Shotcrete Classics

Reprinted courtesy of Engineering News-Record*, McGraw Hill Financial, November 9, 1933*

Technical Editor's Note: The following article is reprinted from *Engineering News-Record*, published November 9, 1933—80 years ago! Reading the article gives a fascinating glimpse of the past in our shotcrete industry, but surprisingly hits on many of the fundamental aspects of shotcrete we still research today: nozzle material velocities, cement ratios and water content of mixtures, size and shape of test specimens, percentage of rebound, and air compressor size. Coincidently, in this issue of *Shotcrete* magazine, you'll find an article detailing current research on nozzle material velocities and another article that details the use of ground recycled glass in shotcrete mixtures, which finds its use helps to reduce water demand. I must admit I also felt a bit of nostalgia seeing the picture of the "latest improved CEMENT GUN" at the end of the article. It looks almost exactly like the double-chamber gun I operated on dry-mix shotcrete jobs in the late 1970s. And although the manufacturer has changed names several times, the same basic gun is still available today! Enjoy this blast from the past!

And here's today's model!

(N-2 Gun, photo courtesy of Putzmeister Shotcrete Technology)

New Test Data Aid Quality Control of Gunite

Tests conducted in relining reservoirs for Syracuse, N. Y., provide basic data on nozzle velocities, size and shape of test specimens, and cement ratio and water content of mixes

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THE RATIONAL CONTROL of mixtures of hydraulic cement and aggregates has been extended by the development of basic data on the constitution and application of gunite. Extensive studies made in connection with the relining of two reservoirs of the Syracuse, N. Y., waterworks have given data of value on nozzle velocity, bulking of sand, cement ratio, water content, age of dry mix and strength. In particular, the study of the important factor of nozzle velocity has been extended to positive determinations of velocities for nozzles of different sizes. —EDITOR.

WOODLAND RESERVOIR of the Syracuse (N. Y) water supply is a kidney-shaped structure 1,737 ft. long and 406 ft. average width. At the maximum depth of water of 36 ft. it holds 125,000,000 gal. The side slopes are 1 on 2. It was constructed in 1892-'95. After a year in operation it was emptied and cleaned (1896), presumably to eliminate algae tastes. From that time it was never emptied again until 1932, when the relining work discussed in this article was undertaken. Based on successful results with the previously lined Westcott Reservoir (*ENR*, Nov. 19, 1931), a $1\frac{1}{2}$-in. gunite lining was adopted.

The original lining consisted of a 9-in. course of hand-mixed concrete on the bottom and up the slope to the berm. On the berm the concrete was thickened to 12 in., and on the upper slope it was 6 in. thick with a 12-in. paving of limestone laid in mortar. No construction or expansion joints had been provided; each day's pour of concrete had been joined to the preceding day's work in irregular lines without special effort to secure bond. An examination of the lining showed little actual concrete disintegration, but the concrete was quite porous. There were many separated construction joints and some settlement cracks. At the angle of the lower slope with the berm and the full length of the berm was a crack $\frac{1}{8}$ to $1\frac{1}{2}$ in. wide caused by settlement of the upper slope.

New lining

The necessity for relining came from a serious leak that occurred in January, 1932, at a point where the embankment is about 40 ft. high. As stated, a $1\frac{1}{2}$-in. layer of gunite was adopted. The reinforcement was 4x4-in. mesh, No. 7 galvanized and electrically welded steel wire. It was fastened to the old lining at regular intervals with $\frac{1}{4}$-in. expansion bolts. During the first part of the work the mesh was held up $\frac{3}{4}$ in. from the old lining by the nozzleman's helper while some gunite was shot under the wire at several points. Later, small stones about $\frac{3}{4}$ to 1 in. thick were put under the wires. Where the side slopes meet the bottom, an extra thickness of gunite was shot. This was doubly reinforced by lapping the bottom mesh over the slope mesh for 1 ft. or more.

Two types of expansion joints were used. At the inner edge of the berm (the edge nearest the center of the reservoir) the settlement crack mentioned above was cut out to V-shape and covered with a strip of mesh and a batten of gunite about 3 ft. wide, and mopped with hot pitch, which hardened to form a smooth, glossy surface. The gunite lining was placed continuous over this batten and pitch. Fig. 1 shows this construction, which allows for movement of the berm slab and slope lining beneath the gunite as the gunite lining floats on the layer of pitch.

Five expansion joints running across the bottom of the reservoir up to the berm, about at right angles to the center line, and one joint running longitudinally about midway between the sides were constructed, copper expansion stops and pitch being used. These joints, which were about equally spaced, did not run in continuous straight lines, as existing cracks and construction joints were taken advantage of as much as possible. Where neither joints nor cracks existed, a joint was formed by cutting through the old lining with an air hammer. Expansion joints in the gunite lining were constructed above these joints in the concrete, as shown in Fig. 2. The copper strips were soldered except where they crossed at right angles, when they were lapped, with a layer of plastic between them. These joints were difficult to make and required care and supervision to insure good construction.

It was decided to rent equipment and construct the new lining with city forces. The Cement Gun Co., of Allentown, Pa., was low bidder on the equipment. It furnished four compressors, two mechanics for operating the compressors and servicing all of the equipment, and two continuous dry mixers. The compressors had a displacement of 1,800 cu.ft. per minute. The actual free air delivered was measured continuously by means of an orifice in the main air line and a recording differential meter. It was found that the volumetric efficiency of the compressors was approximately 79 per cent. In addition, a city-owned compressor was used, making the total output of the plant 1,630 cu.ft. per minute. This amount of air was sufficient satisfactorily to operate four or five guns with $1\frac{1}{4}$-in. nozzles, depending on the use of the blow-down line, and five or six small pneumatic hammers for drilling.

Tests and inspection

A simple field laboratory was set up on the job, where daily tests were made to determine the moisture content of the sand as received and as used in the mixers, and the fineness coefficient and silt content of the sand. Continuous

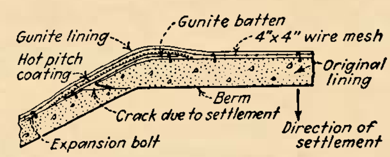


Fig. 1—Detail of expansion joint in gunite relining at angle of slope and berm of Syracuse, N. Y., waterworks reservoir.

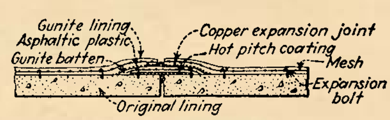


Fig. 2—Detail of bottom expansion joints in Syracuse reservoir, showing copper waterstop.

checks were made to determine the cement ratio in the mix. This was one of the principal routines of the laboratory, as it was found that the mix varied somewhat for a given setting of the mixers, depending on the moisture content of the sand and the manner of feeding the mixers. Daily checks were also run on the moisture content of the gunite shot. By means of these checks the average water content was controlled at each nozzle. This was found to be a highly important feature of the work, as the strength and density of the gunite varied greatly with the water content. Periodic tests were made to determine the moisture content of the rebound, the percentage of rebound and the cement ratio in the gunite. In addition, extensive experiments were conducted on nozzle velocities as a continuation of the study previously conducted at the Westcott Reservoir (*ENR*, Nov. 19, 1931).

Study of nozzle velocity

In connection with the Westcott Reservoir work, it had been found that there is an optimum velocity at which to shoot gunite Before work was begun on Woodland Reservoir, all of the guns were equipped by the city with the nozzle-velocity-measuring devices that were developed on the Westcott Reservoir lining job. The velocity at each nozzle was read at the gun by means of a single manometer and a suitably calibrated scale.

A velocity of 375 ft. per second was first used, as previous experimental work had shown this to be the most satisfactory velocity. Most of the previous tests, however, had been made with a $\frac{3}{4}$-in. nozzle operating with a N-0 gun. As $1\frac{1}{4}$-in. nozzles and N-1 and N-2 guns were being used on this job, several series of velocity samples were shot to determine the proper velocity to use with this larger equipment. The results of these tests showed that gunite of maximum strength and density was obtained with a velocity of about 425 ft. per second as read on the manometer scale.

After making this determination, opportunity was afforded of checking the manometer velocity scales used in all of the Syracuse work against accurate air-measuring standards, and it was found that these scales were in error, showing air velocities less than actually existed at the nozzle. Correcting for this error, the velocity of 425 ft. per second as read on the manometer scale becomes 510 ft. per second. (These velocities and all of the nozzle velocities mentioned in this article are expressed in terms of the cubic feet of free air per second supplied to the nozzle, divided by the area of the nozzle opening in square feet.)

Fig. 3 shows the average results of the velocity tests on the $1\frac{1}{4}$-in. nozzle, *corrected* nozzle velocity in feet per second being plotted as abscissas against compressive strength of gunite in pounds per square inch as ordinates. The graph also shows correct nozzle velocities for the average results of all of the velocity tests with the $\frac{3}{4}$-in. nozzle that were made in connection with the Westcott Reservoir lining and many more recent tests made with the same size nozzle. These velocities are applicable when the nozzle is held at a distance from the work of approximately 4 ft. for the $1\frac{1}{4}$-in. nozzle and 3 ft. for the $\frac{3}{4}$-in. nozzle.

Although no tests were made during the work with a 1-in. nozzle, subsequent tests made under actual working conditions with nozzle-velocity meters, where a 1-in. nozzle was used, developed values and results practically in accord with the $\frac{3}{4}$-in. nozzle, as shown on Fig. 3.

These curves show that a higher velocity is required when using a $1\frac{1}{4}$-in. nozzle than when using a $\frac{3}{4}$-in. nozzle. There are many factors which account in part for this, but it is probably due for the most part to the fact that there is a tendency to hold a large nozzle at a greater distance from the work than a small nozzle. In the former case a

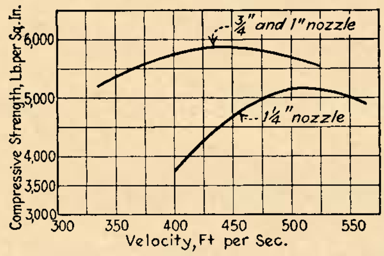


Fig. 3—Graph of compressive strength of gunite placed at various nozzle velocities with three sizes of nozzles, as determined by Syracuse tests.

greater initial speed at the nozzle is required to obtain the same impact for a given particle of sand than in the latter. This is probably due to air friction. Tests showed that holding the nozzle close to the work has the same effect on the quality of the gunite as increasing the nozzle velocity, which means that lower velocities may be safely used on close-up work.

It is probable that the velocity of the sand and cement particles impinging on the surface on which gunite is applied is not that of the air velocity obtained by dividing the air input to the bottom hopper of the gun by the area of the nozzle. The section area of the material and water leaving the nozzle varies with the output of material. Assuming a constant input of air, the nozzle velocity varies, increasing with an increase of material. The sand and cement particles, however, are slowed down between nozzle and work by the friction of the air. Then again the rubber liners of the nozzles wear, reducing the nozzle velocity for a given input of air as the diameter of the liner wears larger. The Syracuse tests were run under normal operating conditions, however, and should be typical and applicable for general use.

The velocities are expressed in terms of air input and of nominal nozzle diameters, as this seems to be the most practical method. On this basis the compressor capacities can easily be calculated for various-sized nozzles, adding 50 to 60 cu.ft. per minute of free air for the air motor on the gun. These velocities are based on free air at 60 deg. temperature at the nozzle.

Fortunately, a relatively large variation in velocity may be used without serious loss of strength and density. As shown by Fig. 3, the velocity, when using $1\frac{1}{4}$-in. nozzles, may vary from 450 to 550 ft. per second without serious loss of quality. Experience on this work showed that it was neither economical, practical nor desirable to shoot at higher velocities than 550 ft. per second. Velocities below 450 ft. are not recommended except where it is necessary to hold the nozzle close to the work.

Correcting for the error in manometer scale, the recommended operating velocities, as set forth in the previous paper on this subject, would be from 400 to 500 ft. per second for the $\frac{3}{4}$-in. nozzle. This would also be true for most work with a 1-in. nozzle. However, as both of these small nozzles are used extensively for close work, such as steel incasement, tunnel and sewer work, where it is sometimes necessary to hold the nozzle at about one-half the normal distance from the work, a velocity of 375 ft. per second is more advantageous and does not sacrifice quality on account of the nozzle distance.

As soon as the results of Fig. 3 were available, the average operating velocity was raised from 375 to 425 ft. a second, as shown on the manometer scale, the latter corrected being 510 ft. per second. Throughout the rest of the job a variation in velocity was not allowed of more than plus or minus 6 per cent of this value. As soon as the lower limit was passed, a gun running low was shut down and not put into operation again until the air supply had increased sufficiently to obtain the proper velocity.

This method of measuring and controlling the nozzle velocity was used successfully throughout the job. It was found that uniform velocity made for uniform production and operation of the guns.

The nozzle-velocity meter was also of further value in that it would indicate a tendency of the hose to plug, thereby warning the operator in advance so that he could cut down on his feed wheel in time to avert a complete obstruction. Moreover it was easy to determine which guns were using more air than necessary, whereupon they were throttled, making more air and pressure available for the guns that required it.

Preparing strength specimens

Tests were run at Woodland Reservoir to determine a practical size of gunite specimen that would be large enough to eliminate errors in determining the section area and yet small enough to be easily and readily shot, cut out and broken. The most successful method used throughout most of the job was to shoot a mound of gunite 4 in. thick and about 6 in. square at the base. When this sample had partially hardened, a specimen was cut 4 in. high and 4 in. in diameter. This was done by placing a 4-in. wooden cylinder on top of the specimen and cutting the gunite away with a trowel. The specimen was finally shaved to true cylindrical form by means of a half longitudinal section of a 4-in. steel pipe sharpened to a knife edge and equipped with a handle. The cylinder was used as a guide for the steel pipe shaver. A comparison test indicated that a sample of these proportions would give the same compressive strength as that of a specimen whose height was twice the diameter.

The results, in lb. per sq.in., of the

compressive strength tests on specimens on this work are as follows:

Average of 66 specimens 3 to 5 days old (majority 3 days)......	4,503
Average of 31 cylinders 5 to 14 days old (majority 5 to 7 days)	5,111
Average of 6 cylinders 28 days old.	6,893

These samples were made with the regular sand used in the work, which, while not as hard as obtainable in some sections, was one of the most satisfactory available in the vicinity of Syracuse.

Bulking of sand

The nominal mix was 1 part of cement to 3½ parts of sand measured by volume, sand containing 4 per cent moisture by weight being taken as the standard. Tests showed that the sand used bulked to the maximum when containing from 3 to 4 per cent moisture. With this moisture content the bulking action gave the sand 26.5 per cent more volume than in a bone-dry state. The amount of sand used in gunite was 6,430 cu.yd. This was measured in a semi-compacted state in the truck bodies as they arrived on the work. The moisture content averaged about 6 per cent. It was found that the sand bulked about 8 per cent from the truck to the storage pile, and that further bulking of 10 per cent occurred when the sand was dried out to contain about 4 per cent moisture. The total sand used on the basis of 4 per cent moisture was therefore 7,570 cu.yd. As the total number of bags of cement used for guniting was 53,718, the average mix was therefore about 1:3.8.

Confirming previous experience at Westcott Reservoir, it was found that sand containing 4 per cent moisture by weight was ideal for the best operation of the mixers and guns. This degree of wetness gave maximum production and uniform application of the gunite.

For this reason and for the reason that the mix was based on sand containing this moisture content, an effort was made to reduce the moisture content of the sand as received to this value before reaching the mixer. While it was not practicable to obtain this ideal at all times, the storing of sand in shallow piles and the manipulation that it received in transporting it from the storage pile to the mixers on a belt conveyor generally accomplished the desired result.

Determining cement ratio

The method used to determine the amount of cement in the dry mix and also in the gunite was to dehydrate a sample with a centrifuge and burning alcohol, and to sieve the material, obtaining the per cent of the sample by weight which passed a 200 sieve. By referring to a curve that was empirically established at the beginning of the job the amount of cement in the sample of mix was easily determined. Data for this curve (Fig. 4) were obtained by making up sample mixes of

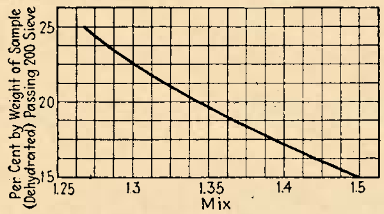


Fig. 4—Ratio of cement to sand in gunite of various proportions, with 4 per cent water content in the sand.

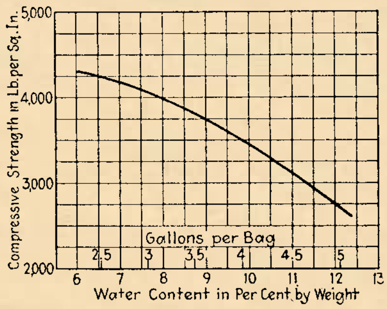


Fig. 5—Relation of strength to water content of gunite mixtures.

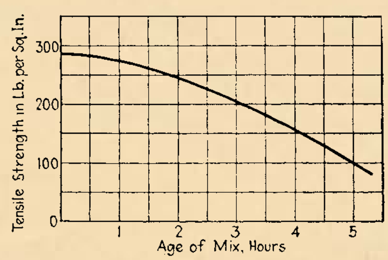


Fig. 6—Strength of gunite as affected by age of dry mix.

various ratios of cement to sand, the latter containing 4 per cent moisture by weight and sieving the samples. The amount passing the 200-sieve was directly proportional to the cement content. The per cent of the samples by weight passing the sieve are plotted as abscissae against mix ratios as ordinates.

Water content

The water content of the gunite was determined by dehydrating a sample of gunite with a centrifuge and alcohol. This was done as soon as it was shot, and the moisture content was expressed in terms of the total weight of the sample before dehydrating. To determine the water content to be used to obtain maximum strength and density, samples of gunite were shot at various moisture contents, and these samples were tested for compressive strength.

Fig. 5 plotted from data obtained by this test shows that the strength increases as the water content decreases. Water content is shown in per cent by weight of the sample and also in gallons per sack of cement. The latter values have been computed, the unit weight of the sand and cement used being known. A 10 per cent moisture content by weight is calculated to be a little over 4 gal. per sack. In the previous article (*ENR,* Nov. 19, 1931) the top of the strength curve corresponded to about 6 gal. per sack. This water content, however, was expressed in terms of the total amount of water used in shooting the gunite, including the moisture content of the sand and the water added at the nozzle. There is a loss of water in the rebound and a considerable loss in atomization. The latter has been found by test to be as high as 1 to 2 gal. per sack.

There was found to be a practical limit to the dryness at which the gunite could be shot. When shot with a moisture content of 8 per cent or less, it was difficult to incase properly the mesh in the gunite without entrapping rebound behind the wires. Experience showed that a 10 per cent moisture content was practical for the gunite under the mesh and 9 per cent for gunite above the mesh. This practice insured a good quality of gunite below the mesh and a denser harder layer above it.

At the beginning of the work, before the men were trained to this relatively dry shooting, gunite was shot somewhat wetter, probably averaging a moisture content of 11 per cent. At the completion of the job it was noted that the gunite that was shot with this moisture content had developed many more hair cracks than occurred in the gunite that was shot with less water. Moreover, the dryer gunite appeared to be of better quality, having a hard dense surface.

Gunite shot with a moisture content of 9 to 10 per cent is relatively dry. In shooting with this moisture content it is necessary to exercise great care to avoid rebound pockets and laminations. The question may be raised as to whether it is economically practicable to shoot with this low moisture content on account of the increase in rebound. If maximum density and strength is not required, it is doubtful if this degree of dryness is necessary. However, for reservoir linings, where the gunite is subjected to extreme ranges of temperature before and at the time of filling the reservoir, and where density and watertightness are of prime importance, experience at Woodland Reservoir would seem to justify the additional cost for sand and the labor of removing the rebound.

It does not follow that the most satisfactory water content on this work, expressed in per cent of a given sample of gunite, will be applicable on other work, as this ratio varies somewhat, depending on the characteristics of the sand and on the mix. It is comparatively easy to obtain these data for a given sand and mix. Once the most satisfactory water content is established on a job, uniform water content of the gunite can be maintained by frequent tests and careful observation.

Age of dry mix

During the early part of the work it was the custom to provide a storage of mixed material in the bin above the guns which would last from two to three hours in the event of a breakdown in the mixing plant. Some of the material in the bin that was mixed early in the morning might not be used until nearly noon, as it was the practice to empty the bin completely every four hours. Laboratory tests indicated that this mix produced gunite of poorer quality than did a fresh mix. Further to study this condition, mortar briquettes were made up at hour intervals after the initial dry-mixing of the ingredients, and the briquettes were tested for tensile strength. The briquettes showed a substantial loss of strength for every hour that elapsed after the mixing of the sand and cement (Fig. 6). From the time that these tests were made it was therefore the practice to provide storage of not over an hour's supply and to keep the mix in the bin above the guns thoroughly stirred up so that no dead areas occurred.

Another special test made was to run sand through a gun under normal operating conditions and to measure the percentage of this sand passing a 200-sieve. The amount of sand passing the sieve was found to be about 7 per cent greater than existed in the sand before shooting, showing that the gun has a considerable pulverizing effect on the soft particles of the sand. This emphasizes the need for a hard sand for gunite work, free from shale and other soft particles.

Strength

The unit strength of gunite, as shown on the accompanying curves, is the strength that was obtained for the particular tests which they illustrate and does not necessarily represent the strengths of gunite that can be obtained under favorable shooting conditions and with the best quality of materials.

The mix, of course, has a direct bearing on the strength. A series of seven-day specimens shot to study the effect of mix on strength showed a variation of from 4,000 lb. per sq.in. for a mix of 1:6 to more than 7,000 lb. per sq.in. for a mix of 1:3. Other specimens have been tested by the writer. These were made with a particularly hard sand and a mix of 1:3½, which tested from 7,000 lb. per sq.in. to nearly 10,000 lb. per sq.in. at an age of 6½ days.

Attention is called to Fig. 5, showing the relation of water content to compressive strength. The strengths obtained in this test were relatively low and do not truly represent the average strength obtained on the job. This is accounted for in part by the fact that the specimens were broken three days after they were made, whereas nearly all of the specimens broken in connection with the experimental work were seven days old. The relationship of water content to strength, however, is typical and agrees substantially, as far as this relationship is concerned, with the data developed on the Westcott Reservoir project.

Conclusions

The following conclusions may be drawn as a result of observations in reservoir-lining work at Syracuse.

Experience at Woodland Reservoir showed that to control the various phases of shooting gunite is not only desirable from an engineering point of view but is also practicable and an advantage to operation and production.

To measure and to regulate nozzle velocities insures a more uniform strength and density than could possibly be obtained by specifying a pressure under which the gun is to operate. The latter depends on many operating conditions and is not a measure of nozzle velocity. Nozzle-velocity meters provide a ready means of observing whether the flow of material through the hose is uniform, indicating at once any tendency to clog. The gunman may avert many shut-downs by slowing down the feed wheel until the obstruction has blown clear. This feature increases production. Then again, it appears that while insufficient velocity reduces the strength and density of the gunite, excessive velocity is also detrimental to the gunite in the same manner and increases the amount of rebound. Regulation can be readily controlled when the cement gun is equipped with a nozzle velocity meter.

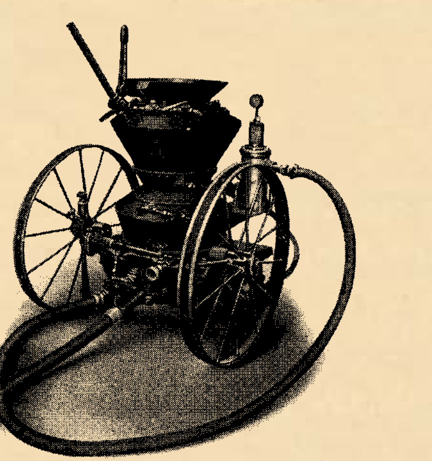
The value of the control of the water content in concrete work has been conclusively demonstrated in recent years. The experimental work to date would indicate that the same is true of gunite. Not only is strength and density sacrificed when excessive water is used, but the results at Woodland Reservoir showed that hair cracks at the surface of the gunite are much more prevalent when the gunite is shot relatively wet than when dry.

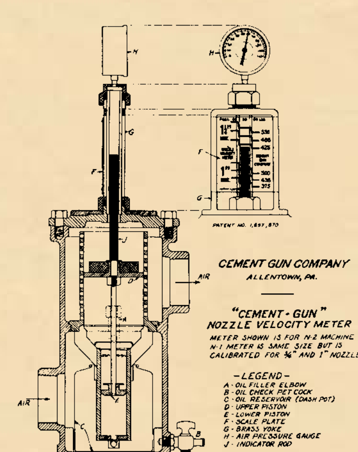
Controlling the moisture content of the sand at the mixer makes for smoothness of operation and maximum production. From 4 to 5 per cent moisture content by weight has given the best results on the work at Syracuse.

The sand should be well and uniformly graded. A hard sand is especially desirable for gunite work, as soft particles are pulverized, forming a dust that may form a film on the harder particles, thereby weakening the bonding action of the cement. The age of the mix is another factor to be considered in obtaining the best gunite. As soon as the cement comes in contact with the moist sand, hydration begins. The result is that the effectiveness of the cement is lost as the mix ages. The storage of mixed materials should therefore be kept at a minimum, and no inactive spots should be allowed to occur in storage bins.

The cement ratio in the mix should be kept constant for uniform gunite. With a change in moisture content in the sand, the per cent of bulking changes, requiring a modification of the mix to maintain a constant cement ratio. If continuous mixers are used, the method of feeding the hoppers should be uniform in order to maintain a constant ratio of cement to sand.

The importance of special care to secure good laps cannot be stressed too strongly, especially for watertight linings. Clean surfaces free from rebound are essential for a watertight bond.





Above, to the left, is a photo of the latest improved "CEMENT GUN." Attention is directed to the NOZZLE VELOCITY METER shown on the photo, (drawing on the right), which was developed from comparative tests made by Mr. Stewart at Westcott Reservoir, (described herein), and was first used on Woodland Reservoir. Since then, all new "CEMENT GUNS" have been equipped with the meter and meters may be purchased for attachment to all "CEMENT GUNS" previously sold. Write to CEMENT GUN COMPANY, Allentown, Pa., for prices and full particulars.