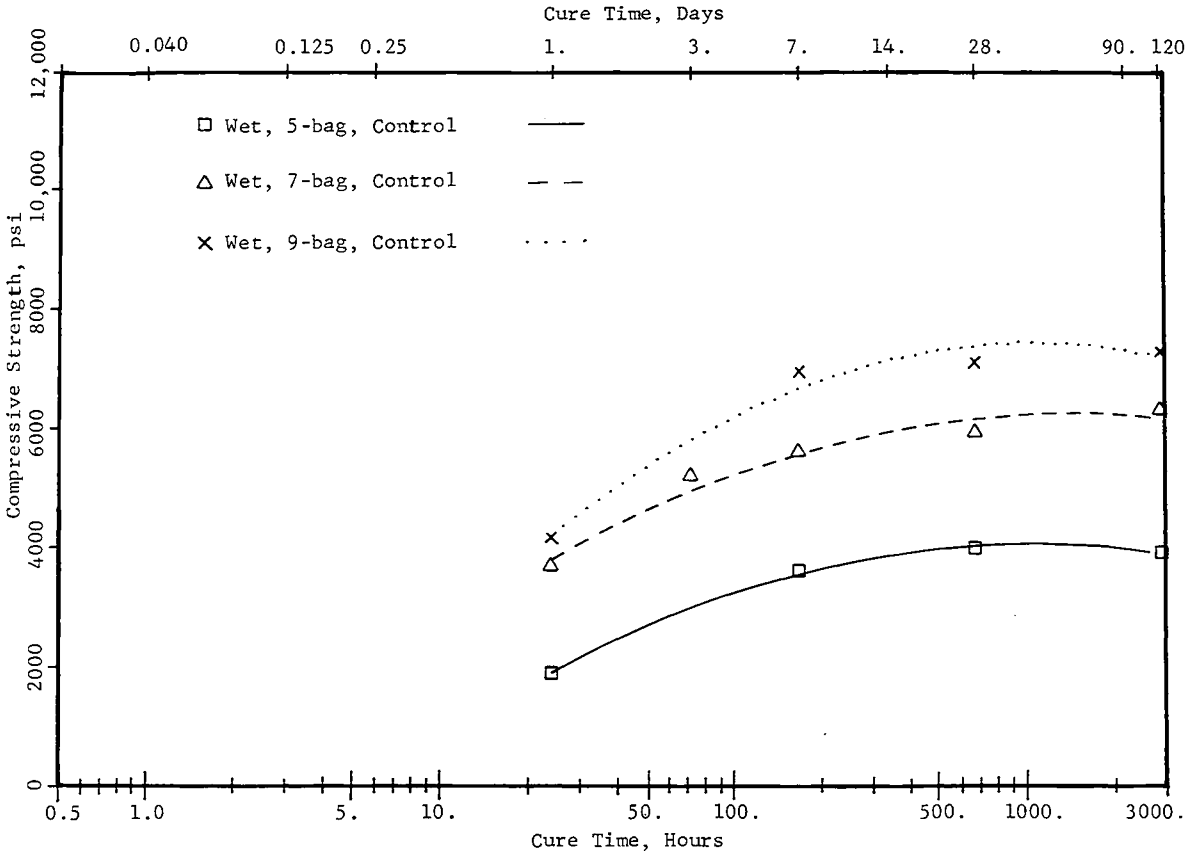

Fig. 7 TYPICAL COMPRESSIVE STRENGTH VERSUS TIME PLOTS FOR TYPE III CEMENT SHOTCRETE

lowest strengths. Control specimens for wet and dry processes depicted that strength increased directly with cement content (i.e. 5, 7, and 9 bags per yard of concrete). Shotcrete with FSA or RSPC did not display marked differences in strength with cement content.

Regulated Set Portland Cement panels fabricated with no soda ash developed early strengths greater than those shown by the cement panels with FSA. Shotcretes with FSA can be handled early, but they gain strength slowly for the first 6 to 8 hours. On the other hand, RSPC shotcretes gain strength rapidly in the first few hours. Some of the data seem to indicate a drop in strength after curing for 90 days, but this needs further investigation.

The data indicate that both wet and dry shotcreting processes are capable of producing quality concrete. The 9-bag controls have 28-day strengths around 8000 psi and the 5-bag mixes produce 28-day strengths in the neighborhood of 5500 psi, with the 7-bag mix falling in between these extremes. The lowest 28-day strengths (3000 to 3500 psi) occur for the highest content of FSA (6 percent) for a 5-bag mix; even this is considered good structural concrete.

The flexure strength did not indicate any significant difference in strength between the 2- and 6-in. panels, even though the 6-in. bars did show indications of lamination due to laying of the thicker panels in 2-in. lifts (see Fig. 8). This is due to the fact that there is enough bond between the lifts to provide monolithic action. The dry process controls produced the highest strength while the FSA concrete exhibited decreasing strength with increasing amounts of additive. The wet process shotcrete data showed lower strengths for both the control and FSA concretes. The flexural strength for the wet process shotcrete is about 50 percent of the dry process shotcrete. There was considerable overlap between the strengths of the 5-, 7-, and 9-bag mixes. A typical plot is seen in Fig. 9. The flexural strength for the dry process shotcrete varied from a 28-day low of 1500 psi for 6 percent FSA mixes, to a high of 3500 psi for the controls and RSPC mixes, and for the wet process a low of 1000 psi to a high of 2000 psi.

A typical plot for the shear stress versus elapsed time is shown in Fig. 10. The shear strength data group tightly with little difference between the mixes. The values ranged from a high of 1200 psi to a low of 500 psi.

Young's modulus and Poisson's ratio were obtained for shotcrete specimens tested in compression. Initial tangent and secant moduli were determined from the stress-strain data, but the latter were found to be highly variable.

The highest Young's modulus values were obtained for the control shotcrete with no additives. The 9-bag mixes exhibited 28-day modulus values in the range of 5 to 6 x 10^6 psi. Use of larger amounts of FSA reduced the 28-day

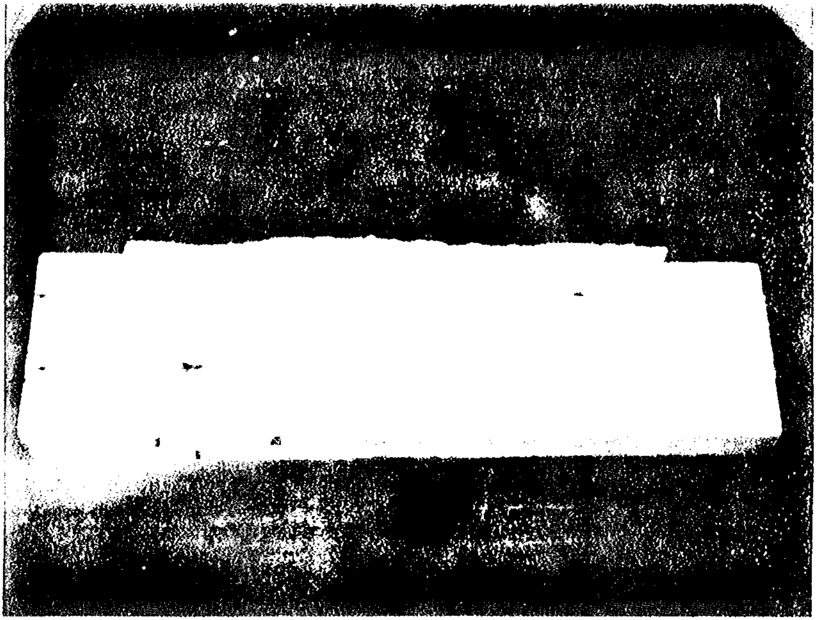

Fig. 8 LAMINATION OF SHOTCRETE DUE TO SUCCESSIVE LAYERING

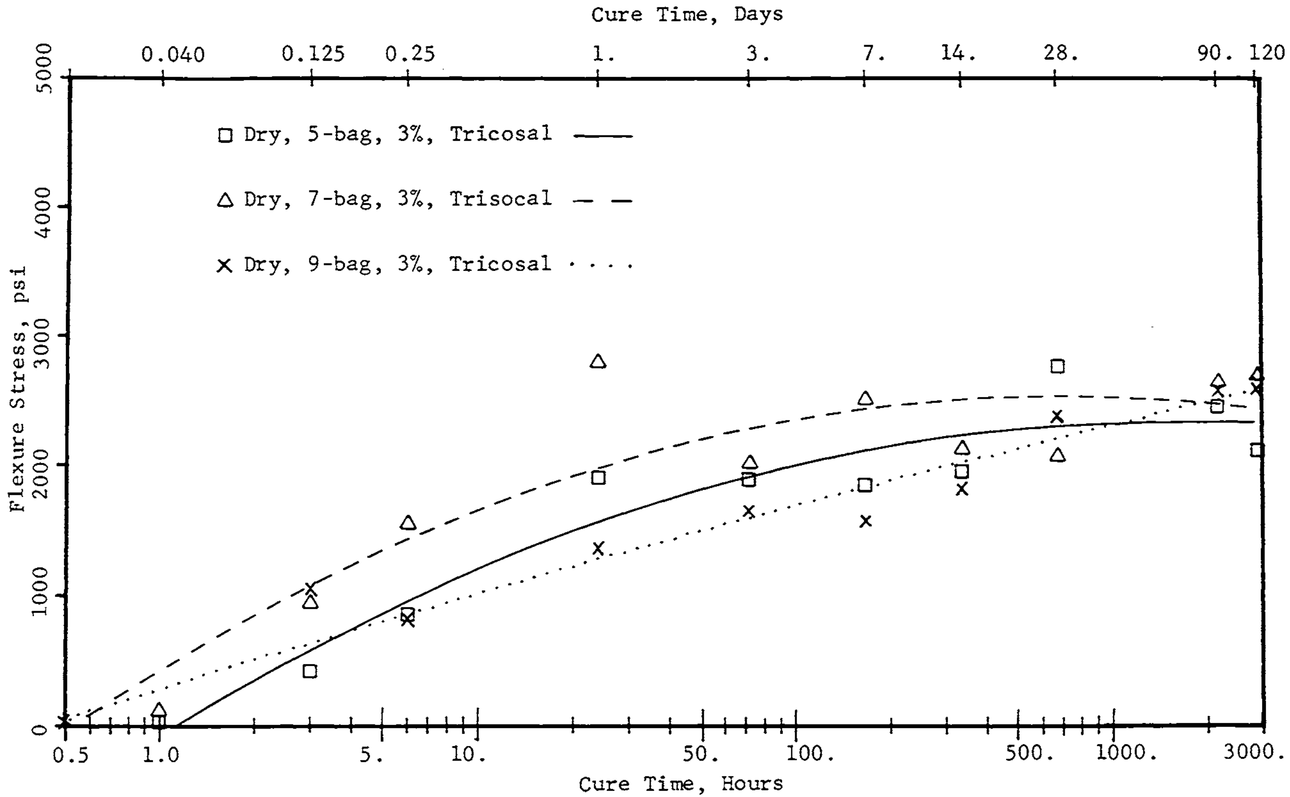

Fig. 9 TYPICAL FLEXURAL STRENGTH VERSUS TIME PLOTS FOR SHOTCRETE

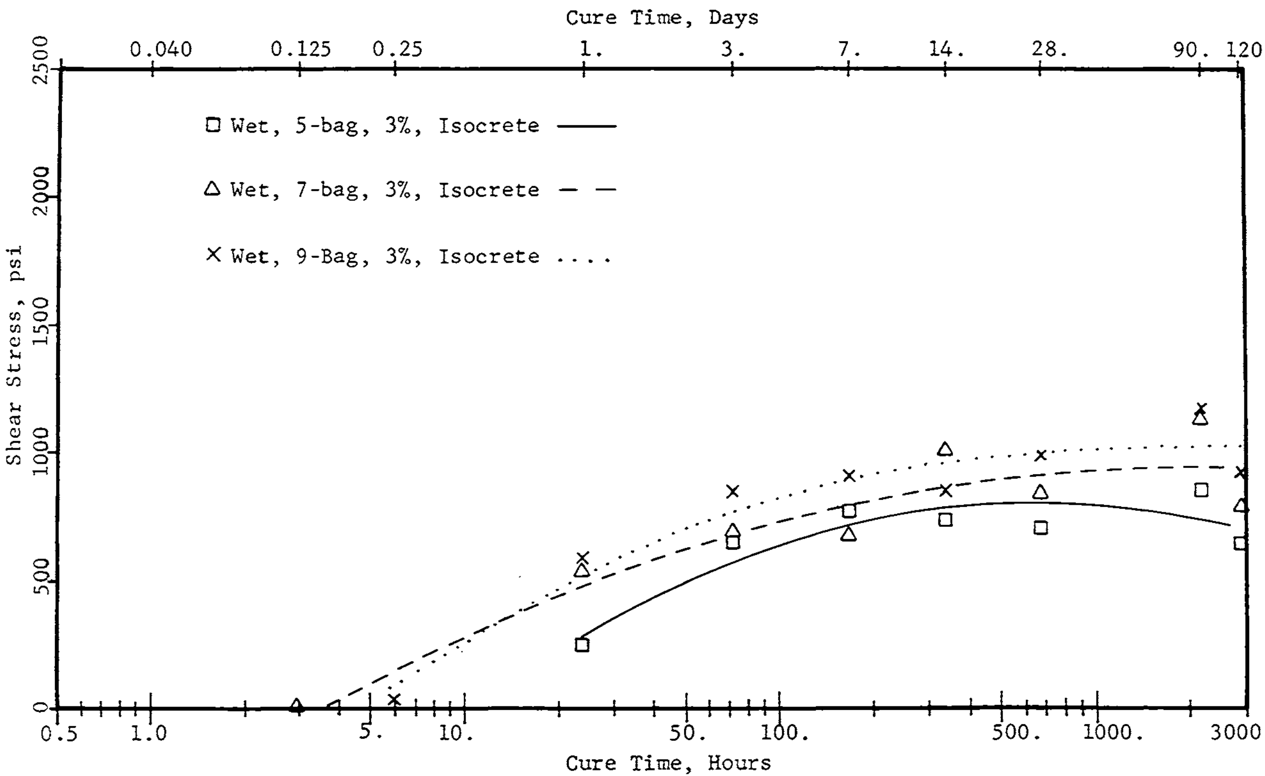

Fig. 10 TYPICAL SHEAR STRENGTH VERSUS TIME PLOTS FOR SHOTCRETE

modulus values to 3 to 3.5 x 10^6 psi. Concrete made using RSPC displayed a lower elastic modulus for the 1 percent soda ash additive than concrete without soda ash. Dry process shotcrete appeared to display more uniform elastic properties than that made with the wet process.

The 28-day values of Poisson's ratio at 25 percent of ultimate load ranged from 0.05 to 0.30 and showed no consistent variation with strength of concrete, richness of mix, or gradation of the aggregate. The only trend which appears to be present is a slight increase in Poisson's ratio with age.

For shotcrete to provide structural support in tunnels it is desirable that there be adhesion between the concrete and the tunnel rock. Bond was measured by shear and tension tests at the interface between shotcrete and a rock substrate. Only 15 percent of the failure in these tests occurred exclusively at the interface; all but one of these occurred in shear specimens. The rest failed in the substrate (coal, sandstone, shale); no breaks occurred in the shotcrete.

In order to check the permeability of the shotcrete fabricated during this series, 2-in. cubes were cut and subjected to 60-psi methane for 5 min. No loss of pressure was observed, indicating relative impermeability to gas flow.

CLOSURE

Shotcreting offers considerable potential for underground support and deserves greater attention. It does not present a panacea for all ground support problems and should not be regarded as such. Further developments would prove beneficial. Fiber reinforcement and polymer-cement concretes are being investigated.

The data presented in this paper clearly indicate that use of reg-set cements would increase the versatility of shotcrete. However, this would require modifications and improvements in current procedure. Included among them might be:

(1) Mixing of the aggregate and cement at the heading, i.e. conveying the two materials separately. Continuous mixing is required; batch mixing is unsatisfactory.

(2) Provision of water heaters to heat the water.

(3) Establishment of an emergency dump and clean out procedure, in case of sudden stoppages.

These procedural changes imply alterations in current equipment. An alternative approach would be the development of suitable additives, so that the cements behave similar to Regulated Set Portland Cement in setting and strength characteristics. This appears quite feasible, but requires investigation. Toxicity affects of the materials need to be considered.

The results of the investigation reported herein also show that if reg-set cement cannot be used, Type III Portland Cement would be preferable to the Type I commonly employed. The use of fast setting agents does not provide the desirable characteristics in shotcrete that reg-set cement does.

The need to obtain better control over the hydration and spraying of shotcrete is evident. Some efforts towards attaining these goals would be worthwhile. Automation of the spraying process would constitute a major advance and enhance the utility of shotcreting as a method of ground control in underground excavation.

ACKNOWLEDGEMENTS

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SUMMARY OF WORKSHOP B
SHOTCRETE DESIGN

by P. L. Boileau,* Reporter

(Conference Chairman's Note: It is very unfortunate that Mr. Boileau's manuscript covering the summary of Workshop B was misplaced subsequent to the conference and is not available for inclusion herein. The following brief summary was prepared by the Conference Chairman.)

The workshop on "Shotcrete Design" met all day Wednesday, July 18, in a morning and evening session. Four speakers presented papers covering a wide range of design considerations. Mr. John Morris, Bureau of Reclamation, opened the session with a talk on Bureau design practices. Dr. Ron Heuer, A. A. Mathews, Inc., discussed the design and selection of shotcrete for use as temporary support, and then Dr. Ed Cording, University of Illinois, discussed geological considerations. In the evening session Dr. Madan Singh, Illinois Institute of Technology, talked on design considerations when using special cements in shotcrete.

Interspersed with these talks were lively discussions among the conferees particularly regarding shotcrete design criteria. A diversity of opinion seemed to exist regarding many of the factors affecting the final design of shotcrete for underground support. There was general agreement that the criteria used in shotcrete design depend on its function in the underground opening; i.e., a temporary or permanent support, a surface seal, a fallout deterrent, a structural ring or arch or a stress relief smoothing component. Some of the participants felt that experience and judgment

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