Mathews, Inc. and made many valuable suggestions and comments regarding the evaluation of the results. Mr. Warren Alvarez was in charge of field work for Granite Construction Company and nozzlemen for all shoot- ings. Complete documentation of the field work was possibly by the enthusiastic work of numerous students and staff members of the University of Illinois.

REFERENCES


REVIEW OF DRY-MIX COARSE-AGGREGATE SHOTCRETE AS UNDERGROUND SUPPORT
by Helmut G. Kobler, P.E.

Late in 1964, while working on the construction of the Montreal Subway, a dear friend of mine, Dr. Emil Schmidt, Past President and Chairman of the Sika Chemical Corporation, asked me to write a paper for ACI dealing with my past experience in the use of dry-mix coarse-aggregate shotcrete as underground support. At that point in time, my knowledge of the subject under consideration was limited and based only upon experience gained while using the process in Venezuela, Switzerland and Austria.

Since, at the time of Emil's request, very little about the material and underground shotcrete procedures was known on the North American Continent, I was indeed most eager to impart to my North American colleagues the limited knowledge I possessed about the subject. The result of my efforts became known as Paper No. 3 of ACI publication SP-14 titled "Shotcreting".

A while back, Professor Parker was kind in asking me to present to you at this conference, an update of my 1966 paper.

Some historical background is appropriate at this point.

Upon my return to Canada from South America, in early 1963, I was able to convince my boss on the many benefits which dry-mix coarse-aggregate shotcrete has when used for underground support and obtained his permission to use it for the first time in Canada. We used it as temporary support in difficult ground for the tunnels and stations comprising the Beaudry and Pappineau Sections of the Montreal subway complex. Sometime thereafter, the Canadian National Railroad demonstrated their
faith in the process by giving the potential contractor an option to bid on the construction of the 11,200-foot long CNR tunnel in Burnaby, British Columbia, by either supporting the tunnel with shotcrete and rockbolts, or closely spaced structural steel ribs and cast-in-place concrete. A joint venture of Northern Construction, Perini & Manix won the bid with the shotcrete option and did a commendable and efficient job. Once the excavation work on the CNR tunnel was in progress and the efficiency of the placed shotcrete support could be properly evaluated, the use of shotcrete as underground support became well established on the North American Continent.

Soon thereafter, new highly specialized companies and shotcrete experts were born nearly overnight, offering their services, equipment, chemical additives and expert advice as a sure cure for all underground support problems a client may have. In fact, for a time a few unscrupulous vendors pushed the use of shotcrete only for the sake of selling the troubled and bewildered client tons of expensive chemical shotcrete additives.

Eager "fast buck" promoters and "instant shotcrete" experts did not hesitate to make false claims as to the underground support capabilities of a shotcrete lining without at all taking into consideration the importance of prevailing ground conditions. Some experts even rushed to their local patent office to try and obtain patents for shotcrete procedures and related ground support systems which have been in constant use for many years.

Pretty soon nearly every shotcrete expert in the country had his own little secret formula of how to prepare the shotcrete dry-mix, resembling in
more than one aspect, a congregation of famous pastry-makers, each with a different recipe to bake the same old cake.

Obviously shotcrete was well on the way to getting a bad name very quickly!

Depending on the type of experience on the part of the person you were talking to at the time, shotcrete was either an excellent support material or just was not worth the powder to blow it to hell!

Contingent upon the skill, judgment and knowledge on the part of the people involved in carrying out the work, some dry-mix coarse-aggregate shotcrete support undertakings have been very successful, some not so successful and some quite unsuccessful. This pattern went on until early 1973 when five knowledgeable men got together and organized an international conference for the prime purpose of putting the use of shotcrete for underground structural support in the proper perspective it deserves. This conference, held in cooperation with ASCE and ACI took place between July 16th and July 20th, 1973 at Beckwick Academy, South Beckwick, Maine. It was a resounding success resulting in the valuable ACI publication No. 45.

We are now again assembled here to hold another such conference, to communicate and share with each other, our shotcrete experiences and knowledge. I am confident that this one will prove a success.

The application principles for dry-mix coarse-aggregate shotcrete are basically the same as discussed in detail in my 1966 paper. We are still shooting a dry concrete mix on to an exposed excavation surface and hope it
will stick and dry into an efficient support material. Briefly, the ingredients consisting of cement, sand and coarse-aggregates are dry mixed and fed into the hopper of the delivery equipment, from which it is transported by a high velocity airstream through a rubber hose and/or a steel pipe to the discharge end of the hose. A discharge nozzle may be used. Nowadays, better results are obtained without the use of a nozzle; whenever frayed the discharge end of the delivery hose is simply cut back some 8 to 10 inches at a time. The required water usually is introduced at the nozzle. However, based upon past experience, it was found that by positioning a single or double watering "O" ring some 3 to 6 meters back from the discharge end of the delivery hose, the quality of the shotcrete in place is better and rebound is less. Also, the production rate of the machine is somewhat increased.

For the benefit of my "wet-mix" colleagues, I must admit that sadly the very important function of adding the required amount of water to the dry mix is still in the hands of the nozzleman, making the quality of the shotcrete in place very much contingent upon his skill and on how he may have felt at the time of the application. A very unsatisfactory arrangement indeed, but I hope not for very long, since we are at present engaged in carrying out various tests with a number of equipment modifications which, if successful, will do away with this undesirable feature of the dry mix system.

Fine and coarse aggregates used for shotcrete should fully comply with ACI specifications. Natural well-rounded aggregates are still preferred, but crusher runs, or a combination of both, will serve the purpose
just as well. Although it has been said before that coarse-aggregates up to a maximum of 1-1/4 inch can be used, experience has since shown that 3/4 inch minus is best all around. Care in the selection of suitably graded aggregates of good quality for the shotcrete mix is still very important and cannot be overemphasized. Aggregates of poor quality and/or improperly graded result in an inferior quality of the shotcrete in place, no matter how much additional cement one puts into the mix.

The quality of the shotcrete in place still depends to a great extent on proper proportioning of all the ingredients in the mix and care must be taken not only when designing the shotcrete mix, but also the dry batching process of the material must be continuously controlled. Water cement ratio should be kept to a minimum. However, it should be kept in mind that with shotcrete, just as with conventional concrete, the principal objective is the attainment of maximum strength at a minimum cost.

For most underground support purposes, a final strength of the shotcrete lining in place ranging from 3,000 psi to 3,500 psi is quite sufficient.

Ideally, for underground support, a higher tensile strength of the material is still very much desired, but not much progress has been made in this direction. As a rule, the final compressive, or tensile strength of shotcrete, used for underground support, is of secondary importance, since ground pressure loads and stresses occur shortly after excavation during the setting process of the shotcrete in place. Therefore, the principal aim in proportioning dry mix shotcrete for underground support, should be an
economical mix design capable of developing maximum strength as early in the setting process as possible. Excellent progress was made towards this goal.

We have worked in the past with mixes designed to set fifteen seconds after application and become completely hard after one minute. We have used them successfully on numerous occasions in wet ground to support tunnel excavations under very difficult ground conditions. However, there is ample room for additional research and improvement, since such specially designed mixes are very costly to use, and our aim is still the requirement that the use of special shotcrete mixes become in the near future an economical reality.

To date, the simplest means presently available to accelerate the initial set of any shotcrete mix is achieved by the inclusion of chemical admixtures into the mix. Initially when shotcrete was finding its way into the North American continent, only one such chemical accelerator was available and was marketed by Sika Chemical Corporation under the trade name of Sigunit; a good reliable product still widely used.

Today, one may select a suitable accelerator from a great number available on the market either in liquid or powder form. Some perform well, some not so well, and some just do not perform at all. Some manufacturers and suppliers will claim that their product is better than the other fellow's, that besides accelerating the final set, it will practically eliminate rebound, prevent dusting, etc., practically an aspirin for all shotcrete ailments.
As a matter of fact, it is advisable to carefully contemplate all the advantages and limitations before using any chemical accelerators. Once the inclusion of chemical accelerators into the dry mix has been decided upon, only well tested and field proven admixtures should be used. To start out with, it is recommended that the compatibility of the accelerator with the locally available cement be checked and established.

It happened many times in the past that a certain German-made accelerator was not compatible with an American cement or an American produced accelerator did not perform with a certain Canadian West Coast cement.

In the past there has been a lot of abuse in the improper use and dispensation of accelerators. Without doubt, this particular phase of shotcrete technology has a definite need for research standardization and uniformly written specifications.

It should be borne in mind that for structural underground support purposes, only the initial shotcrete application needs to be accelerated. Excessive quantities of an accelerator in the mix may be harmful in the long run. To use an expensive accelerator just for the purpose of reducing rebound is wasteful and uncalled-for. The same effect can be achieved by other less expensive means. Past experience has shown that accelerators in liquid form perform better than the powder varieties since proper dispensing, mixing and control are somewhat simplified. Above all, it should be kept in mind that the high unit cost of an accelerator does not necessarily guarantee
its satisfactory performance.

Excellent results were obtained while using inexpensive, locally available calcium chloride or sodium silicate to successfully accelerate the shotcrete setting process. As a matter of fact, for a difficult support job, I prefer to use the inexpensive sodium silicate than most of the expensive accelerators on the market.

From an economical point of view, rebound, associated with the application of dry-mix coarse-aggregate shotcrete for underground support becomes a very important consideration and must at all times be kept to a minimum.

Unfortunately, the amount of rebound depends on many factors, conditions and not least of all, is contingent upon the application skill of the man operating the nozzle, either handheld or boom mounted. We have a long way to go before the problem of rebound is solved. On the whole, statements made in my 1966 paper regarding hydration, rebound, surface preparation, application procedures and curing still stand.

Great progress has been made in the development of modern delivery equipment. Besides the equipment described on Page No. 45 of the 1966 paper, we have available today a good selection of delivery machines capable of placing structurally sound high quality dry-mix shotcrete at an acceptable production rate. All are capable of placing good quality shotcrete, but differ greatly in output rate, quality, cost and operational procedures. To name a few, we are acquainted with the Aliva-250 and Aliva-260 series,
the Maynandier GM-57 series, the Reed IASC III Guncrete, the EIMCO Cyclone series and the ICOMA machines. All of these models are suitable for placing dry-mix coarse-aggregate shotcrete economically and at an acceptable production rate.

As is the case with so many other jobs, a special shotcrete operation requires the design of special equipment to properly do the job. Most of these special sophisticated application designs are made by a few highly specialized engineering firms, (such as Jacobs Associates, the firm I am working for) and in most cases are built in the contractor's equipment yard or on the job site.

I participated in a number of modifications made to the above noted machines which in all instances resulted in improved shotcrete operation and increased production rates. I am confident that in the future, new improved machines and operational procedures will come forward giving the men in the field the proper tools we need to do a better job. I am well aware that bringing new sophisticated shotcrete machines on the market costs money. I hope that the future resulting increased equipment costs will be reasonable and that dry-mix shotcrete will not be priced out of today's market.

Looking back to the early sixties, I am very pleased with the progress made in this field. Dry-mix coarse-aggregate shotcrete has become an effective economical means of efficiently supporting difficult underground excavations and has been successfully used on numerous underground construction projects throughout the world.
Dry-mix shotcrete has been successfully used as temporary and permanent structural support of large and small diameter tunnels and shafts, large underground caverns and mine openings, large surge shafts, penstocks, draft tubes and a number of other underground structures. It always performed satisfactorily wherever and whenever applied with proper technological criteria, and based upon sound judgment of prevailing ground conditions and field tested expertise.

During the past years, world wide confidence in the capabilities of dry-mix shotcrete has greatly improved with the increase of experience in its proper use.

Shotcrete has successfully been used as underground structural support either by itself in thin and thick linings, or in combination with rock-bolts, wire mesh, resteel or structural steel ribs.

It was successfully used in conjunction with full face tunneling methods, top heading and bench operation or on multiple drift excavation through heavy, loose and moderately wet ground.

Of course, the main advantage of shotcrete as underground support is its unique capability to prevent early loosening and disintegration of the excavated surfaces, (either in rock or earth) by providing sufficient shear resistance to the crown arch and wall of the excavated tunnel or other underground opening.

The quick setting and early development of high compressive and tensile strength of the shotcrete in place, is of utmost importance, therefore the inclusion of chemical accelerating admixtures properly proportioned
in the mix is essential. The technological principles and theories involving
the use of shotcrete for underground support are by now well known and
established.

The new Austrian method is not new anymore, and we here in the
United States should make full use of the experience and knowledge gained
by others in other countries.

Unfortunately, in the past, we did not make full use of all the
benefits shotcrete possesses as an efficient underground support for excava­
tions carried out under difficult, adverse ground conditions.

It should be stressed that the full benefits of a shotcrete lining are
realized only when used to support underground excavations carried out
under difficult geological conditions.

Unfortunately, coarse-aggregate shotcrete still remains an expensive
material, and as matters stand today, it will become even more expensive
to use as time goes on. Therefore, substituting a shotcrete tunnel lining
for conventional cast-in-place concrete support in sound rock, behind the
tunnel face, is to my way of thinking, a waste of good effort and money.

During the past years, I have seen a number of underground construction
projects where thousands of tons of expensive structural steel were used
to temporarily support a tunnel or cavern where, in fact, a thin inexpensive
shotcrete lining would have been just as effective to serve the required
purpose.

In summary, I will quote from the 1966 paper, "Shotcrete support is
mainly intended to halt the development of troublesome loosening pressure and associated decompression of the formation, early in the excavation process. Its main economy and advantage is in excavations carried out through difficult ground conditions, particularly through unstable formation materials where shotcreting becomes an integral part of an excavation cycle."

Correct realistic evaluation of all prevailing geological conditions, and its associated effects upon the proposed support media, is the key to a successful job.

Of course, in comparison to the classical structural steel support, shotcrete has its limitations. For instance, one cannot drive a tunnel using a forepoling method or drive the occasional spiling when the need arises, nor can one breastboard the face when the ground starts running. And above all, shotcrete will not perform in very wet or water-bearing ground.

Last, but not least, come safety and health considerations for the crews working underground. Excessive dust conditions associated with the dry-mix process most definitely cause a health hazard, not only to the nozzleman and the machine operator, but to everyone working in the tunnel. In the future, dust conditions resulting from the use of the dry-mix process will have to be eliminated, or at least improved to a marked degree.

The short and long term health effects of the chemical accelerators on the working crews will have to be studied, evaluated and standard workable guidelines and norms will have to be established and enforced.
We have come a long way towards making shotcrete a respectable and an efficient means of sound underground support. However, we will have to continue our efforts to make the process universally acceptable.

I am confident that this conference is a giant step in this direction. Parting with the word "confidence", a word of caution about the dangers of becoming "overconfident" when working under a shotcrete underground support lining, is appropriate. Be aware, and mindful of the fact, that it takes only a very thin shotcrete coat to cover a multitude of sins, and that by its sound appearance, gives you, the man standing underneath, a very false sense of security.

Make sure that the crews who place the shotcrete underground are well trained in the art. And you, my friends, don't take the required shotcrete lining thickness for granted, because, in most cases, it is much thinner than was specified, or appeared to be.