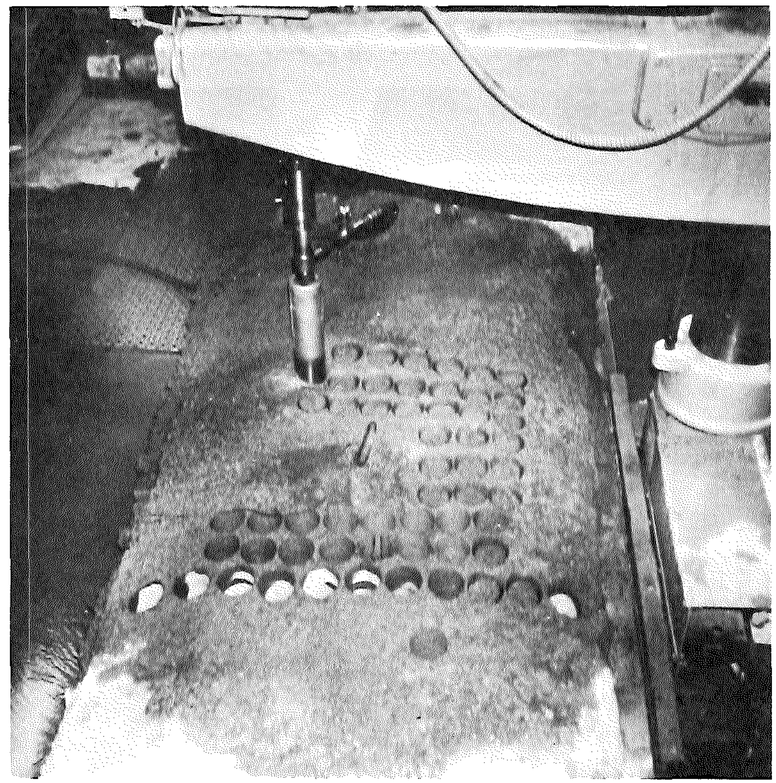

FIGURE 4. - Specimens being cored from panel.

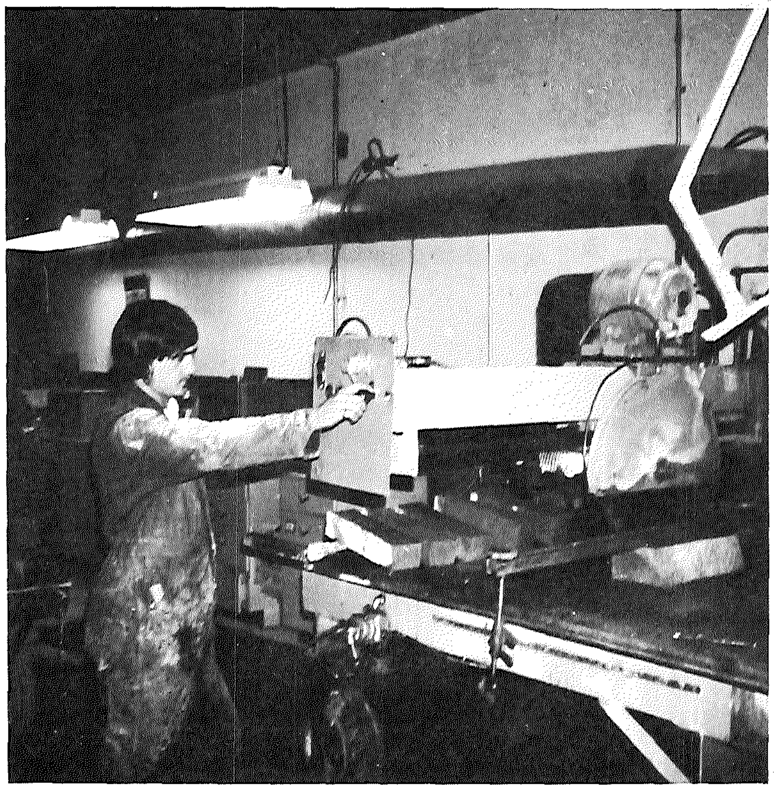

FIGURE 5. - Preparing flexural beams.

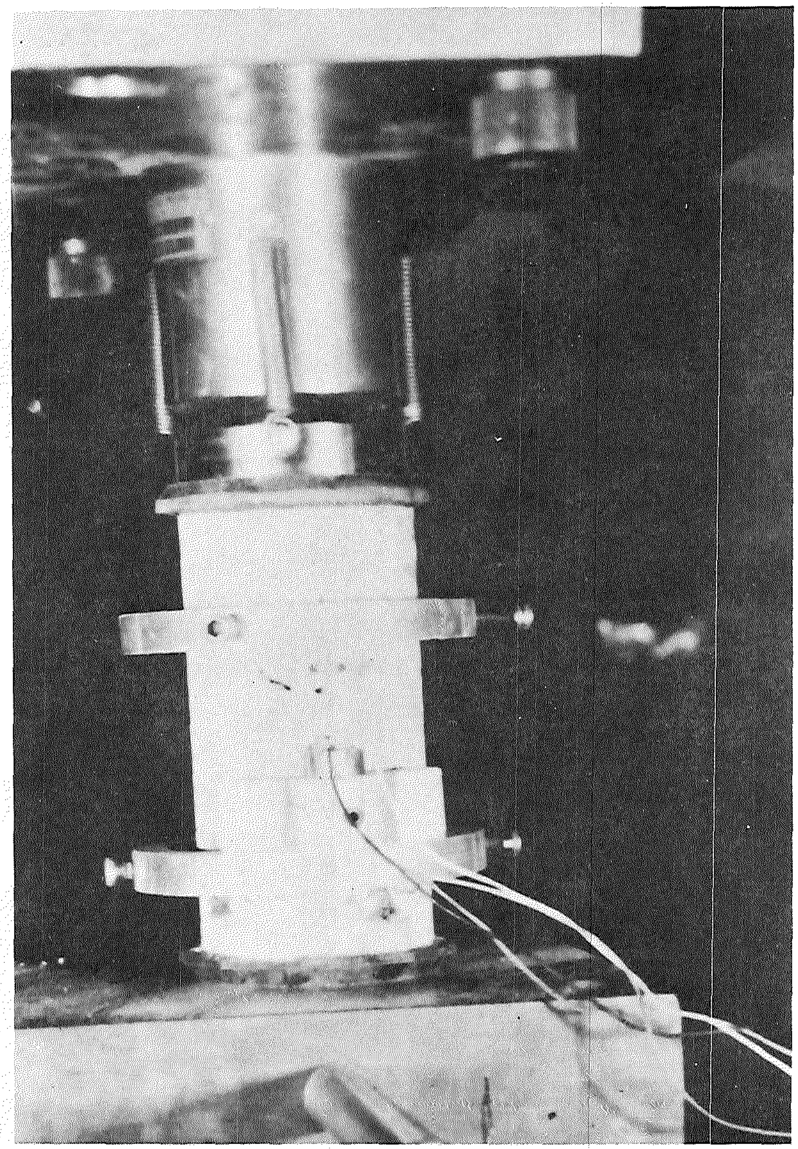

FIGURE 6. - Instrumented cylinder with mechanical strain gage.

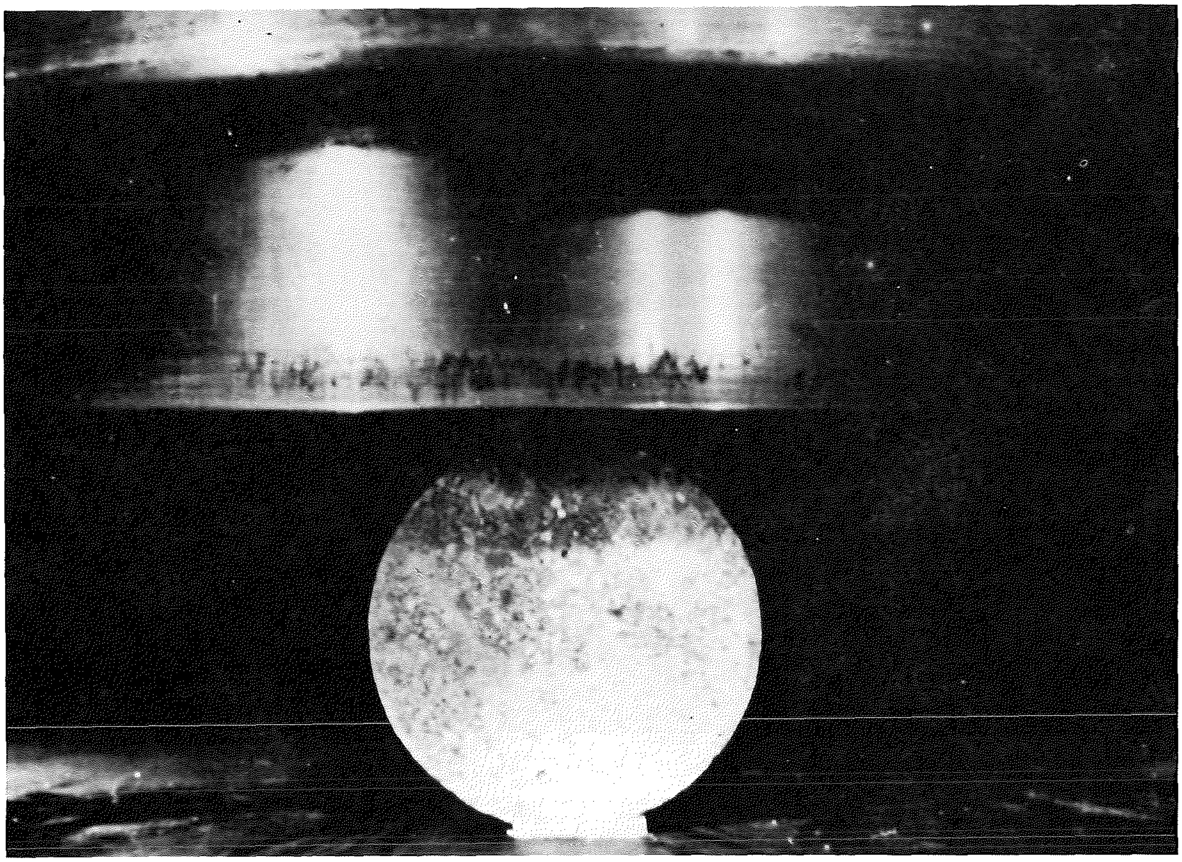

FIGURE 7. - Splitting-tensile test.

Flexural specimens (18 by 3 by 4 inches) were cut from the control and fibrous panels. Specimens were tested using 1/3-point loading on a 16-inch span.

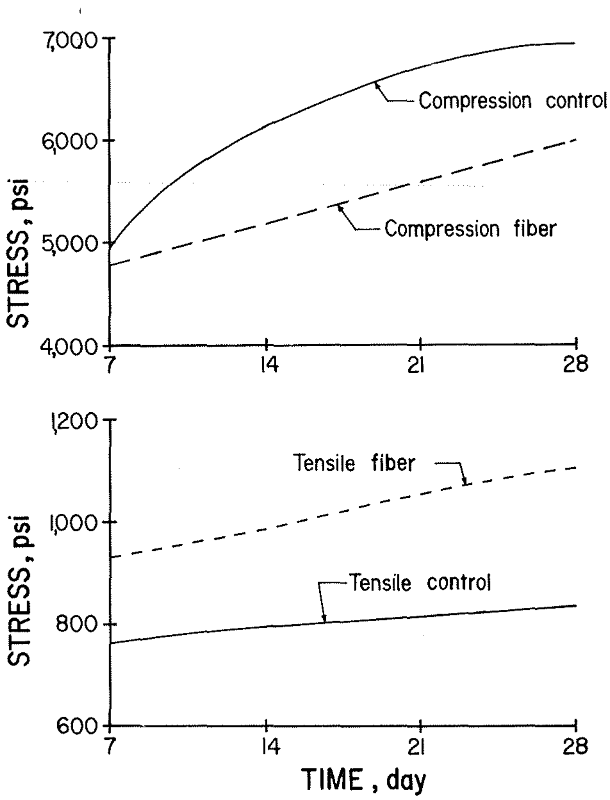

FIGURE 8. - Compression and splitting-tensile values for shot-crete with 16-mil, 3/4-inch fibers.

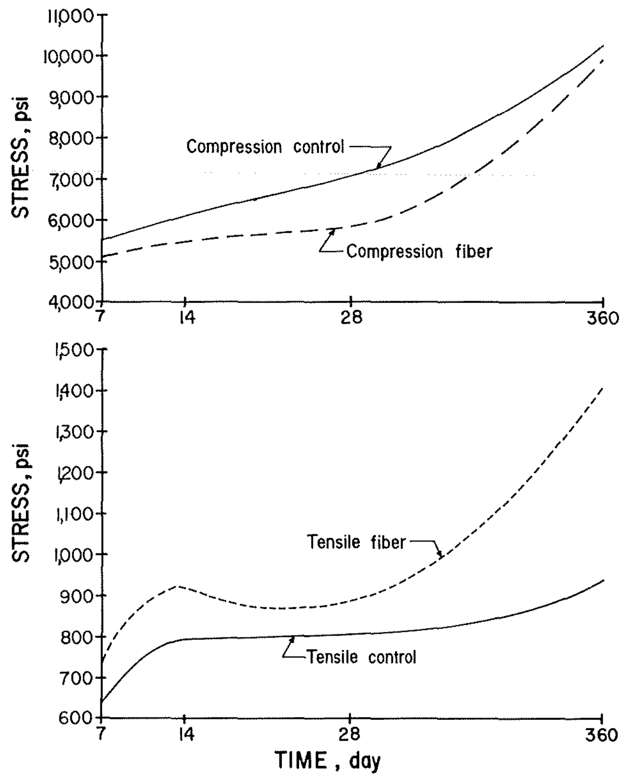

FIGURE 9. - Compression and splitting-tensile values for shot-crete with 16-mil, 1-inch fibers.

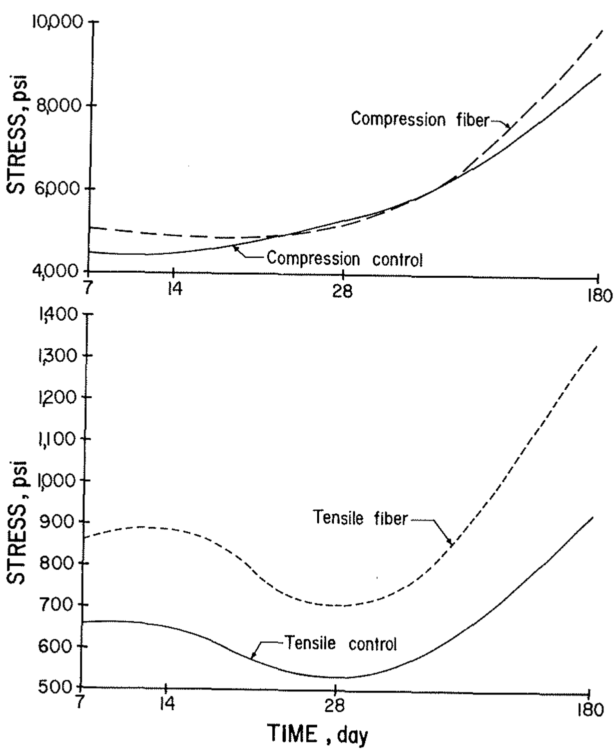

FIGURE 10. - Compression and splitting-tensile values for shotcrete with 10-mil, 3/4-inch fibers.

For each test, samples were chosen at random to prevent preference. Tables 2-7 and figures 8-10 show the compression, splitting-tensile strengths, and densities of the control and fibrous mix. The sample number designation refers to the panel, and to the column and row position within the panel. For example, the top left-hand side of panel A is represented by A-C1R1. Tables 8 and 9 show the tangent and the 0.1-percent secant moduli values. Figures 11 and 12 show typical stress-strain curves for control and fibrous shotcrete, respectively. Figures 13 through 16 represent typical specimens after testing.

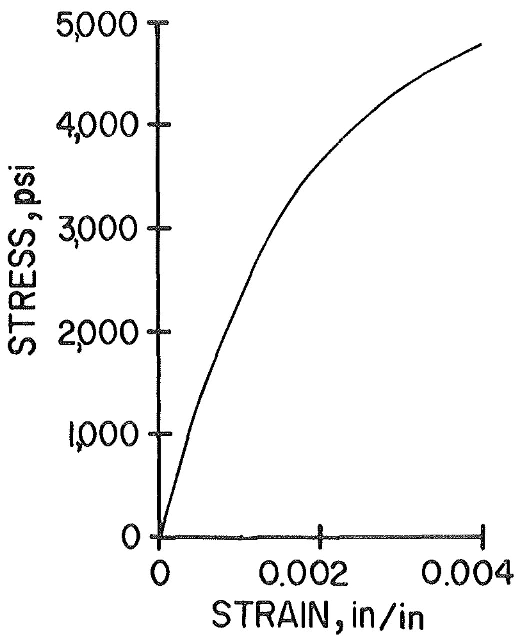

FIGURE 11. - Typical stress-strain curve for control cylinders.

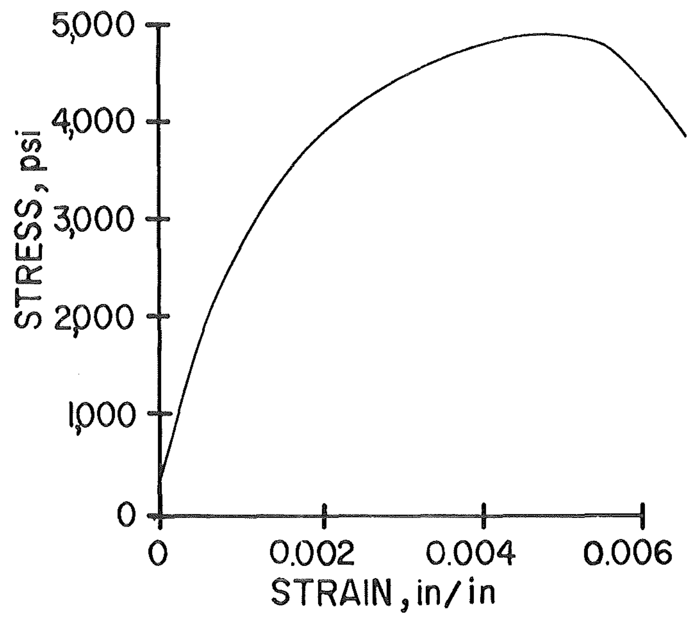

FIGURE 12. - Typical stress-strain curve for fibrous cylinders.

TABLE 2. - Compression and density for shotcrete with 16-mill, 3/4-inch fibers

Control shotcrete			Fibrous shotcrete		
Sample	Stress, psi	Density, lb/ft^3	Sample	Stress, psi	Density, lb/ft^3
7 DAYS					
A-C2R3	5,022	143	D-C6R4	4,499	148
A-C3R3	4,067	146	D-C6R3	4,329	148
A-C4R2	4,739	145	D-C4R5	5,051	145
A-C1R3	4,591	145	D-C2R5	5,065	148
A-C3R2	4,937	145	D-C3R4	4,937	145
A-C6R2	4,753	146	D-C1R4	4,619	148
A-C5R2	5,234	145	D-C5R5	5,135	147
A-C2R2	5,164	147	D-C4R2	4,074	146
A-C7R2	5,086	145	D-C2R4	4,994	147
A-C8R2	5,234	147	D-C5R3	4,470	148
Mean and std. dev	4,883±362	145±1.1	Mean and std. dev	4,717±367	147±1.2
14 DAYS					
A-C1R8	6,366	145	D-C6R6	5,404	145
A-C3R8	6,056	145	D-C2R3	5,135	148
A-C6R5	6,310	145	D-C4R8	4,485	145
A-C6R8	6,366	147	D-C5R6	5,631	146
A-C4R8	6,027	144	D-C1R3	5,333	146
A-C1R6	6,027	145	D-C2R7	5,532	147
A-C1R7	6,012	150	D-C5R2	4,308	146
A-C5R6	5,984	150	D-C6R7	5,546	144
A-C3R6	5,885	145	D-C1R7	5,532	147
A-C7R1	6,112	148	D-C5R8	5,291	147
Mean and std. dev	6,115±171	146±2.2	Mean and std. dev	5,220±460	146±1.2
28 DAYS					
A-C3R1	6,932	145	D-C3R9	5,800	144
A-C4R5	7,597	145	D-C2R9	5,517	147
A-C1R2	6,593	145	D-C6R10	6,154	148
A-C3R7	7,152	147	D-C5R10	5,715	145
A-C1R9	7,215	147	D-C6R8	6,281	145
A-C2R7	6,861	150	D-C3R10	6,112	147
A-C4R1	6,621	144	D-C1R9	6,027	148
A-C2R9	6,819	145	D-C1R10	6,861	146
A-C6R6	6,734	154	D-C7R8	6,041	145
Mean and std. dev	6,947±324	147±3.0	Mean and std. dev	6,056±384	146±1.4

TABLE 3. - Splitting-tensile strength and density for shotcrete with 16-mil, 3/4-inch fibers

Control shotcrete			Fibrous shotcrete		
Sample	Splitting-tensile strength, psi	Density, lb/ft^3	Sample	Splitting-tensile strength, psi	Density, lb/ft^3
7 DAYS					
A-C5R3............	806	143	D-C1R5............	951	145
A-C3R4............	792	145	D-C6R2............	852	148
A-C1R4............	767	143	D-C4R3............	895	145
A-C4R4............	762	146	D-C4R4............	944	148
A-C6R3............	828	145	D-C6R4............	992	145
A-C6R4............	796	145	D-C1R6............	990	146
A-C2R4............	718	145	D-C7R3............	870	145
A-C7R3............	722	145	D-C3R3............	895	145
A-C4R3............	789	143	D-C5R5............	996	145
			D-C3R5............	943	147
Mean and std. dev.........	776±37	144±1.1	Mean and std. dev.........	933±52	146±1.3
14 DAYS					
A-C2R8............	785	145	D-C5R7............	1,010	147
A-C1R1............	684	143	D-C2R6............	937	145
A-C8R1............	785	145	D-C7R5............	937	145
A-C4R6............	762	148	D-C4R7............	884	149
A-C7R5............	840	145	D-C1R8............	1,079	146
A-C2R5............	831	145	D-C3R6............	1,052	146
A-C1R5............	842	147	D-C2R8............	1,047	145
A-C5R5............	875	147	D-C7R7............	1,008	145
A-C2R6............	707	145	D-C2R7............	1,079	147
			D-C4R6............	884	145
Mean and std. dev.........	790±64	146±1.5	Mean and std. dev.........	992±76.8	146±1.3
28 DAYS					
A-C5R1............	877	144	D-C4R10..........	1,026	145
A-C7R1............	753	146	D-C4R9............	1,075	147
A-C8R8............	891	143	D-C7R9............	1,132	145
A-C6R7............	870	146	D-C3R8............	1,082	145
A-C5R8............	877	147	D-C7R10..........	1,082	145
A-C7R7............	799	145	D-C4R7............	1,142	149
A-C6R1............	778	145	D-C8R8............	1,100	144
A-C7R6............	821	150	D-C6R9............	1,107	149
A-C5R7............	821	145	D-C2R10..........	1,128	149
			D-C5R9............	1,149	146
Mean and std. dev.........	832±49	146±2.0	Mean and std. dev.........	1,102±38	146±1.9

TABLE 4. - Compression and density for shotcrete with 16-mil, 1-inch fibers

Control shotcrete			Fibrous shotcrete		
Sample	Stress, psi	Density, lb/ft^3	Sample	Stress, psi	Density, lb/ft^3
		7 DAYS			
B-C6R1.......	5,800	145	D-C4R3.......	5,164	147
B-C3R3.......	5,871	144	D-C3R3.......	5,093	146
B-C1R2.......	6,154	145	D-C1R4.......	5,206	146
B-C4R2.......	5,517	142	D-C6R2.......	4,626	149
B-C4R3.......	5,517	143	D-C2R5.......	5,362	144
B-C4R1.......	5,517	144	D-C3R2.......	5,418	145
B-C5R1.......	5,588	145	D-C6R3.......	4,555	143
B-C3R2.......	5,249	144	D-C2R2.......	5,390	146
B-C5R2.......	5,475	143	D-C5R3.......	5,376	150
B-C3R1.......	4,881	139	D-C2R3.......	5,234	145
Mean and std. dev.	5,556±346	143±1.8	Mean and std. dev.	5,142±294	146±2.0
		14 DAYS			
B-C2R6.......	5,744	145	D-C5R5.......	5,206	144
B-C7R5.......	6,423	145	D-C3R5.......	5,234	146
B-C5R4.......	6,083	145	D-C2R5.......	5,331	144
B-C4R6.......	6,029	146	D-C3R3.......	5,305	146
B-C1R6.......	6,762	148	D-C7R1.......	5,418	145
B-C7R4.......	5,631	143	D-C3R4.......	5,051	145
B-C2R5.......	5,461	143	D-C8R1.......	5,107	145
B-C8R4.......	6,154	145	D-C4R1.......	5,687	148
B-C8R5.......	6,225	144	D-C6R5.......	5,786	145
B-C8R4.......	6,253	145			
B-C6R3.......	5,390	141			
Mean and std. dev.	6,014±420	145±1.8	Mean and std. dev.	5,347±248	145±1.2
		28 DAYS			
B-C1R8.......	7,074	144	D-C7R4.......	5,857	143
B-C5R6.......	7,180	144	D-C2R3.......	5,956	152
B-C6R8.......	6,579	144	D-C5R4.......	5,659	149
B-C5R7.......	7,102	148	D-C4R5.......	6,253	145
B-C2R4.......	6,380	142	D-C10R4......	5,093	-
B-C6R4.......	6,805	141	D-C5R3.......	5,715	152
B-C6R7.......	6,890	146	D-C2R1.......	5,488	150
B-C6R5.......	6,932	144	D-C7R3.......	5,456	141
B-C4R8.......	7,243	145	D-C2R2.......	5,517	142
B-C2R4.......	7,781	142	D-C9R2.......	5,588	140
Mean and std. dev.	6,997±385	144±2.0	Mean and std. dev.	5,658±316	146±4.8
		360 DAYS			
B-C10R5......	8,842	141	C-C1R5.......	9,231	145
B-C3R6.......	10,823	145	C-C2R6.......	10,504	145
B-C10R6......	10,716	141	C-C8R4.......	10,115	144
B-C2R6.......	10,186	145	C-C4R6.......	10,469	147
B-C6R6.......	9,903	139	C-C6R4.......	9,054	143
B-C2R7.......	10,788	148			
B-C2R8.......	11,000	143			
B-C1R4.......	10,540	141			
Mean and std. dev.	10,349±708	143±2.9	Mean and std. dev.	9,875±688	145±1.5

TABLE 5. - Splitting-tensile strength and density for shotcrete with 16-mil, 1-inch fibers

Control shotcrete			Fibrous shotcrete		
Sample	Splitting-tensile strength, psi	Density, lb/ft^3	Sample	Splitting-tensile strength, psi	Density, lb/ft^3
7 DAYS					
B-C8R1........	704	143	D-C5R2........	654	145
B-C2R2........	566	143	D-C6R4........	757	146
B-C7R1........	746	142	D-C3R6........	729	145
B-C7R2........	601	143	D-C1R6........	884	143
B-C7R3........	467	142	D-C5R6........	700	145
B-C6R3........	576	141	D-C4R6........	718	143
B-C6R2........	647	144	D-C7R4........	729	143
B-C1R3........	594	142	D-C4R2........	612	144
B-C5R3........	704	143	D-C2R4........	732	147
B-C2R3........	714	147			
Mean and std. dev..	632±87	143±1.6	Mean and std. dev..	724± 75	145±1.4
14 DAYS					
B-C4R7........	817	148	D-C3R1........	1,019	145
B-C3R5........	686	143	D-C4R4........	927	143
B-C3R7........	828	149	D-C6R1........	859	148
B-C9R5........	803	144	D-C4R3........	803	147
B-C3R5........	736	143	D-C8R3........	948	145
B-C5R8........	799	147	D-C1R5........	916	147
B-C2R7........	754	148	D-C7R1........	955	145
B-C1R4........	831	141	D-C5R1........	916	147
B-C5R5........	778	144	D-C4R1........	859	148
B-C3R4........	824	142	D-C4R2........	1,019	144
Mean and std. dev..	785±48	145±2.8	Mean and std. dev..	922± 69	146±1.7
28 DAYS					
B-C1R5........	803	143	C-C6R1........	813	142
B-C3R4........	843	142	C-C1R1........	1,008	150
B-C3R6........	799	145	C-C1R3........	902	142
B-C7R4........	852	143	C-C1R2........	764	141
B-C4R4........	750	146	C-C10R2.......	1,096	143
B-C7R7........	729	145	C-C3R2........	764	145
B-C1R7........	817	147	C-C6R2........	1,012	143
B-C6R6........	753	147	C-C8R2........	792	143
B-C8R6........	831	146	D-C6R6........	958	145
B-C8R7........	792	147	D-C5R1........	785	147
Mean and std. dev..	797±41.5	145±1.8	Mean and std. dev..	889±122	144±2.7
360 DAYS					
B-C1R7........	1,029	143	C-C9R4........	1,418	143
B-C4R6........	845	142	C-C9R5........	1,461	145
B-C9R6........	817	140	C-C7R4........	1,471	144
B-C1R6........	962	143	C-C5R6........	1,362	144
B-C7R6........	1,050	142	C-C7R5........	1,238	146
B-C8R6........	1,008	143	C-C1R6........	1,510	147
B-C5R7........	810	150	C-C2R4........	1,386	143
B-C4R7........	962	145			
Mean and			Mean and		

TABLE 6. - Compression and density for shotcrete with 10-mil, 3/4-inch fibers

Control shotcrete			Fibrous shotcrete		
Sample	Stress, psi	Density, lb/ft^3	Sample	Stress, psi	Density, lb/ft^3
7 DAYS					
A-C6R11	5,390	132	D-C2R2	4,850	137
A-C3R1	5,120	132	D-C7R2	5,065	136
A-C2R3	3,720	132	D-C5R2	4,415	136
A-C2R2	3,720	133	D-C6R2	4,685	136
			D-C2R1	5,375	136
			D-C1R1	5,530	136
			D-C3R1	5,490	136
Mean and std. dev.	4,480± 893	132±0.25	Mean and std. dev.	5,059±429	136±0.37
14 DAYS					
A-C1R4	5,010	132	D-C2R5	4,925	135
A-C1R12	3,890	132	D-C8R5	4,910	135
A-C2R1	4,320	134	D-C3R5	5,050	135
A-C6R14	5,190	135	D-C5R5	4,810	134
A-C3R2	4,925	130	D-C7R5	4,950	136
A-C9R14	3,255	134	D-C6R4	5,095	136
A-C2R11	4,910	132	D-C7R4	5,150	136
Mean and std. dev.	4,500± 711	133±1.7	Mean and std. dev.	4,984±119	135±0.74
28 DAYS					
A-C1R15	2,885	134	D-C1R9	4,935	134
A-C1R7	6,310	133	D-C9R6	5,180	136
A-C4R15	4,935	133	D-C10R6	5,000	135
A-C2R15	4,770	134	D-C5R9	5,320	135
A-C7R15	6,255	134			
A-C9R13	5,985	133			
A-C5R15	6,365	133			
Mean and std. dev.	5,358±1,275	133±0.42	Mean and std. dev.	5,109±175	135±0.81
180 DAYS					
A-C2R6	6,480	133	D-C5R8	8,345	135
A-C2R10	9,620	130	D-C7R7	8,630	136
A-C5R12	10,129	131	D-C5R7	8,235	134
A-C3R11	7,980	132	D-C8R6	8,135	135
A-C2R5	8,573	132	D-C1R8	9,080	135
A-C4R7	9,480	133	D-C9R5	9,180	136
A-C2R7	10,185	133	D-C2R8	8,990	135
Mean and std. dev.	8,921±1,343	132±1.1	Mean and std. dev.	8,956±430	135±0.69

TABLE 7. - Splitting-tensile strength and density for shotcrete with 10-mil, 3/4-inch fibers

Control shotcrete			Fibrous shotcrete		
Sample	Splitting-tensile strength, psi	Density, lb/ft^3	Sample	Splitting-tensile strength, psi	Density, lb/ft^3
7 DAYS					
A-C4R4	709	132	D-C1R2	888	137
A-C5R4	732	132	D-C5R6	813	137
A-C1R5	637	133	D-C4R1	909	136
A-C2R4	566	132	D-C3R2	789	136
A-C4R5	700	133	D-C7R1	852	135
A-C5R5	647	133	D-C4R2	859	136
A-C6R5	619	132	D-C6R1	891	136
Mean and std. dev.	659±58	132±0.53	Mean and std. dev.	857±44	136±0.69
14 DAYS					
A-C3R7	714	132	D-C7R3	920	135
A-C5R14	672	133	D-C1R4	941	136
A-C1R6	439	132	D-C8R4	898	136
A-C10R14	676	133	D-C9R4	764	135
A-C1R10	658	132	D-C4R5	863	136
A-C3R5	686	132	D-C4R3	916	134
A-C6R15	672	133	D-C3R4	983	134
Mean and std. dev.	645±93	132±0.53	Mean and std. dev.	898±70	135±0.89
28 DAYS					
A-C5R6	665	134	D-C6R6	757	139
A-C3R12	442	131	D-C11R8	693	136
A-C4R11	566	132	D-C7R6	691	139
A-C1R8	499	133	D-C10R8	725	136
A-C2R8	463	133	D-C11R7	591	135
A-C7R14	506	134	D-C3R8	693	135
			D-C2R7	757	136
Mean and std. dev.	524±81	133±1.2	Mean and std. dev.	701±57	137±1.7
180 DAYS					
A-C4R14	937	134	D-C6R7	1,330	134
A-C4R9	927	130	D-C3R7	1,386	135
A-C1R11	881	132	D-C8R8	1,149	135
A-C2R10	817	132	D-C5R4	1,362	134
A-C2R12	944	132	D-C1R7	1,369	136
A-C5R11	958	132	D-C6R8	1,337	136
A-C3R9	980	130	D-C3R6	1,393	139
Mean and std. dev.	921±55	132±1.4	Mean and std. dev.	1,332±81	136±1.7

TABLE 8. - Tangent and secant moduli determinations for shotcrete with 16-mil, 3/4-inch fibers

Control shotcrete			Fibrous shotcrete		
Sample	Tangent, 10^6	Secant, 10^6	Sample	Tangent, 10^6	Secant, 10^6
7 DAYS					
A-C2R3.............	3.4	2.7	D-C3R4.............	3.2	2.5
A-C5R2.............	4.0	2.8	D-C5R5.............	3.4	2.6
A-C3R2.............	3.1	2.6	D-C4R2.............	3.8	2.6
Average.......	3.5	2.7	Average.......	3.5	2.6
14 DAYS					
A-C3R6.............	3.8	3.5	([1])	([1])	([1])
A-C5R6.............	3.7	3.2			
A-C7R4.............	3.6	2.9			
Average.......	3.7	3.2			
28 DAYS					
A-C6R6.............	4.2	3.4	D-C1R9............	2.9	2.8
A-C5R9.............	3.4	3.2	D-C7R8............	3.4	3.1
Average.......	3.8	3.3	Average......	3.2	3.0

[1] A lack of samples resulted in the elimination of some tests.

TABLE 9. - Tangent and secant moduli determinations for shotcrete with 16-mil, 1-inch fibers

Control shotcrete			Fibrous shotcrete		
Sample	Tangent, 10^6	Secant, 10^6	Sample	Tangent, 10^6	Secant, 10^6
7 DAYS					
B-C4R2.............	3.1	2.9	D-C1R4.............	2.5	2.2
B-C4R3.............	3.6	2.9	D-C2R5.............	2.5	2.8
B-C5R2.............	3.1	2.8	D-C3R3.............	2.5	2.3
			D-C5R3.............	2.2	2.0
Average.......	3.3	2.9	Average.......	2.4	2.3
14 DAYS					
B-C8R4.............	3.3	2.9	D-C6R3.............	2.4	2.3
B-C8R5.............	3.6	2.0	D-C6R5.............	2.6	2.3
Average.......	3.5	2.5	Average.......	2.5	2.3
28 DAYS					
B-C1R8.............	4.3	3.2	A-C2R3.............	3.6	2.9
B-C5R6.............	3.3	3.1	A-C5R4.............	3.3	2.8
B-C6R8.............	3.8	3.2	A-C7R3.............	3.1	2.7
Average.......	3.8	3.2	Average.......	3.3	2.8

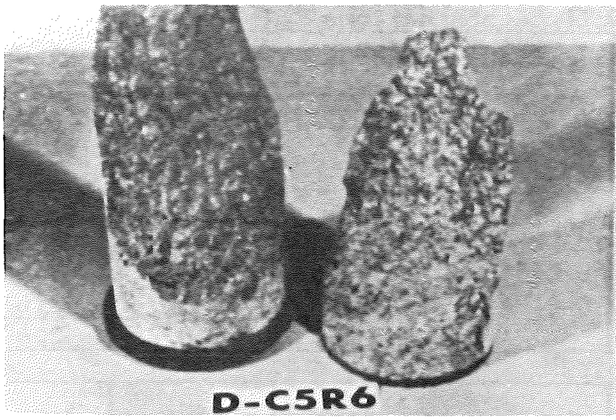

FIGURE 13. - Control cylinder used in compression test.

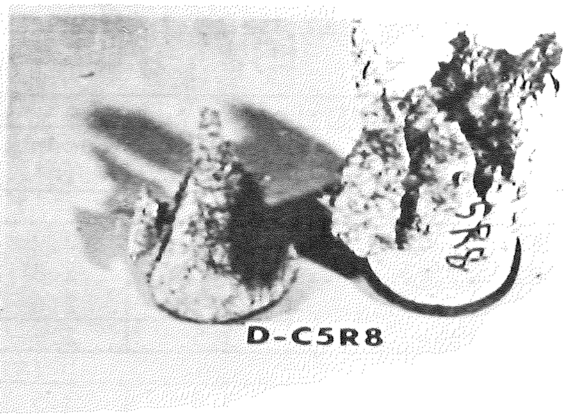

FIGURE 14. - Fibrous cylinder used in compression test.

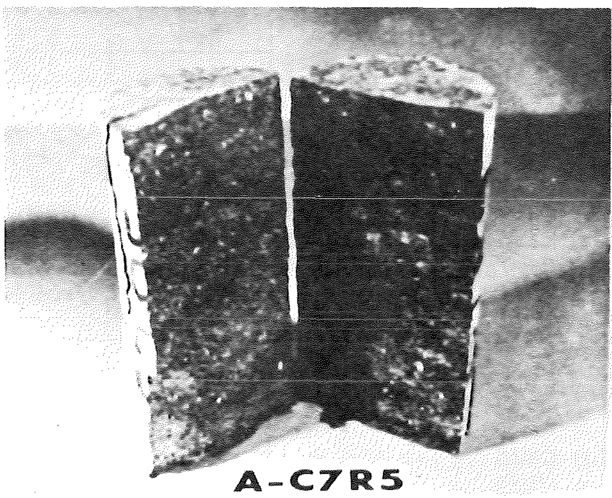

FIGURE 15. - Control cylinder used in tensile test.

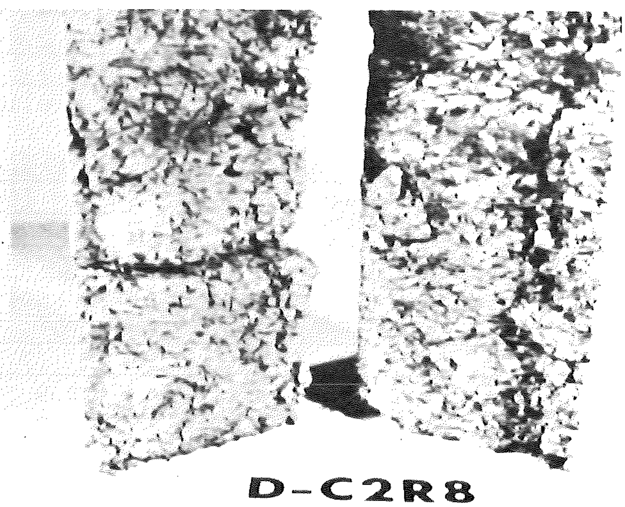

FIGURE 16. - Fibrous cylinder used in tensile test.

Table 10 shows the results of flexural tests at 28 days on shotcrete containing 16-mil, 3/4-inch fibers. Table 11 shows the results of flexural tests at 360 days on shotcrete containing 10-mil, 3/4-inch fibers. Figure 17 depicts a fibrous beam after failure. Figures 18 and 19 show the loading history of a control and fibrous beam, respectively.

Fiber compressive strengths were 13 percent lower and splitting-tensile strengths 25 percent higher than control strengths for 16-mil, 3/4-inch fibers at 28 days. Although compressive strengths were 19 percent lower at 28 days for 16-mil, 1-inch fibers, there was only a 5-percent reduction in strength at 360 days. Splitting-tensile strength increased from 10 percent at 28 days to 50 percent at 360 days. Shotcrete using 10-mil, 3/4-inch fibers exhibited a 5-percent decrease in compressive strength at 28 days and a slight increase at

180 days; splitting-tensile strengths increased from 34 percent at 28 days to 45 percent at 180 days.

TABLE 10. - Flexural strengths for shotcrete with 16-mil, 3/4-inch fibers at 28 days

Control shotcrete			Fibrous shotcrete		
Beam	Load, lb	Fiber stress, psi	Beam	Load, lb	Fiber stress, psi
1.............	1,530	1,020	1.............	2,230	1,487
2.............	1,840	1,227	2.............	1,970	1,313
3.............	1,300	867	3.............	2,040	1,360
4.............	1,050	700	4.............	2,510	1,673
			5.............	2,690	1,793
Average..	1,430	954	Average..	2,860	1,525

TABLE 11. - Flexural strengths for shotcrete with 10-mil, 3/4-inch fibers at 360 days

Control shotcrete			Fibrous shotcrete		
Beam	Load, lb	Fiber stress, psi	Beam	Load, lb	Fiber stress, psi
1.............	3,730	2,487	1.............	6,900	4,600
2.............	3,140	2,093	2.............	6,950	4,633
3.............	3,230	2,153			
Average...	3,366	2,244	Average..	6,925	4,617

At 28 days, the shotcrete with 16-mil, 3/4-inch fibers showed higher compression and splitting-tensile values than shotcrete with 16-mil, 1-inch fibers. Direct comparison cannot be made with the 10-mil-, 3/4-inch-fiber shotcrete because a different type of cement and additive was used; however, all values at 28 days are lower.

Shotcrete using 16-mil, 3/4-inch fibers exhibited a decrease of 16 percent in tangent moduli and a 9-percent decrease in secant moduli. There was a 13-percent reduction in both tangent and secant moduli when 16-mil, 1-inch fibers were used.

Flexural tests determined an increase in fiber stress of 60 percent at 28 days for shotcrete using 16-mil, 3/4-inch fibers, and an increase in fiber stress of 106 percent at 360 days for shotcrete using 10-mil, 3/4-inch fibers.

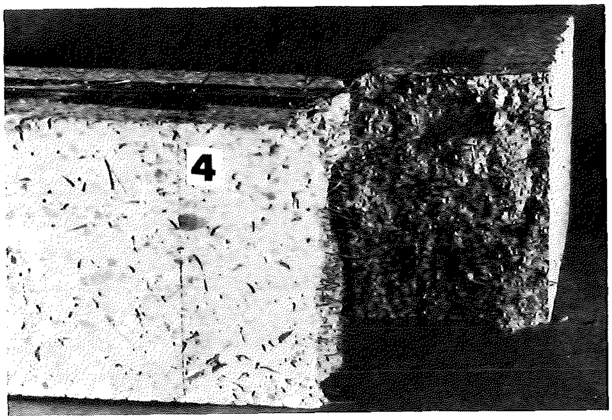

FIGURE 17. - Fibrous beam after failure.

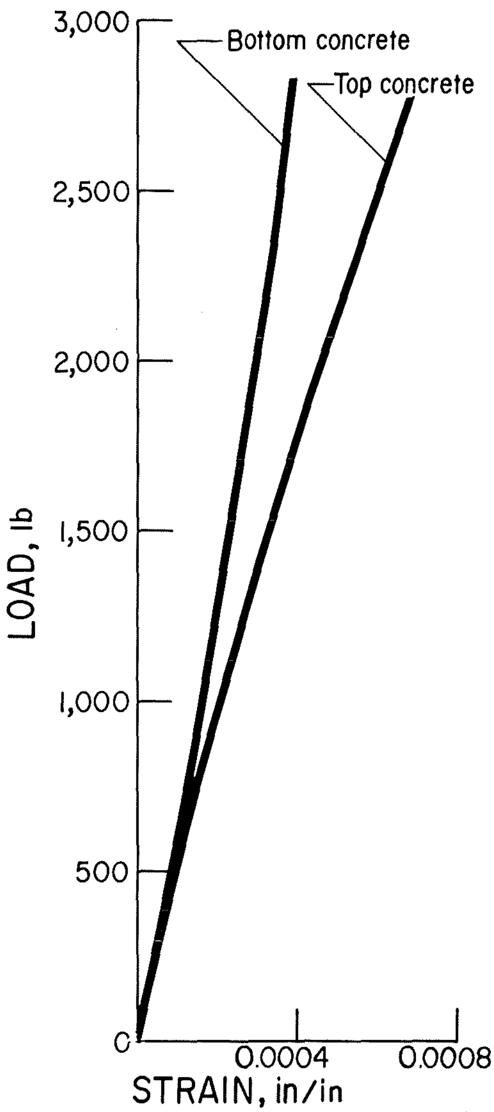

FIGURE 18. - Loading history of a control beam.

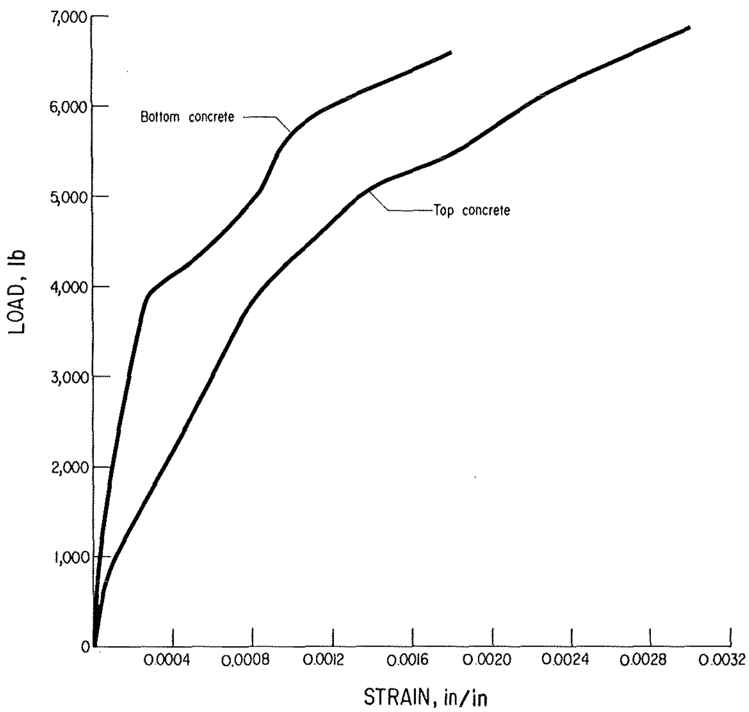

FIGURE 19. - Loading history of a fibrous beam.

Polymer-Impregnated Shotcrete

Numerous research organizations (Bureau of Reclamation, Brookhaven National Laboratories, Bureau of Mines, and others) have been developing and evaluating polymer concrete. The method takes cured concrete, dries it to a constant weight, and places it under a vacuum to remove excess water and air. The concrete is then saturated under pressure with a monomer, which is polymerized in place with heat or radiation after the excess monomer is drained from the surface of the specimen. Some remarkable properties have been obtained. Compressive and flexural strengths have been increased fourfold. The material is impermeable, is resistant to chemical attack, and exhibits excellent wear resistance (1).

To further evaluate the potential of plain and fibrous shotcrete, a laboratory study of polymer-impregnated shotcrete was undertaken to determine if a higher strength matrix could fully use the strength of the fibers. Samples of the shotcrete reported earlier were used.

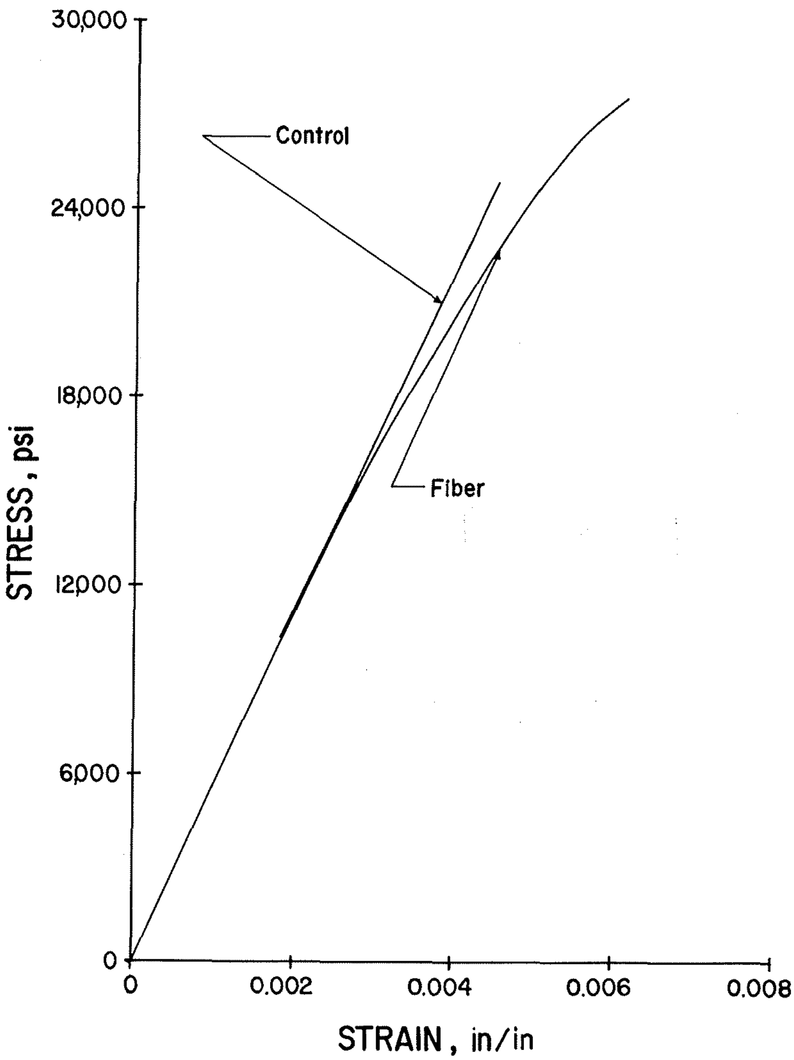

FIGURE 20. - Typical stress-strain curve for control and fiber-impregnated shotcrete.

Eight 6-inch cylinders, four control and four fibrous (16-mil, 1-inch fibers), were sent to Brookhaven National Laboratory. The samples were impregnated with methyl-methacrylate and polymerized in place with cobalt 60. Table 12 lists the compressive strengths, tangent and secant moduli, evacuated and impregnated densities, and monomer loading for the samples. Figure 20 depicts typical stress-strain curves for the impregnated control and fibrous shotcretes.

Another set of specimens, control and fibrous (10 mils, 3/4 inch), were sent to Bureau of Reclamation. The samples were impregnated with methyl methacrylate (catalyzed with DA79) and polymerized at 167° F for 12 hours. Table 13 lists the compressive strength, moduli, densities, and loading, and table 14 lists the splitting-tensile strength, densities, and loading for the samples. Figure 21 depicts a typical compression sample after failure.

TABLE 12. - Compressive strength, tangent and secant moduli, density, and monomer loading of impregnated shotcrete with 16-mil, 1-inch fibers

Sample	Compressive strength, psi	Tangent, 10^6	Secant, 10^6	Dry density, lb/ft^3	Impregnated density, lb/ft^3	Loading, pct
CONTROL SHOTCRETE						
C4R5..............	23,292	7.33	6.00	133.6	144.2	7.9
C3R5..............	26,863	5.93	5.25	134.6	145.4	8.0
C5R6..............	24,767	7.41	5.75	135.5	146.6	8.2
C8R5..............	25,409	5.93	5.25	135.5	146.5	8.1
Average......	25,083	6.65	5.56	134.8	145.7	8.1
FIBROUS SHOTCRETE						
C2R5..............	27,549	5.63	5.25	133.2	144.5	8.5
C5R5..............	21,940	5.00	5.00	133.2	144.7	8.6
C1R4..............	26,249	5.85	5.25	135.0	146.3	8.4
C10R4.............	26,494	5.78	5.25	131.4	142.3	8.3
Average......	25,558	5.56	5.19	133.2	144.5	8.5

TABLE 13. - Compressive strength, tangent and secant moduli, density, and monomer loading of impregnated shotcrete with 10-mil, 3/4-inch fibers

Sample	Compressive strength,	Tangent, 10^6	Secant, 10^6	Dry density, lb/ft^3	Impregnated density, lb/ft^3	Loading, pct
CONTROL SHOTCRETE						
R6C7..............	24,404	5.00	4.80	125.6	135.0	7.84
R13C10............	22,989	4.65	4.20	123.6	134.2	8.58
R13C8.............	24,121	-	-	124.5	135.4	8.04
R4C3..............	21,928	-	-	124.5	134.8	8.32
Average......	23,361	4.83	4.50	124.6	134.9	8.20
FIBROUS SHOTCRETE						
R6C5..............	25,748	-	-	125.9	136.5	8.45
R3C1..............	25,606	4.71	4.50	126.0	135.6	7.57
R8C9..............	26,314	-	-	124.9	135.5	8.48
R7C13.............	24,722	4.55	4.00	124.5	135.8	8.49
Average......	25,598	4.63	4.25	125.3	135.9	8.22

TABLE 14. - Splitting-tensile strength, density, and monomer loading of impregnated shotcrete with 10-mil, 3/4-inch fibers

Sample	Splitting-tensile strength, psi	Dry density, lb/ft^3	Impregnated density, lb/ft^3	Loading, pct
CONTROL SHOTCRETE				
R8C4	2,741	125.6	135.7	7.96
R7C5	2,149	124.2	134.5	8.22
R8C3	2,706	124.6	134.8	8.20
R5C7	2,741	125.9	135.8	7.80
Average	2,584	125.1	135.2	8.00
FIBROUS SHOTCRETE				
R7C10	2,130	124.6	135.2	8.51
R7C9	2,626	126.0	136.0	8.03
R6C11	2,485	124.1	134.7	8.58
R8C7	2,661	125.0	135.5	8.40
Average	2,476	124.9	135.4	8.38

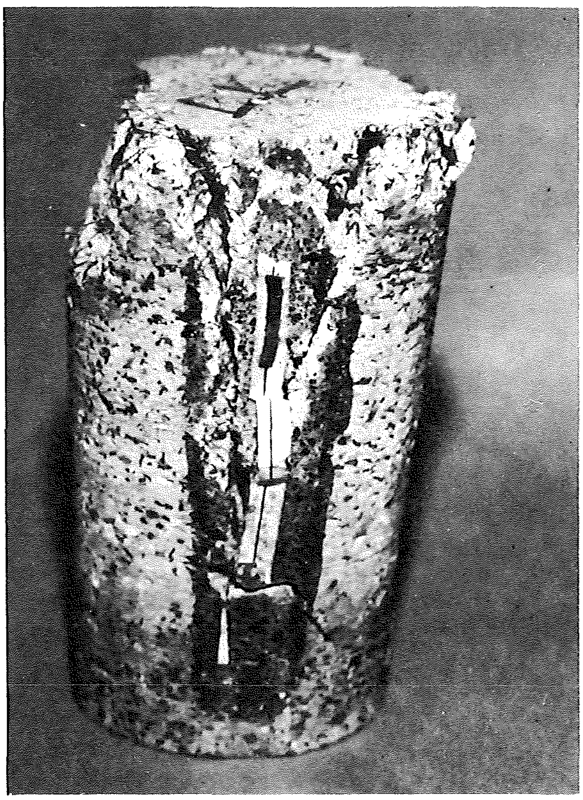

FIGURE 21. - Polymer-impregnated fibrous specimen after failure.

Polymer-impregnated shotcrete with 16-mil, 1-inch fibers exhibited an increase of 2 percent in compressive strength, and a decrease of 16 percent and 7 percent in tangent and secant moduli, respectively. Polymer-impregnated shotcrete with 10-mil, 3/4-inch fibers had an increase in compressive strength of 10 percent and a decrease in splitting-tensile strength of 4 percent. Tangent and secant moduli were reduced 4 percent and 6 percent, respectively.

CONCLUSIONS

Fibrous shotcrete is a new and promising structural material for ground support. Splitting-tensile strengths can be increased 50 percent and flexural strengths 106 percent, thus providing more versatility for a wider range of ground conditions. Equipment is available for field application; however, improvements could be made in dispensing and mixing the fiber.

Polymer-impregnated shotcrete exhibits the same characteristics as polymer-impregnated concrete. There is little difference between fibrous shotcrete and the control samples in either compression or tension. The fiber does produce a slightly more plastic material (as is shown by the stress-strain curves) and, when failure does occur, the material tends to hang together instead of shattering. However, visual examination of failed samples indicated that the bond between the matrix and fiber is the weak link since there were no broken fibers.

Rubber suits and face masks are required for anyone working in the "shooting" vicinity because the fibers act as lethal missiles. A flash coat without fibers should be placed over the protruding, brushlike ends to cover and prevent rusting.

There should be more research on shotcrete, especially fibrous shotcrete, since some of the observed phenomena are not fully understood. These include the following: (1) Effect of fibers on compressive strength (which tends to be lower at early cure age and then regains at a later age); (2) relationship between fibers, and shotcrete produced with Type III cement and additives and regulated-set cement; (3) bond characteristics of fibers; (4) various fiber material (steel, fiberglass, etc.) shape, and percent of fiber; (5) different mix design and aggregate loading; (6) additional flexural tests to demonstrate the increased energy-absorbing capacity of fibrous shotcrete; (7) the reduction of tensile strength between 14 and 28 days; and (8) methods for reducing fiber rebound.

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