

Keynote Address

by

A. A. Mathews*

Five years ago this conference would have been impossible. At that time, the Burnaby Tunnel in Vancouver, B. C., was about the only North American underground project of any magnitude which had successfully used shotcrete as the prime support medium. The Bureau of Reclamation had not written a shotcrete specification for its work, Kirk Fox was just developing a keen interest in the subject, and some of the more progressive mining companies were working on experimental programs. Most designers had never even heard of shotcrete and consequently our tunnel contractors had no incentive to develop an expertise in the field.

I well remember my initiation into the clan. Along with Dr. Vic Dolmage, I was on a consulting panel concerned with the excavation of the Portage Mountain Underground Powerhouse in northern British Columbia. On one of our flights from Vancouver to Hudson Hope, Vic told me of a railroad tunnel in Vancouver which his firm had recently designed. The geology consisted of inter-bedded shales, sandstones, and conglomerates. Instead of the usual steel supports followed by a concrete lining, the tunnel would be permanently supported by layers of shotcrete, 6-in. thick on the arch and 4-in. on the sidewalls.

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I had too much respect for Vic Dolmage to tell him what I thought of such a scheme. So, I decided to just let him find out for himself. Later, during another flight to Hudson Hope, I asked Vic how the tunnel was coming. To my surprise, he reported that the shotcrete support was a success and that good progress was being achieved in driving the tunnel. After that, I simply had to see for myself.

I visited the Burnaby Tunnel later that week upon my return to Vancouver. To my amazement, some 25 ft of essentially finished tunnel was being completed every day. This was a single track railroad tunnel, about 18 ft wide and 28 ft high. With these dimensions, it was possible to use a drill jumbo that would permit a Conway Mucker to work underneath the topdeck.

After blasting, the flyrock and the toe of the muck pile were loaded out. Then the jumbo was moved in and an extension of the upper deck was telescoped over the muck pile to the face. The newly exposed arch was then shotcreted from this platform while the mucking continued underneath. Successive layers of shotcrete in the arch and on the sidewalls were applied later during the drill cycle. Obviously, here was a technique which promised to really advance the state of the art of tunnel construction.

Later, I inspected a subway tunnel under construction in Milano, Italy. The ground was sand and gravel. But by means of making the excavation in small increments followed immediately by shotcrete, the contractor was able to advance the tunnel without the use of a shield or temporary supports.

I visited Stabilator, Inc., in Stockholm and learned how this firm had developed remote-controlled spraying equipment and

used it successfully on difficult tunnels in Hong Kong. I visited Walter Lang, a manufacturer of shotcrete spraying equipment in Switzerland.

We began collecting technical articles on the design and execution of shotcrete structures. Since most of the work to date had been done in Europe, many of these articles had to be translated from the original German, Italian, or Swedish.

What is it that permits a relatively thin layer of shotcrete to do the work of heavy steel supports and concrete? Certainly, the fact that the additive induces very quick set and high early strength is a factor. Also, the early application of shotcrete helps prevent the start of loosening. If the first fragment is never allowed to fall from the excavated surface, the tunnel will obviously be permanently stable. But there must be more to it than that.

It has long been recognized that some yielding of the excavated tunnel periphery must be allowed if the load on the supports is to be minimized. On the other hand, unless this yielding is controlled, intolerable displacements frequently occur. A layer of shotcrete, rapidly applied to the freshly excavated surface, seems to have the flexibility to yield as required and also has the structural capacity to maintain stability. But the achievement of this objective requires the application, coordination, and control of many elements.

The designer must properly apply the principles of rock mechanics or soils mechanics to the design under consideration. Then he must dimension and schedule the shotcrete and select any

complements, such as rock bolts, supplemental supports, or reinforcing. Suitable materials and equipment must be provided. Skilled workers must be found or trained. Quality control must be maintained.

Here in the United States, our failure to satisfy all of these requirements simultaneously and promptly has placed us at a cross-roads. In some quarters, shotcrete has been discredited as an effective medium for the design and construction of tunnels. But most of the so-called failures can, in retrospect, be ascribed to deficiencies in one or more of the essential elements noted before.

In California, we have learned the importance of proper control on the job. This was emphasized again in Charleston, South Carolina, along with the necessity for using proper techniques. In Washington, we learned more about the importance of specifications and bidding schedules as well as the necessity for providing suitable equipment and skilled workmen. More appreciation has been developed for the use of rock bolts or light supports to complement the shotcrete.

We know that the shotcrete in a tunnel arch must be tied into a stable foundation. If there is no stable or sound material below the springline, it may be necessary to close the invert. We know that in some types of very blocky ground, the shotcrete may not develop strength rapidly enough to maintain stability. However, the judicious use of supplementary rock bolts may solve the problem.

Light steel supports have been used to complement a

shotcrete design for long spans or other severe conditions. But to embed a structural support of fixed dimensions can consume a lot of shotcrete where overbreak is excessive. Also, a rolled structural shape is not the best configuration for embedment. Perhaps a member built up from round bars, as practiced in Europe, would be better.

Remote-controlled equipment for shotcrete application and rock bolt installation has been built. Is such equipment perfected and readily available so that its use may be specified in the interest of safety without unduly handicapping the work?

What type of specification should be written for shotcrete, the method type or the performance type? The method type does not encourage the development of better materials, equipment, and techniques. But the performance type may bewilder the inexperienced contractor and be difficult to administer. How should shotcrete be measured and paid for, so that the contractor is compensated fairly, but also has an incentive to improve performance and minimize rebound?

Many of these problems stem from our mode of contracting for civil projects in this country. The designer prepares the design and writes the specifications. Then the contractor performs the work under the supervision of the engineer. But the engineer can only require the contractor to comply with the plans and specifications. He cannot direct the contractor's work.

Since the behavior of an underground structure depends as much on the construction method and workmanship as it does on the design, the designer is reluctant to utilize an unfamiliar

structural element when he has little control over the actual construction. By the same token, the contractor is not likely to welcome a new construction concept when he cannot assess his potential difficulty in meeting the specification requirements.

Some of you can remember when only rivets were used to connect structural steel members. Now, only bolts or weldments are used. But this change was not accepted overnight by the design profession or the construction industry. Years of development and education were necessary.

Today, we in the shotcrete field face a similar challenge. Our manufacturers have to understand the practical problems of the contractor--safety, quality control, equipment availability, compatibility with the tunnel environment and space parameters. Our contractors must be acquainted with available equipment, acceptable operating practices, and materials requirements. They must be prepared to train skilled workmen. Our designers must understand the virtues and limitations of shotcrete. They must know when to incorporate complementary elements in their designs. They must know how to instrument and monitor the work so that it can be used with confidence. Our owners must realize that this is a fledgling industry offering a potential for significant cost and time reductions on a variety of underground work. But in order to realize these benefits, the industry must be supported and nurtured during its development.

It has been well stated that in the evolution of the art of tunnel design, there has been far too much calculation and too little observation. We are tempted to view the tunnel support

as a free-standing structure, like a bridge. We then estimate the loads the structure must support and design it accordingly.

For rock tunnels, the load is estimated as being equivalent to a certain thickness of loosened rock overhead, depending on the dimensions of the tunnel and the quality of the rock.

Years ago, that method worked fairly well. If the tunnel required temporary steel support, the steel ribs were usually supporting the ground satisfactorily before the concrete lining could be placed. So, as long as the concrete adequately protected the ribs from damage or corrosion, it was generally satisfactory regardless of its structural capability.

In deep tunnels through poor quality ground, the foregoing rules didn't work. The builder would run into squeezing ground that required re-mining, additional support, and various other expedients. But again, by the time he was ready to place the concrete lining, he had already stabilized the ground.

More recently, the use of rock bolts has, in many cases, eliminated the need for temporary steel supports. Again, when the final concrete lining is placed, the ground is already stable. If the rock bolts have been fully grouted, they can be considered permanent, and all the concrete really has to do is protect the ends of the rock bolts and the rock surface between bolts. And since six or eight inches is about the smallest lining thickness which can be satisfactorily placed behind forms, a highly sophisticated method for designing the lining is unnecessary.

Now, the rules of the game are completely changed. We have a substance which can be applied to the excavated surface

immediately after exposure. Frequently, it eliminates the need for any temporary steel supports. In other cases, supplemental rock bolts may be necessary. How can the designer dimension this support system and how can he assure himself that his design is indeed adequate?

The behavior of the excavated opening supported with shotcrete, together perhaps with rockbolts, depends primarily on the in situ rock pressures, the effective physical properties of the rock mass, and the dimensions and physical properties of the shotcrete-rockbolt combination.

Since the relevant effective physical properties of the rock mass depend partly on the size of the tunnel, they cannot be measured in laboratory samples. However, we do have means for measuring some of these properties in situ, and we have means for estimating the value of others. Thus, we can choose parameters for design which, although admittedly inaccurate, at least permit a rational approach to the problem.

We can also calculate the stresses and strains in the structure, or the behavior of the completed tunnel opening, using formulae developed by investigators of rock mechanics theory. The advent of the computer has, in addition, given us more sophisticated solutions, such as the finite element analysis.

But, given inaccurate design parameters and unproven behavior theories, we still need some means to evaluate the performance of our design. Fortunately, we have this capability. We can measure the movements, deflections, and strains in the completed opening and in the surrounding rock.

pressures on the shotcrete lining, and we can calculate the stresses. This in turn will allow us to reevaluate our original design criteria and its application to our problem.

To summarize, if we are to successfully meet today's challenge to our industry, we must give our designers the benefit of all of the knowledge which can be gained from past studies and continuing observations.

In our competitive society, the success or failure of any product or any process is, in the final analysis, determined in the marketplace. Technically, it may be great to devise a technique whereby a few inches of shotcrete and some rock bolts do the work of heavy steel supports and a thick concrete structure. But if this new technique doesn't reduce the total cost, we cannot justify its use.

Our tunnel builders must devise methods for getting the shotcrete in place with a minimum of lost time to the tunnel progress. This requires detailed planning, especially for smaller tunnels. Materials handling in confined quarters becomes a major problem. Remote-controlled equipment may be dictated for safety or other reasons.

Specifications and bid schedules must be written so as to not unduly favor some particular tunnel technique versus another. The Contractor should have an incentive to use the method which has the best ultimate potential for the Owner.

I am convinced that we need a permanent organization to gather and disseminate information on the design, instrumentation, and construction of underground shotcrete structures.

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nonprofit organization, similar to the American Concrete Institute, dedicated to the public service.

Two of our participants, Dick Robbins and Skip Hendron, are members of Standing Subcommittee No. 2 of the U. S. National Committee on Tunneling Technology. Perhaps they could sound out their Subcommittee about getting funding to help organize and launch such an Institute.

This conference is a great way to focus on our problems and to create the kind of interest to solve them. We have a wonderful slate of participants and a tremendous attendance. I'm sure you will all absorb a lot, but I hope this is only the beginning.

USE OF SHOTCRETE
FROM THE STANDPOINT OF THE OWNER

Gordon M. Miner*

The principle of spraying a cement-sand mixture was developed in the early 1900's (trade name of Gunitite) and has been used for special applications by the mining industry throughout the years. However, this same process using a coarse aggregate (now called shotcrete) was not developed until the mid-50's when it was used on a tunnel project in Austria. Even after the initial application, it took ten years before it was tried on the North American continent on the Burnaby-Vancouver railway tunnel. Since this introduction of shotcrete in 1967 in British Columbia, several Canadian and American mining firms have experimented or started to use shotcrete.

Hecla Mining Company became knowledgeable of shotcrete in 1967 and sent some of our engineering people to visit the Burnaby tunnel. As a result of this visit, and because we in the mining industry are constantly searching for ways and methods to reduce costs, improve techniques and safety, it was perfectly natural that we evaluated this new process and soon determined we had positive applications for shotcrete in our operations.

In late 1967, we ordered a True Gun-All Model F-2 wet machine, which was delivered in early 1968, and to the best of my knowledge, this gave Hecla the distinction of being the first mining company to use shotcrete in the United States. I assume that the fact we were one of the first

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companies to work with shotcrete is the reason I was invited to talk to you people today.

In reviewing our experiences and attitudes related to shotcrete, I find we diverted considerably from our original thinking that was developed in 1967. For instance, we originally felt that the wet process was best, then proved to ourselves that we were wrong and it was really the dry that was best and now, I believe we are again about to convince ourselves that the wet is the best. However, I am confident there is a need for both. We were also very optimistic at one time that shotcrete would replace practically all timbering and maybe eventually eliminate rockbolting. We then reached a point where we doubted if it had a practical use for much of anything and are now back again to the realization that even if there are inherent problems with the process these will be overcome and the application of shotcrete will probably expand as we develop better techniques and ideas.

I feel it is important to call this cyclical trend to your attention because I suspect that many owners or users probably have or will have the same experience and it may be helpful to know that others have gone the same route. It may ease your frustrations.

Although I will not use my allotted time to give you the details of the different applications of shotcrete used by Hecla, I do believe you will find a few brief comments on each application of interest.

- (1) Our first experience was the application of six inches of shotcrete to the ground in an underground hoistroom which was 105 feet long by 40 feet wide by 40 feet high. This opening was excavated using pre-split blasting techniques, then it was

rockbolted adhering to a pre-determined pattern and then shotcreted. The back and upper portion of the arch was shotcreted from the muck pile. A True Gun-All machine was used and operated satisfactorily up to a vertical height of 45 feet, or a horizontal distance of 200 feet.

- (2) A 250-foot long rope raise with an elliptical cross-section, which changed from 10 feet by 6 feet to 25 feet by 12 feet and rotated around the long axis of the ellipse through a 45-degree angle was shotcreted. A 48-inch diameter pilot borehole was drilled to a depth of 250 feet, then slabbed to the desired cross-section and shotcreted as sinking was advanced.
- (3) Next, we sunk a vertical shaft through a faulted zone using epoxy-grouted rockbolts and standard shaft timber with jacket sets. The nature of the ground was to squeeze or close, so a decision was made to shotcrete about 80 feet of the shaft by removing one timber set at a time, barring down loose rock, applying shotcrete and retimbering. After shotcreting, the closure of the ground continued at the same rate of 3.5 inches per year for an additional month and then decreased to about 3 tenths of an inch per year. It is interesting to note that in some sections deformations up to two inches have now taken place with no visible failure of the shotcrete.
- (4) At one of our operations, temporary ground support (usually timber) is used in stopes having widths up to 8 feet. The support is needed until the ore is extracted and sandfill completed. We have, in certain cases, used two inches of shotcrete

and eliminated timber, which provides more room and improves the mining cycle.

- (5) We have constructed dams underground for water sumps and completed other projects of a general nature that would normally require concrete. We find shotcrete eliminates a lot of forming and sealing costs that are necessary when using concrete.
- (6) By using the Aliva dry machine with ample accelerator, we have corralled water flowing from cracks in the rocks and isolated the flow into pipes so that we could handle the water more economically.
- (7) We have used shotcrete for ground support in development headings with poor ground conditions along with rock bolts, mats and steel sets.

As you can see, we have attempted to use shotcrete in a variety of ways so it is somewhat natural that we have had varied reactions to its use.

Now to return to the title of my remarks, "The Use of Shotcrete from the Standpoint of the Owner", I feel the use of shotcrete by mining companies to date has been quite limited. However, I think the potential use is unlimited. In order to take advantage of this old, but yet relatively new technique of shotcreting by the mining industry, I believe some practical, and I emphasize the word practical, research should be undertaken. One suggestion for a leader or someone to act as a catalyst might be the USBM, some other government research-oriented group or maybe this Engineering Foundation. It is imperative this research be done with full cooperation and general guidance from industry.

In general, I feel one of the greatest difficulties in using shotcrete in mines is the materials handling problem. Before it is to be used as regular ground support throughout a whole mine, better equipment and techniques must be developed to make the method economically feasible. Shotcrete will continue to be used on special projects, but only on a limited basis, unless improvements are made so mine operators "think shotcrete".

I hope you realize my assignment was to make a short, hopefully stimulating, opening speech regarding the use of shotcrete to the owner. I hope I have fulfilled my assignment so will stop at this point. However, I will be more than happy to expand or discuss further any points that I have covered with these remarks.

Thank you for your attention.

USE OF SHOTCRETE
FROM THE STANDPOINT
OF THE DESIGNER

by
Cole R. McClure*

Our experience with shotcrete has been somewhat varied and I would like to describe some aspects which may be of interest to you.

During the early 1960's we first became involved in the application of shotcrete. It was not our plan to use shotcrete; we planned initially to use rock bolts for support and hoped to avoid lining. The project was the construction of three, 12-foot wide, straight horseshoe section tunnels as a part of the Transalpine Pipeline Project in Austria and Italy. We had included a pay item in the contract for pneumatically applied mortar, which we planned to use as a non-restrictive term for **gunite**. However several European contractors assumed we meant to use large aggregate shotcrete and we agreed to try shotcrete in an attempt to increase the overall rate of tunnel advance.

We learned that shotcrete had a real place in successful tunnel construction, when applied very soon after the excavation cycle and when applied with reasonable care. Our attitude had changed from not wanting to use it, to reluctantly accepting it, to becoming enthused with shotcrete as an effective means of support. Not only was it effective in fractured rock, but also in soft ground and very wet areas. It even provided

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support to lateral pressures in the vertical portion of the side walls.

At that time admixtures and accelerators were treated as a part of the patented process; therefore we learned very little about accelerators and early strengths. The maximum aggregate size was about one-half inch. The dry mix method was used.

We were next involved with shotcrete in Canada in the construction of a large diameter shaft and a short tunnel section. Here the contractor got into trouble with excessive overbreak and problems of support. Shotcrete was suggested and he purchased the equipment. With limited technical guidance and training he was able to achieve an efficient support with his first use of shotcrete. Time has proved that this application was successful in supporting vertical walls with highly jointed and blast damaged rock, even by an inexperienced contractor.

On these different jobs with different rock types, varying rock conditions and even with inexperienced contractors, shotcrete was a successful means of support. These jobs did all have one thing in common - the contractors wanted it to work. Incentive is all-important.

I believe shotcrete has a great potential and several years ago, recommended that our company take advantage of it for both support and lining. Failures and unsuccessful uses of shotcrete have occurred; but, I believe these are generally due to lack of desire and experience. One example of this occurred recently in a large diameter tunnel in fairly good metamorphic rock. The contractor placed the shotcrete days after the excavation;

he had much of the wall and arch areas covered with plywood (to reduce the amount of shotcrete required). Not that it was important after the first two factors but he also had no knowledge or interest in the strength of his shotcrete. Its use was abandoned and shotcrete was considered a failure. However, during the removal of this mess I became truly impressed with the amount of support that had actually developed. In discussions with the contractor he stated that he had worked underground for twenty years and that no designer would ever convince him that three inches of concrete was safe tunnel support. I couldn't help but think back about a dozen years to a similar meeting with the same contractor where we were discussing rock bolts as support. Here another representative said, "I worked underground all my life and no one can tell me a little one inch bolt can support a tunnel."

To me these comments express reasonably well the status of shotcrete today - about where rock bolts were a dozen years ago. Steel liner, steel sets, rock bolts and shotcrete all have their place as supports. Shotcrete is not the cure-all, but it does have a great deal to offer the owner and contractor. Experience will slowly overcome many fears and shotcrete will become more acceptable and with development more desirable. I believe there are economically borderline underground projects which would become feasible using shotcrete for support and lining.

Today the designer has only judgment and limited experience to guide him. There is no real, reliable, mathematical design approach available. We can and do make parametric studies, review case histories but really the

design is based on judgment. I don't feel this is very different from the design approach to other means of tunnel support: rock bolts, steel sets, and concrete.

Where the designer feels that shotcrete is the applicable method of support based on reasonable geologic evaluation of the proposed tunnel alignment he should include it in his design. Furthermore, he should urge the owner to establish incentive for the contractor to use shotcrete and to do a good job. Those managing construction and the contractor must be responsible for their portion of the project and the designer must assume their work will be accomplished properly.

The designer could improve his approach greatly if he can be provided with good case history data. For example older shotcrete jobs where reasonable construction records are available, e.g., type of accelerator, concrete mix, and compressive strength test results, could provide excellent data if new studies were made of the existing conditions including careful examination of the surface, compressive tests of cored samples, petrographic analyses and perhaps non-destructive tests. I would be most interested in the effect of time on the various high early strength shotcretes using different accelerators.

I believe Al Mathews' proposed shotcrete organization might well begin its work with such a study. I feel confident industry would be interested in supporting such an effort.

USE OF SHOTCRETE FROM THE STANDPOINT OF THE CONTRACTOR

By: KIRK H. FOX

Seven years ago, a friend of mine came to me on our tunnel job in the Tehachapi Mountains and in a very low voiced, secretive, manner told me of a substance that would solve all my bad ground problems. He said this was a substance that was easy to mix, simple to apply, and would setup immediately and be as strong as concrete. After seven years of shotcrete experience, if I were to repeat my version of this, I would say that it was difficult to mix properly; the devil to apply; and if you do everything right it will set-up quickly and be as strong as concrete.

I have used shotcrete in lieu of steel ribs and lagging. I have used it instead of rock bolts. I have used it to replace breast boards and many other applications and I will say this: If it is handled properly it is one of the finest tools we underground contractors have ever been given to aid us in building tunnels.

Let us talk about our Tehachapi Tunnels for a few moments, about some of the things that we learned and about some of the mistakes that we made.

In our Tunnel Number One, we broke the Miners in to one of shotcretes real values. We replaced steel ribs and lagging with it and were able to apply it over the muck pile while we mucked out, which actually speeded up our heading. We also made some mistakes. For instance, I

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was convinced that I could automate the application of the shotcrete by the use of two nozzles operated by remote controls. After spending a considerable sum of money on this innovation, we finally put it into operation. I found it one morning in the junk heap. I immediately approached the Graveyard Walker in a "concerned manner", should we say. He asked me just one question, "What in hell are we supposed to do with this machine when the nozzles plug up?" We left it in the junk heap. That was mistake number one.

Mistake number two was a lot more serious. We advanced our tunnel into a faulted area without increasing our peripheral area of shotcrete coverage. The cave-in started below spring line, or I should say, just below our shotcrete. To have a cave-in in a heading, when only shotcrete is being used for support, is a mighty serious situation. There is absolutely nothing you can do but stand back and let it cave. We later learned that if we had extended our shotcrete to the invert, the cave-in would not have occurred.

We were using extensimeters near the heading during this period, at our own expense, as I was worried about just this very thing happening. They monitored the cave-in very nicely, but there was no one there to interpret them at the right time. Mistake number three.

A note of interest: After the cave-in occurred, expansion cracks appeared in the shotcrete for at least seventy-five feet back from the heading. We called them relief cracks. Apparently, when the cave-in occurred stresses were relieved to the point of actually causing the shotcrete to separate, causing cracks. This is the only time I have ever seen cracks in shotcrete.

I then set up a rather homely method of gauging the difference between competent and incompetent rock. If a sample pick could not be sunk into the rock it was competent and vice versa, it worked. In other words, we shotcreted to spring line in competent rock and to the invert in incompetent rock.

In Tunnel Number Three we went through a live faulted area where our line points actually kept moving from day to day. We hit nothing but running mud in several areas under very high pressures. Our ground was such that ribs on twelve inch centers were mandatory. As you know, placing closely spaced steel ribs is a very tedious task because there is no way of spiling. So, instead we placed our ribs on three foot centers which allowed us to spile. We then cut the tails off the spiling and filled between the ribs with shotcrete. This gave us the strength that we required and at the same time allowed us to advance at a reasonable rate. This innovation is a very important one. You can't actually realize this unless you have been in this situation.

We also used shotcrete in the crown as we dug ahead of our breast boards. We had two shotcrete jumbos with two Aliva's on each jumbo. They were going steady twenty-four hours a day for ten months. We were fortunate to get a man that I had met in Europe, to show us how to properly mix and make our initial application of shotcrete. He is here now, Mr. Jan Blanc.

Perhaps the biggest problem with shotcrete is to be able to get it in the right place at the right time. For instance, if we could apply shotcrete three hundred and sixty degrees directly behind the cutter head of a mole we could:

1. Make mole ground out of a lot of what is now considered shield ground.
2. Be able to progress at full speed with the mole with no delay for support installations.
3. Complete many tunnels as the heading advanced with no additional cost and time for concreting.
4. Many other advantages, such as safety, no initial cleanup, more efficient haulage, etc.

I believe this will be the future number one use for shotcrete. I also believe when we do arrive at the solution for this problem it will be done with wet material instead of dry and I hope by a very simple gun. Mole manufacturers shudder at the mere mention of the word shotcrete.

Remember, I am not talking about shotcrete ten feet or fifteen feet back from the heading, I am talking about shotcrete immediately behind the cutter head. Believe me, it can and will be done by someone.

In the conventional tunneling when an Estimator estimates the cost of shotcrete, he usually ends up with a cost somewhere between sixty and ninety dollars per cubic yard through the gun. When the tunnel man estimates his costs of driving the tunnel on a three shift basis, he has a certain number of dollars per foot. He then includes the cost for shotcrete, which will be used as the heading advances. Now, when he actually drives his tunnel, he suddenly finds the heading shut down approximately twenty-five percent of the time for shotcreting and immediately his carefully calculated estimate goes out the window.

We have been able to shotcrete without slowing down the heading in tunnels larger than twenty feet in width, but we need the ability to do it in all sizes of conventionally driven tunnels in order for shotcrete to be a uniform method of tunnel support.

Shotcrete cannot be treated with indifference by the contractor. His management has to recognize the fact that shotcrete is a technically made substance and should be supervised by an expert. The product, in the past, has received a bad name in several areas because the contractor refused to recognize the technicalities involved.

In order to overcome this, we recently had to guarantee to an owner that our shotcrete in the arch and side-walls of our underground powerhouse that we were building, would be an absolute minimum of six thousand pound strength.

We gave him what he wanted.

Our Designers also have to become acquainted with what it can or cannot accomplish. For instance, I will never trust shotcrete that is applied with wire mesh reinforcing. The peening action of the course aggregate against the mesh will too often ruin the density of the product. If reinforcing is needed, use reinforcing steel. This is heavy enough to keep from vibrating and a good bonded product will result.

We, the contractors, have all made mistakes but I believe that we are now in a position to give you Engineers and Designers the product that you demand. I feel that the owners throughout the country are beginning to realize that the underground contractors have a product that can save them money. I am also convinced that shotcrete, as we now know it, is in its infancy stage.

I recently made a trip to Europe. Our Earl Woodward accompanied me. We visited nine tunnel projects in four countries in eleven days. I certainly don't remember the names of the projects, but I do remember the things that we saw and more especially, I remember the fine manner in which we were received wherever we visited. I found that tunnel language is universal. Problems underground are the same wherever we might be.

One of the projects was a railroad tunnel approximately forty miles north of Rome. The rock was volcanic tuff. A full width top heading was being driven in, more

or less, a conventional manner. The support system consisted of steel ribs on about five foot centers. Immediately after the rib was blocked, the space between the ribs was filled with shotcrete. There is nothing unusual about this and I really wasn't much enthused. The crew was shotcreting when we reached the heading. I noticed the Nozzleman was not wearing any protective clothing. I also noticed that there was no dust and very little rebound. I walked to the ready-mix truck and watched a wet mix being discharged into a small duplex piston pump which transported the material through approximately a two inch hose about one hundred feet to the nozzle. I asked to see the nozzle. It had two additional small hoses connected to it. I turned on one valve and it was air. I turned the other and a clear liquid came out. I got a handful of it and realized that it was nothing more than simple Sodium Silicate, water glass to us farm boys.

I checked the ribs with my sample pick and as far as I could tell it was a fair grade of shotcrete.

There apparently are many different ways of making shotcrete. I believe it is about time we found out what they all are.

This conference is very timely. I have high hopes that a real stride forward will be accomplished.

SUMMARY OF SESSION I - OPENING

' by Charles F. Corns*

The opening session was chaired by Mr. D. J. Duck, and the panel consisted of Messrs. A. A. Mathews, the keynote speaker; G. M. Miner, C. R. McClure and K. H. Fox. The latter three gentlemen spoke on the use of shotcrete from the viewpoints of the owner, designer and contractor, respectively. The urgent need throughout the industry for a better understanding of shotcrete for use as underground structural support was the principal theme developed by the keynote session. The free exchange of ideas at this conference should help to focus on the involved problems and to create the kind of interest conducive to solving them. A consensus was developed regarding the need for a permanent organization to collect and distribute information on design, construction and surveillance of underground structures.

In his keynote address, Mr. Mathews reviewed the background and development of shotcrete for use as underground support and summarized the present "state-of-the-art" in the United States. The main ingredients to the success of shotcrete have been its early application together with a quick set, and sufficient flexibility to permit yielding without losing stability. He listed those elements most essential to the successful use of shotcrete as competent designs, suitable materials and equipment, skilled workers and good quality control. All failures can be attributed to deficiencies in one or more of these factors.

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Proper design, Mr. Mathews continued, depends upon the competent application of the principles of mechanics of materials to the specific situation at hand. Designers must understand the virtues and limitations of shotcrete and they need to know when to incorporate complementary elements such as rock bolts, steel supports or reinforcing steel. He pleaded for more observation data and stated that surveillance of the behavior of openings supported by shotcrete would yield invaluable information to aid the designer. The measured movements, pressures, deflections and strains would afford the means to evaluate original designs and also to develop new concepts of design. He also advocated establishment of a vehicle through which to supply designers with the knowledge gained from past studies and continuing observation programs.

Speaking of the contractor, Mr. Mathews related that his role in a successful operation is to provide suitable material handling equipment and skilled workmen to insure placement of the shotcrete in a safe manner with a minimum of lost time and with the desired results. A specification is needed that both encourages the development of better materials, equipment and techniques and at the same time is fair to the contractor and easy to administer. Contractors must be knowledgeable of available equipment, acceptable operating practices and procedures, and materials requirements. Skilled workmen must be available and utilized.

It behooves the owners to recognize the potential for significant cost and time savings offered by shotcrete. They should, therefore, be willing to support and nurture its development. Mr. Mathews closed

with a recommendation for the establishment of a permanent organization to gather and disseminate information concerning the design, instrumentation and construction of underground structures, and hoped for a free exchange of ideas at this conference to promote the interest necessary to solve the many involved problems.

Mr. Gordon M. Miner reviewed several interesting experiences of an owner, the Hecla Mining Company. He stated that one of the greatest problems in using shotcrete in mines is that of materials handling. Better equipment and techniques must be developed to make the shotcrete method economically feasible. A program of practical research should be undertaken which could be promoted by the United States Bureau of Mines or some other research oriented Governmental agency. Such a program is urgently needed and should be pursued with the full cooperation and general guidance of the industry.

Mr. C. R. McClure reviewed the use of shotcrete from the viewpoint of the designer. He opened that past successes were due in large part to the constructors' determination to make the system work. Design today is based principally on judgment, and in view of the estimates needed to derive parameters for use in a theoretical analysis, it is just as well to estimate the design shotcrete thickness. The method of shotcrete installation is extremely important and many past failures have been due to disregard for the method of application. The problem in design is to insure that support is provided. Mr. McClure pointed out that current design practices for shotcrete were not much different than those for rock bolts and other supports with respect to theoretical limitations, and closed with a recommendation that case histories of

older shotcrete applications be developed, including admixture effects and rock conditions, and that this information be distributed to all concerned.

Mr. Kirk H. Fox described the shotcrete experience of a contractor, the Gates and Fox Company. He emphasized the requirement of proper materials handling and cited some past mistakes and their resulting lessons. These included the requirements for extending the shotcrete lining to the invert, in lieu of springline in the bad ground, the necessity of evaluating instrumentation data expeditiously, and the detrimental effect of wire mesh reinforcement. He reminded that shotcrete is in an infancy stage with much yet to be learned of different ways of making shotcrete, citing a case where sodium silicate in the mix was used successfully and advantageously.

Questions and comments received from the audience following the presentations of panel members concerned such topics as the dry mix vs wet mix question, the deleterious effects of wire mesh, the importance of qualified, competent nozzle men, criteria for high strengths and methods for quality control. Detailed discussion of most questions was delayed in recognition that these subjects would be discussed in later sessions of the conference. One participant regarded the function of reinforcement as twofold: (1) as an element of the permanent structural support (reminding of reduced shotcrete density and honeycomb at bar intersections and advocating single circumferential bars), and (2) to resist short standing ground pressures until the shotcrete develops strength. With respect to the expressed need for a permanent organization to collect and distribute pertinent information, a division within ACI was suggested as a possibility.

DEVELOPMENT OF SHOTCRETE FOR METRO CONSTRUCTION IN WASHINGTON

by
K. S. Bawa*

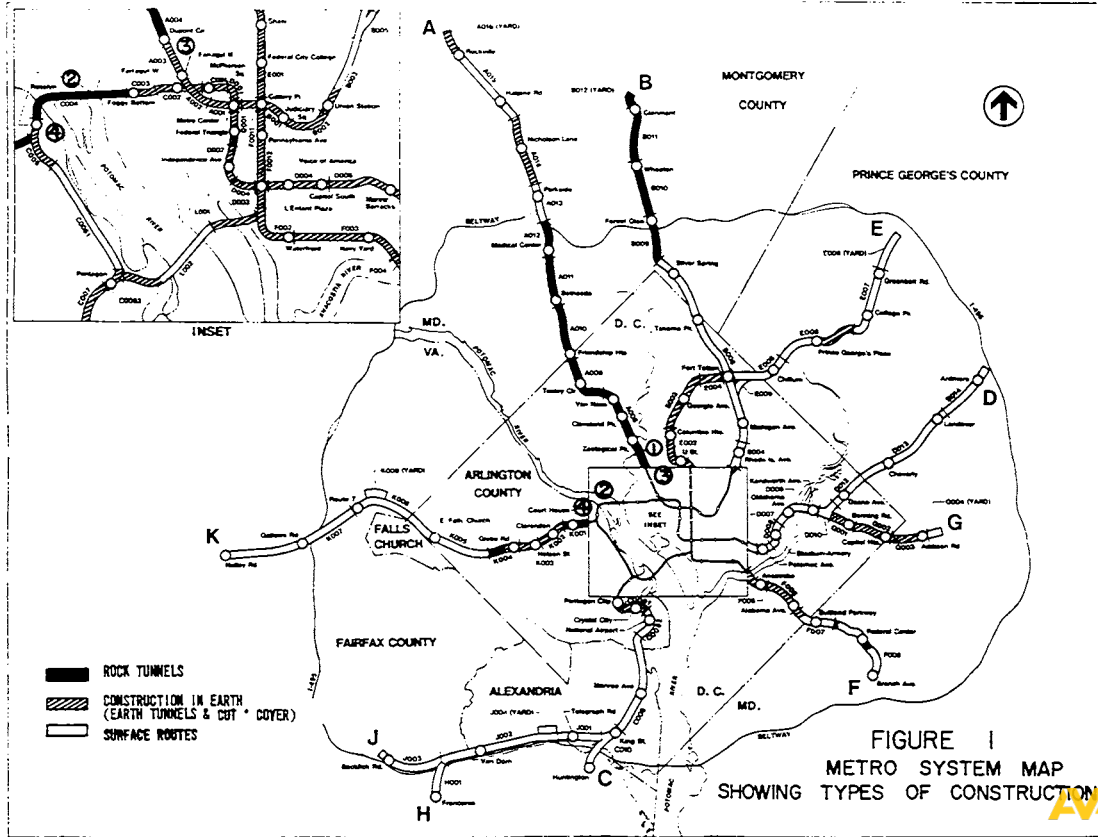
1. Introduction

A rail rapid transit system called the "Metro" system has been under construction in the Washington area for the last four years. When completed, the Metro system will comprise nearly 100 route miles, serving the Nation's capitol and the adjoining counties. About 30 per-cent of this mileage is now under construction, while the designs for the remainder are in various stages of completion. The system is scheduled for completion around the year 1980 at a cost somewhat in excess of 3 billion dollars.

The Metro system will involve nearly all types of construction generally used for rapid transit projects. About half of the mileage (Figure 1) will be underground, comprising about 16 miles of rock tunnels, 10 miles of earth tunnels, and nearly 21 miles of cut and cover construction in earth. The remaining nearly 51 miles are planned to be constructed on the surface as at-grade or elevated structures. The system includes 86 stations, 53 of which will be underground structures. Twelve of the underground stations will be large size chambers in rock, while the other underground stations will be constructed in earth as cut-and-cover structures. Thus about one-fifth of the system will be designed as underground structures (running tunnels and station chambers) in rock.

As early as 1966, while general designs for rock tunnels were being prepared, it was felt that the conventionally-used concrete

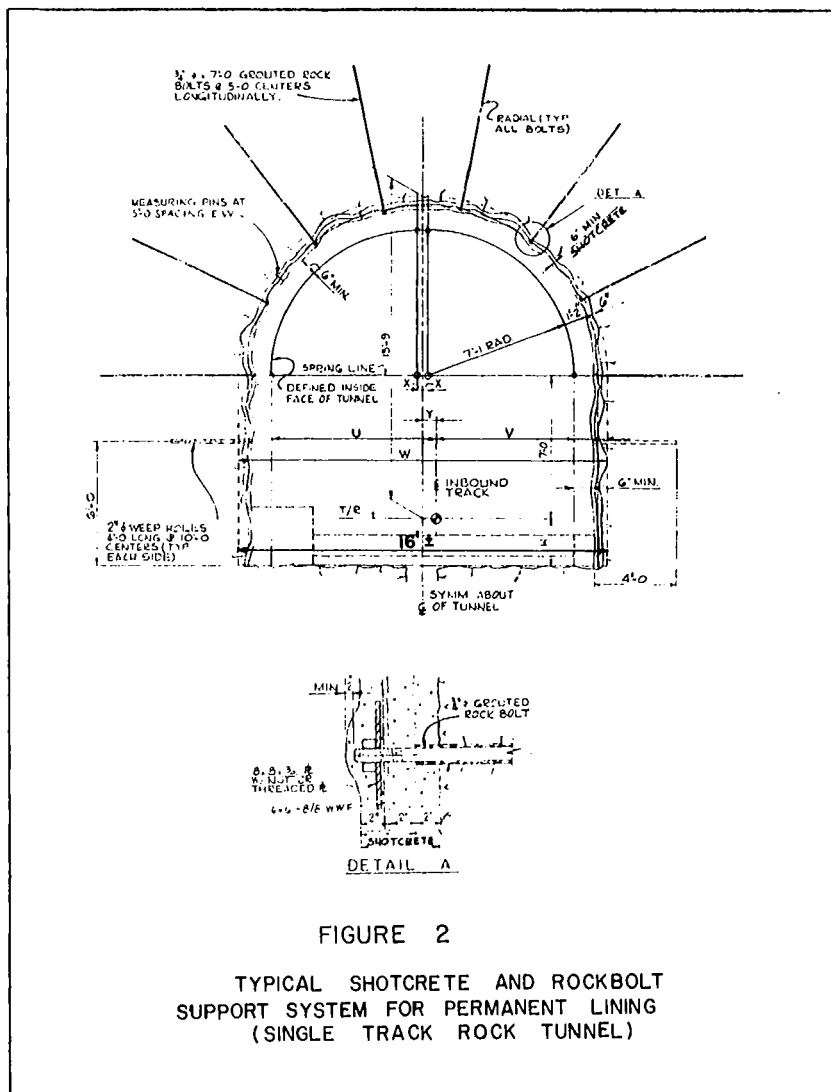
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lining for rock tunnels, and more particularly for the rock chambers, would involve considerable cost. Investigations at that time showed that lining of such structures with shotcrete and rock bolts would be more economical and would also minimize the hazard of construction under adverse rock conditions. Therefore, typical shotcrete designs were developed for the permanent support of rock tunnels. The study of anticipated rock conditions suggested that for low to moderate overbreak (RQD of 60-70 and above), the application of a 6-inch thickness of shotcrete with rock bolts could adequately serve as a permanent lining. A typical shotcrete lining permanent support is shown in Figure 2. The use of shotcrete offered flexibility, in that the first application of the material within a few hours after blasting would serve as a temporary support in lieu of the costly steel ribs frequently used for the purpose. Actually, the concept of temporary and permanent support seems to vanish when shotcrete is utilized, because the initial application for the so-called "temporary support" is really the first installment of the permanent lining.

While designs for shotcrete linings were being prepared, consideration was given to the development of shotcrete. This consisted of preparation of construction specifications and testing procedures before and during construction. It is important to note that the term shotcrete used here refers to the fast setting coarse aggregate shotcrete applied by dry mix method for structural support. This definition is at variance with the broader ACI definition which also includes the fine aggregate mixes and non-structural applications.

This paper outlines the basic steps utilized in developing shotcrete and includes the experience gained in implementing the specifications.



2. Specifications

About six years ago, when the subject of shotcrete specifications for the permanent lining of Metro tunnels was being discussed, there were no standards or specifications which could suit the purpose; although there was some literature indicating a variety of uses. Therefore, a set of construction requirements was prepared which were believed then to be the first complete set of shotcrete specifications for the permanent support of rock tunnels.

An important question related to the specifications was the selection of values for early set and the final (28-day) compressive strengths. The early set of shotcrete was selected at 500 psi at 8 hours, and the 28-day strength was specified to be 5,000 psi. It is now a well-known fact that such high early strength of shotcrete can be easily attained by addition of suitable accelerating compounds, while the high final strength is primarily a function of cement factor and the water-cement ratio. However, very high initial and final strengths are conflicting requirements which have to be optimized. The early set requirement is determined primarily by the rock quality and water conditions. If the stand-up time of rock after blasting is expected to be relatively short, or if excessive water inflows are anticipated, high early strengths are called for. It must be noted that high early strength of shotcrete invariably depresses its final strength. However, to stabilize poor rock conditions and/or to arrest high water inflows, high early set will be necessary and the final strength may have to be sacrificed. The final strength is mainly based on durability considerations, although sometimes structural analysis may dictate higher 28-day strength to minimize thickness. Therefore, the

early and final strength values should be selected for optimum effect.

3. Selection of Ingredients

Although the general requirements for choice of ingredients for shotcrete are usually similar to those that apply to good concrete practice, there are a few differences as indicated below.

a. Aggregates

The maximum size of the coarse aggregate is greatly dependent upon the ability of the shotcrete spraying equipment. Larger sizes would result in uneconomical rebound, while the smaller sizes can cause excessive cement demands, increasing the possibility of shrinkage cracking. In addition, the choice was also governed by the availability of certain standard sizes economically produced in the area. For most of the Metro work, sound gravel, granitic in origin (Figure 3) was utilized except that some limited applications with crushed stone were also made. Although two maximum sizes (3/4" and 1/2") were specified, most of the Metro shotcrete has been done with 1/2" aggregate due to ready availability of this size.

The fine aggregate was primarily concrete (silica) sand (Figure 3), conforming to the requirements of ASTM C-33. Sand was obtained from the Potomac River as well as from land sources. The land mined sand was properly screened and washed to conform to gradation requirements.

The following two gradations were specified for the combined coarse and fine aggregates:

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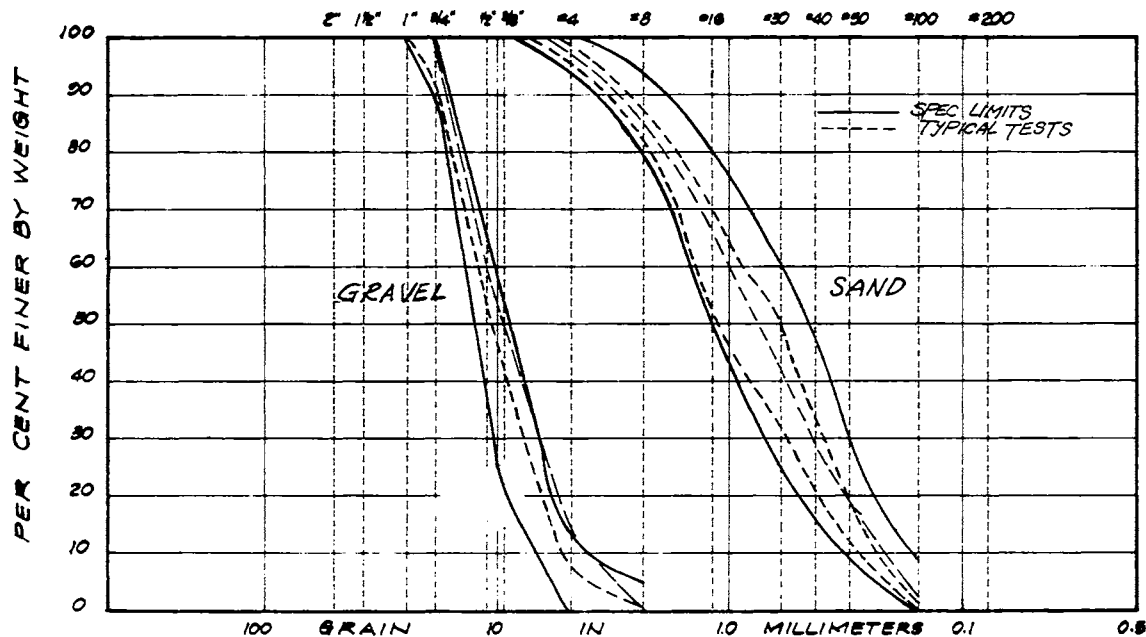


FIGURE 3
AGGREGATE GRADATION FOR SAND & GRAVEL FRACTIONS
FOR SHOTCRETE

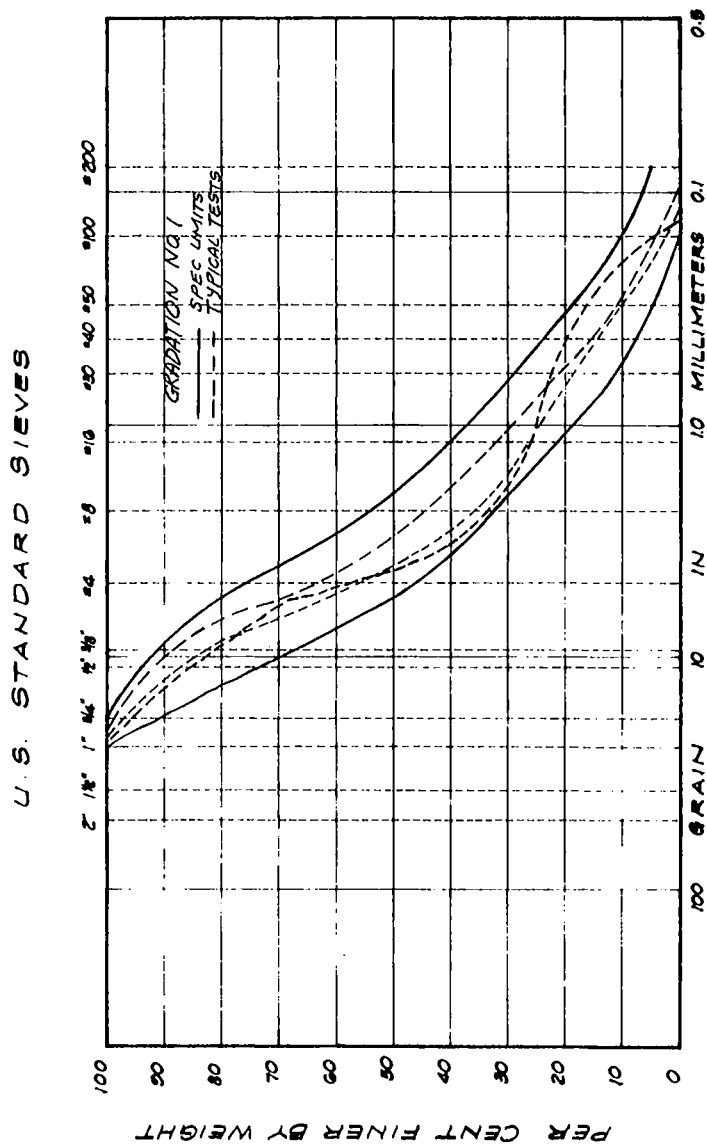
METRO CONSTRUCTION

<u>U.S. Standard Sieve Size</u>	<u>Gradation No. 1</u>	<u>Gradation No. 2</u>
1 inch	100	
3/4 inch	95-100	
1-2 inch	75-95	100
3/8 inch	65-88	95-100
No. 4	48-74	72-85
No. 8	34-57	52-73
No. 16	22-44	36-55
No. 30	12-31	20-38
No. 50	5-20	7-20
No. 100	2-10	2-12
No. 200	0-5	0-5

The combined gradation was designed for maximum density, and could be economically produced by blending in suitable proportion the locally produced standard aggregate sizes. In practice, there were some departures from the specified gradations due to lack of smaller sizes. In such cases, if the strength requirements were met, the deviations were not usually questioned. The combined aggregates were required to have 2-4% of moisture to enable thorough blending of cement.

b. Cement and Accelerating Admixture

Cement used was Type I portland cement, conforming to ASTM C-150. Although the use of Type III cement was permissible, it was generally found to be less compatible with accelerating admixtures. One contractor was able to obtain a special cement from the manufacturer to obtain greater compatibility with the accelerating admixture. The cement was labeled as Type II-III because its characteristics were between these two types. Shotcrete produced with this cement was



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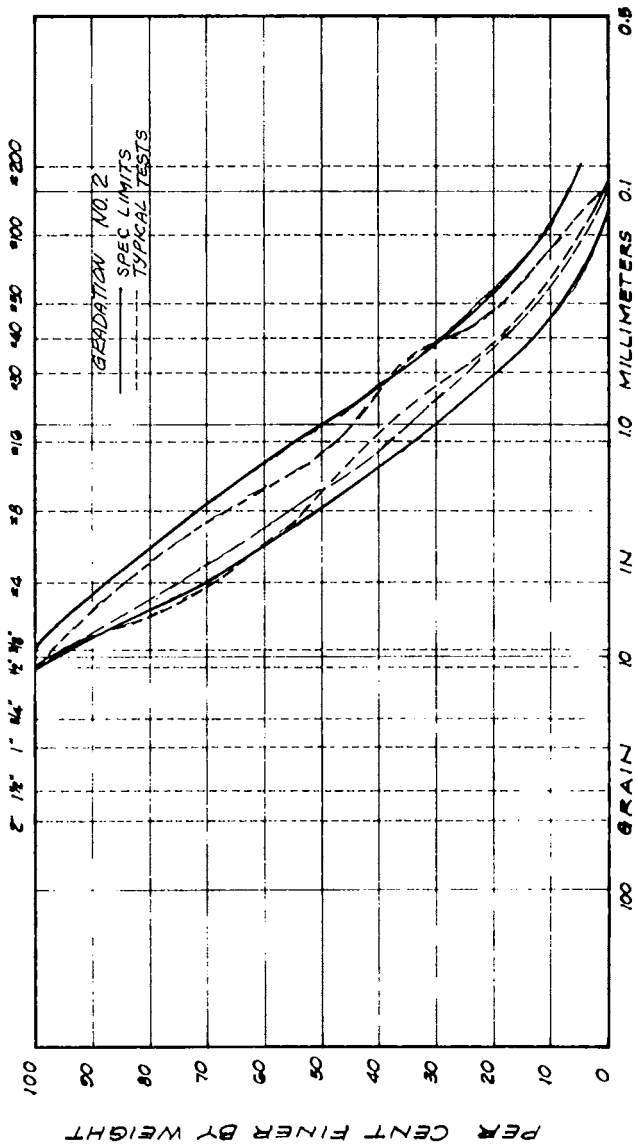


FIGURE 5
COMBINED AGGREGATE GRADATION FOR SHOTCRETE
GRADATION NO. 2

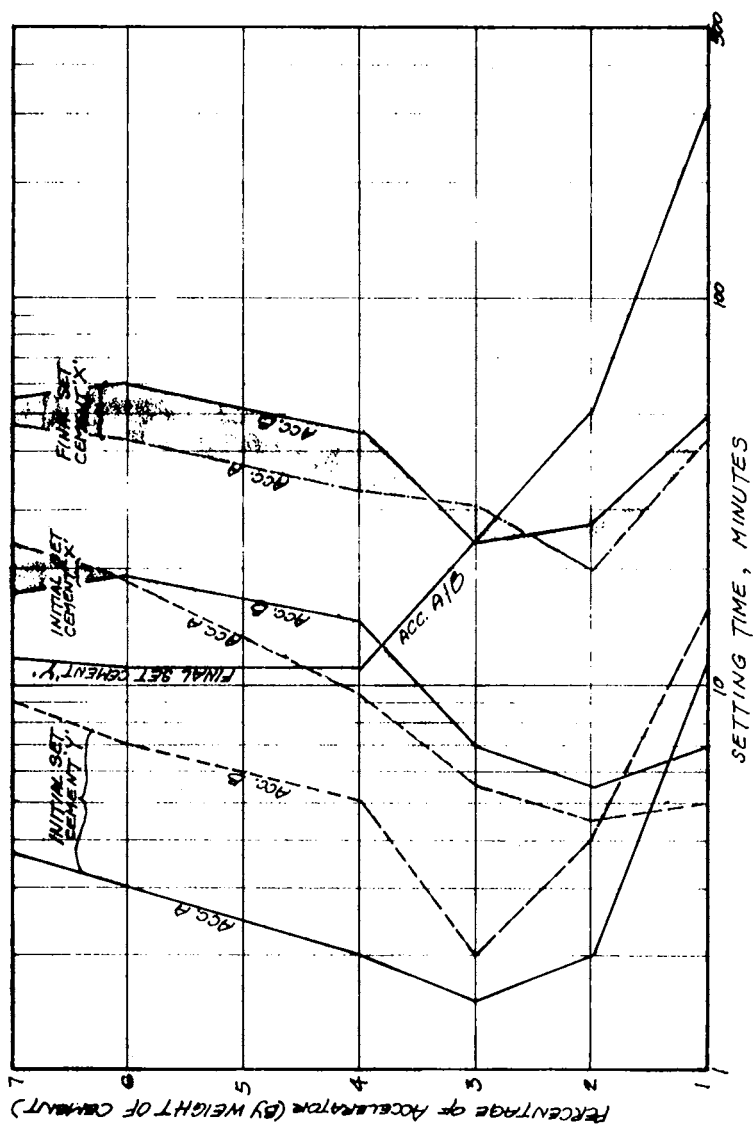


FIGURE 6
CEMENT ACCELERATOR COMPATIBILITY LAB TESTS

generally in compliance with the requirements. The selection of a cement brand was based on compatibility trials with the different accelerators as shown in Figure 6. The cement-accelerator combination with lowest initial and final setting times has the best promise of giving satisfactory field results.

The choice of accelerator was based upon its ability to produce early set with the proposed cement as outlined below. The accelerators frequently used on Metro projects to date were "Sigunite," a product of Sika Chemical Company, and "Tricasol," a product distributed by Aliva Manufacturing Company in pulverized form. The specifications required that the combination of cement and accelerator should develop a quick set defined as follows:

Time of initial set:	3 minutes maximum
Time for final set:	12 minutes maximum
Compressive strength: in 8 hours	600 psi minimum

Determination of setting times was made by Gilmore needles, ASTM C-266 except that the water to be added was based on arbitrarily chosen water-cement ratio of 0.40, and the accelerator to be added was in the proportion to be used in shotcrete (usually 2-5 percent by weight of cement). The compressive strength was determined on the same basis in accordance with ASTM C-109.

4. Pre-Construction Testing

The pre-construction testing was designed primarily to prove before hand that the combination of the proposed ingredients would result in early and final strengths of shotcrete. The specified strength requirements for shotcrete were as follows:

Compressive strength after 8 hours:	500 psi
" " 72 hours:	2,500 "
" " 28 days:	5,000 "

As indicated previously, these strength requirements can be varied depending on rock and tunneling conditions. The pre-construction testing was a two step procedure consisting of laboratory tests followed by field trial.

The laboratory tests were made to determine the optimum proportion of the proposed ingredients. Laboratory mixes were prepared based on 6.5 - 7.5 bags (611-705 lbs.) of cement, 0.40 water-cement ratio, and percentage of accelerator to be determined from trial. The test specimens for compressive strength consisted of 3-inch diameter by 6-inch high cylinders. In a few trials, 3" x 3" x 12" beams were also molded for flexural strength, which was required to be 15 percent of the compressive strength at 28 days.

The field trials followed the laboratory tests to prove that the shotcrete mix, when proportioned on the basis of the laboratory tests and applied with the proposed equipment and workmanship, would meet the specifications. The field trials consisted of application of shotcrete mixes to 36" x 36" horizontal and vertical wood forms in one or two layers to a total thickness of about 3 inches. From these forms, test specimens by coring 2-3 inch diameter cylinders, and by sawing 3" x 3" x 12" beams, were obtained in accordance with ASTM C-31. The specimens were tested in accordance with ASTM C-42 and ASTM C-78.

The field trials are an important phase of shotcrete development, as they afford an opportunity to test the shotcrete mix, application equipment and techniques and most importantly the skill of the nozzleman,

which is a very vital element in the success of the final product.

Shotcrete ingredients were generally batched by weight from stock-piles of coarse and fine aggregates and cement, although the volumetric method has also been used with varying degrees of success. These ingredients were mixed dry and transported to the shotcrete application machines in concrete trucks. The dry mixing was greatly facilitated by the presence of 3-4 percent moisture in the fine aggregate.

5. Production and Application

For Metro work, most of the shotcrete was produced by weight although volumetric method was also used with varying degrees of success. One contractor used a small portable on-site ('Ross') weight-batch plant, and met his production requirements quite satisfactorily.

A number of different shotcrete machines (or 'pots') were used, including the American "Reed" and the Swiss "Meynadier" and "Aliva" pots. The accelerator was added at the machine by an attached screw feed dispenser, which had to be calibrated frequently. The work accomplished to date indicates that the foreign machines gave rise to more consistent results and fewer breakdowns. Experience has indicated that for uniform shotcrete out-put, the maintenance of steady water and air pressure is quite important; and to ensure this, pressure gages close to the nozzle are advisable.

Although a number of details are involved in ensuring proper application, none is as important as the workmanship of the nozzleman. The nozzleman's control of the mixing water and application distance and angle determines the uniformity of application and the rebound losses. There was considerable difficulty in finding qualified nozzle-men, and hence initial shotcrete applications did suffer. Even now, with the`

growing use of shotcrete, there is a dearth of experienced nozzlemen. Hence there is a need for the development of a sound training program for their proper training.

A typical shotcrete mix on a cubic yard basis consisted of:

Coarse Aggregate (Gravel):	1,431 lbs
Fine Aggregate (Sand):	1,431 lbs
Cement (Type I):	165 lbs (7 bags)
Accelerator	19 lbs

One of the major problems encountered during shotcrete application was excessive quantities of shotcrete required to fill large (overbreak) voids which were caused by poor rock conditions and/or improper blasting methods. This condition arose in steel rib sections of the tunnel, where the space between the ribs and rock surface had to be filled in with shotcrete. In such cases, shotcrete was acting primarily as a 'filler' material, which amounts to misuse of shotcrete. Because shotcrete as formulated for Metro tunnels was designed as a high strength (and relatively expensive) structural concrete, its use as a filler proved to be extremely expensive, causing large over-runs of estimated quantities in some cases.

Therefore, if shotcrete is to be applied in combination with steel rib tunnel supports, requiring filling in of large voids, such an application can be very uneconomical and should be avoided.

6. Testing During Construction

In order to control the quality during production, specimens were removed by coring from shotcreted areas in the tunnels to check the compressive strength at 8 hours, 72 hours, and 28 days. Specimens were removed in each case just before testing, and therefore tested under field-cured conditions. A set of specimens (minimum of two) was

generally taken for each 50 cubic yards of application at each test age; although in the initial applications, the frequency was increased, and later decreased when quality reached acceptable limits. Each core was visually examined to determine the uniform distribution of the mix and evidence of laminations, if any. The test data were interpreted statistically in accordance with the specifications based on ASTM C-94. The specifications required that not more than 20 percent of the tests were to have values lower than the specified strength, and that the average of any six consecutive tests was to be equal to or greater than the specified strength.

Tests were also made to study the development of the hourly rate of increase in shotcrete strength under tunnel conditions. Considerable difficulty was encountered in performing these tests because there was rapid build-up strength within the first few hours, yet shotcrete was too green to lend itself to conventional coring techniques. A core pull-out test used for concrete was modified to determine the hourly strength increases. It is planned to compile the pull-out test data and make it available in the near future.

7. Concluding Remarks

These somewhat elaborate investigations of shotcrete ingredients and testing procedures were necessary at the time shotcrete was first developed, about five years ago, for the permanent lining of Metro tunnels. With the availability of more knowledge and experience with shotcrete for underground work in North America, it is now possible to produce good quality shotcrete without such extensive investigations. However, most projects would require a certain amount of testing and quality control measures to ensure uniformity of the end product. If

the engineer and/or the contractor on a project, however small, lacks sufficient experience of shotcrete production and application, detailed specifications for testing and quality control at various stages will be justified in order to achieve a good and economical product.

The author is obliged to his employers, Lorenzi, Dodds & Gunnill, for facilities allowed during the preparation of this paper. However, the views expressed herein are purely those of the author.

SHOTCRETE PRACTICES
AT THE
HENDERSON MINE

by
Robert C. Jones*

The Henderson Mine is being developed by American Metal Climax. It is located about 50 miles west of Denver, Colorado, adjacent to the Continental Divide. The mine site is in a narrow canyon at an elevation of 10,400 feet above sea level.

The body of molybdenum ore is 3,000 feet below the surface of near-by Red Mountain, to the south of the shafts. The ore is about 800 feet thick and 1,700 feet by 2,200 feet horizontally. The eastern and south-eastern boundaries are still to be defined at the present time. The ore will be mined by caving methods from two successive 400 foot levels. It will then be transported by electric train 9.5 miles underground through the Continental Divide to the concentrating mill 14 miles west of the mine site. Construction on the mine was started in 1967. Initial production is expected to commence early in 1977. It should average 7,500 tons per day for the year and build up to a rate of 30,000 tons per day by 1979. The mine and mill will operate on a seven day a week basis.

We are presently developing the mine through two large concreted shafts totaling well over a mile in depth. No. 1 shaft is a round 22 foot in diameter shaft, 2,441 feet deep. It is used for exhausting ventilation air from the mine, pumping mine water to the surface, secondary access to the mine, and hoisting development muck from the 8100

* American Metal Climax, Inc.

level. The 8100 level will be the initial production level.

No. 2 shaft is a round 28 foot in diameter shaft 3,103 feet deep. It is utilized for primary access to the mine, intake ventilation air, and hoisting development muck from the 7500 foot or rail haulage level.

Development mining is being carried out on a 24-hour day, seven days a week basis. Present rates of mining are about 2,000 feet of drifting each month at the mine site. We have completed more than ten miles of drifts at the present time. Work on the 9.5 mile rail haulage tunnel has just begun from the east at the mine site. Over three miles have been driven by contractor from the west portal.

Except for the rail haulage trains that transport the development muck to the No. 1 shaft for hoisting, all equipment utilized underground is rubber tired and diesel powered. To accommodate this equipment and to insure proper ventilation, the drifts are relatively large. The fringe drifts are 13.5 feet by 14 feet and the production drifts are 12.5 feet by 12 feet.

We are just completing an underground maintenance shop having eight repair bays 14 feet by 16 feet wide and 54 feet long. It has a central overhead crane room 21 by 21 feet in cross-section and 130 feet long.

We have begun work on an intake ventilation drift 18 feet by 22 feet and several thousand feet long. It, like the crane room, will be benched. The top portion of the drift will be mined and supported before the bottom 6 or 7 foot bench is mined out.

The mine rock is a rhyolite porphyry and in general is hard and brittle. There is a well defined northwest-southeast joint pattern and