INTRODUCTION

Some rebound is an inevitable consequence of a shotcrete operation. The many various factors leading to excessive rebound were identified and appreciated by those familiar with shotcrete long ago. Studebaker (1939) was only one of the early researchers. However, the relative significance of many of these factors is not yet well understood. The magnitude of rebound is difficult to determine and "eyeball estimates" cannot always be relied upon to base conclusions about the various factors of rebound.

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There are many reasons for measuring the magnitude of rebound frequently during the shotcrete operation. Rebound has a significant impact on the cost of the shotcrete. In addition to the obvious increase in materials cost, there are many intangible or less obvious cost penalties that usually increase the cost to the Contractor. These include an increased shooting time, which in some instances could result in a slower rate of advance; increased manpower requirements for materials handling and batching, reduced efficiency of all the crews at the heading, and increased costs for muck removal.

This paper is based upon a portion of the rebound studies done as part of a much larger shotcrete field research program conducted by the authors at the University of Illinois at Urbana-Champaign (Parker, Fernandez, and Lorig, 1975). The process of rebound was studied in detail by means of field rebound tests; close visual observation; high-speed photographic studies; and by evaluation of the fresh samples taken from the dry mix, wall, and rebound pile; and by theoretical means. Some of the results were developed during another study (Mahar, Parker, and Wuellner 1975). The field work was conducted at the Dupont Circle Station in Washington D.C. using typical dry-mix shotcrete equipment and mixes used by heavy construction contractors. Hence, these results are relevant primarily for coarse-aggregate mixes (0.5 in, 1 cm., maximum) with powdertype accelerator shot by the dry-mix process at rates on the order of 5 cubic yards per hour (3.8 cu.m. per hour).
The dynamics of rebound of dry-mix shotcrete can be idealized by separating the process into two Phases. Phase 1 is defined as the time during which a thin cushion-like layer of shotcrete is being established. The rate of rebound during Phase 1 is extremely high; the weight of material falling to the ground in any given period of time is between 50 to 100% of the weight shot at the wall in the same time period. Phase 2 is defined as the period when the incoming shotcrete impacts on a relatively soft cushion of fresh shotcrete.

The very high rebound rates during Phase 1 occur primarily because the aggregate bounces energetically off the bare hard walls with little energy dissipation. Some fines begin to stick to the wall, however, and a layer of fines or paste is gradually built up. The paste acts both as a cushion to absorb some of the impact energy of particles and as a restraining layer tending to hold particles in it. As the layer of paste gets thicker, its effect on restraining the particles increases and particles lose an increasing amount of energy while penetrating the cushion. Consequently, the energy after impact is lower and the thicker cushion provides more resistance against breakout. The transition from Phase 1 to Phase 2 is a function of a fast buildup of the thickness of shotcrete. Hence, the transition from Phase 1 to Phase 2 is relatively sharp. There is a rapid reduction of rebound going from Phase 1 to Phase 2.
During Phase 2, as long as the fresh shotcrete on the surface of the wall remains in a relatively plastic state, the mechanics of energy loss and entrapment are similar with the result that the rate of rebound remains low. Tests indicate that, so long as the shotcrete is built up at a uniform consistency, the instantaneous rate of rebound is relatively constant.

If the fresh shotcrete on the surface becomes harder, conditions for the retention of material become less favorable and the rate of rebound begins to increase. This transition back to higher rebound could be caused by increased accelerator dosage, shooting drier, or by a brief period of setting before the nozzle is pointed at that spot again. The transition from Phase 2 back to Phase 1 is a result of subtle changes in consistency and the increases in rebound are gradual. However, if the shotcrete on the surface sets and becomes non-plastic, there is a complete return to conditions of Phase 1. This is the case for multiple-lift shotcreting. Finally, during normal shooting, the nozzle is often directed at the edge of the buildup of shotcrete in a manner that part of the material in the shotcrete airstream is directed at a bare surface and part of it is directed at the edge of the fresh built-up shotcrete. Hence, the sharp differences between Phases 1 and 2 are masked somewhat during normal shotcrete operations.
BACKGROUND

It was found that the true mechanism of rebound could not be studied without supporting quantitative data about the shooting rates, mix design, accelerator dosage, temperature, and a vast amount of other data. To correlate the conditions and rebound results of one shooting with another, it was found that it was necessary to define new parameters that are described below. Care should be taken when first using these parameters. These new parameters include cumulative sums, instantaneous rates, average rates, and parameters based upon ratios of rates. A clear understanding of the physical significance of each parameter is helpful to the understanding of the mechanics and dynamics of rebound.

CUMULATIVE WEIGHT PARAMETERS

Though the dynamics of rebound is evaluated in terms of weight rates and the changes in these rates, the only practical way to determine these rates is by physically measuring the total weight shot or rebounded during a known time interval, then converting the weights to a rate.

The following parameters were defined for use in these studies.
By appropriate subscripts, these summation parameters can also be identified as being the total weight during a specific phase, time, or thickness increment. For instance, \( \text{RSUM}_{0-1} \) might be the rebound collected during a rebound test up to 1 minute; \( \text{RSUM}_{1-5} \) might be the rebound collected during the interval from 1 to 5 minutes. This nomenclature is helpful when separating the rebound for Phase 1 from Phase 2.

**MATERIAL DELIVERY RATE (MDR)**

One of the most important basic parameters is called the Material Delivery Rate (MDR). It is the weight rate of all the material leaving the nozzle as defined as the total weight shot divided by the net time to shoot that weight. It should be considered as an instantaneous rate but it can be approximated in the field by weighing a given batch, adding the weight of water added at the nozzle, and measuring the net time it takes to shoot the batch. To obtain the net time, all interruptions such as plugs when material is not flowing must be subtracted from the gross shooting time. MDR is defined as follows:

\[
\text{MDR} = \frac{\text{Total Weight Shot}}{\text{Net time to shoot weight}}
\]
The Material Delivery Rate (MDR) is an instantaneous weight equivalent of the familiar rate "cubic yards per hour". For example, at 3800 pounds per cubic yard (1727 Kg per m³), 5 cubic yards per hour is equivalent to about 5 pounds (2.3 Kg) per second or 315 pounds (144 Kg) per minute. In the field work done for this study, all field operations were timed with an accuracy of less than 5 seconds. Such accuracy is required for detailed studies since some 25 lbs (11 Kg) is shot during 5 seconds.

REBOUND RATE (RR)

The weight rate of rebound bouncing off the wall is called the Rebound Rate (RR). It also is an instantaneous rate which typically ranges from 1 to 5 lb/sec (0.5 to 2.3 kg/sec). The Rebound Rate (RR) is high during Phase 1 and reduces considerably during Phase 2 after the initial critical thickness is established.

Since the rebound rate is the rate of material falling to the ground, the Yield Rate (YR) can be defined as the difference between the Material Delivery Rate and the Rebound Rate. Thus, the Yield Rate is the instantaneous rate at which material is accumulating on the wall in units of pounds (Kg) per second. With the customary constant MDR, the Yield Rate is very low during Phase 1 and high during Phase 2.
Both Rebound Rate (RR) and Yield Rate (YR) are instantaneous rates so they are not easily measured in the field. They were approximated during the field tests for this study by using a multiple-tarp technique described in a later section.

INTERRELATIONSHIPS BETWEEN MDR, RR, AND YR

Figure 1 is a reasonable hypothetical example of how rebound decreases with time as the shotcrete on the wall gets thicker. Two relationships are shown on Fig. 1; the solid horizontal line is MDR while

![Diagram showing relationships between MDR, RR, and YR]

\[
RRR = \frac{RR}{MDR} \quad YRR = \frac{YR}{MDR}
\]

Area Between MDR And Dashed Lines = YSUM

Area Under Dashed Line = RSUM

FIG 1. VARIATION OF REBOUND RATE WITH TIME

the curved dashed line is the Rebound Rate, RR. The length of any vertical line from the x axis to the solid line is the numerical value of MDR in pounds (kg) per second. The length of any vertical line
between the x axis and the dashed curve is the numerical value of RR in pounds (Kg) per second. The length of any vertical line from the dashed curve up to the solid MDR line is the numerical value of the Yield Rate, YR, or the number of pounds (Kg) per second of shotcrete staying on the wall. Thus, YR is equal to (MDR - RR).

The whole area beneath the horizontal MDR line is SSUM which equals RSUM + YSUM. The area under the RR-versus-time of shooting curve (the integral of the curve) in Fig. 1 is the total weight of material that has rebounded, RSUM. The area between the dashed curve and the horizontal MDR line is equal to YSUM.

REBOUND RATE RATIO (RRR)

It is convenient to think about rebound and yield not only in terms of weight per unit of time but also as a ratio of the amount of material shot against the wall. Rebound Rate Ratio, RRR, is the ratio of the amount of material falling to the ground to the amount of material shot at the wall at any given precise instant or any convenient short period of time. The ratio of the length of the line RR to the length of MDR is the Rebound Rate Ratio, RRR, while YR to MDR is the Yield Rate Ratio, YRR. Formulas for RRR and YRR are given in Fig. 1. Rebound Rate Ratio, RRR, is based upon instantaneous rates and must not be confused with the parameter termed percentage of rebound universally used by the Industry and commonly reported in the literature. To avoid confusion, Rebound Rate Ratio, RRR, is expressed as a ratio, never as a percentage.
So long as MDR is constant, the RRR-versus-time curve is similar in all respects to the RR-versus-time curve; the area under the RRR curve is directly related to RSUM by the term MDR. At the beginning of shooting, almost 100 percent of the material bounces off with very little sticking. This is shown in Fig. 1 at zero time of shooting where RR is as large as MDR. The Rebound Rate Ratio, RRR, is 1.0 at this instant. As the layer increases in thickness, the rebound rate decreases and, thus, RRR decreases.

It is more appropriate, however, to plot rebound and yield data with respect to thickness rather than to time since the phenomenon is governed by the thickness on the wall. Thickness of the layer of shotcrete on a given area is related to time of shooting by a non-linear function.

**AVERAGE REBOUND (RAVE)**

Average Rebound, RAVE, is defined as the total weight of rebound divided by the total weight shot, expressed as a percentage, as shown below.

\[
RAVE = \frac{RSUM}{SSUM} \times 100\%
\]

Average Rebound is the parameter most often used in the industry and commonly called percentage rebound. It is extremely important to recognize that RAVE is an average value of all rebound losses (both Phase
1 and Phase 2) that occurred before the determination is made. Furthermore, because of the nature of Phase 1 and Phase 2 rebound losses, RAVE varies with the thickness on the wall rather than being constant. Both Average Rebound, RAVE, and Rebound Rate, RR, are very high at the beginning of shooting against a bare wall. As soon as the initial critical thickness is built up, the high Phase 1 losses no longer occur and the rebound losses are just the relatively low rebound losses associated with Phase 2. At the transition to Phase 2, the magnitude of the instantaneous parameters, RR and RRR, drop sharply to low values that remain low and relatively constant for the remainder of the rebound test. Average Rebound, RAVE, however, is an average that continues to be strongly affected by the very high rebound losses that occurred during Phase 1. Therefore, even though during Phase 2 the instantaneous rebound rate is constant at only 10 to 20% of the shooting rate of material, the parameter Average Rebound is quite high and is slowly decreasing as a feeble response to the lower Phase 2 rebound losses.

The following hypothetical example is given to illustrate this point because this unique aspect of RAVE is so very important to the understanding of what is really being measured when rebound tests are conducted in the conventional manner. Assume that a rebound test is made in such a way that the nozzle pointed just to one spot on the wall and RSUM and SSUM could be measured every two seconds. If MDR is 5 lbs per second, then the total weight shot per interval would be 10 pounds. High rebound rates, say 6 to 8 pounds per interval, would be
expected during Phase 1 but only 1 pound per interval might be expected during Phase 2. The data for this hypothetical rebound test are assembled in Table 1.

It can be seen from this table that during Phase 2, the value of RAVE is slowly decreasing at a time when the true rebound rate is constant. It can also be seen that the magnitude of Average Rebound, RAVE, measured could have been any value from 80 to 25% depending upon when the test was stopped.

It is extremely important to understand that all rebound tests conducted by the industry suffer from this thickness, or time of shooting, effect. Accordingly, many of the actual rebound tests conducted in the past and reported in the literature can not be compared because the total thickness shot was not reported along with the results. Generally, thin linings should have a high Average Rebound while thick linings should have a relatively low Average Rebound. In fact, previously-reported high rebound values may not have been the result of poor workmanship but only the result of the fact that the test thickness was relatively thin.

More importantly, if a rebound test is conducted to determine the actual losses, that rebound test must be made to the same thickness as that of each lift of the production shotcrete operations or the test results have no relevance to that project.
### TABLE 1

**HYPOTHETICAL REBOUND TEST**

<table>
<thead>
<tr>
<th>Interval</th>
<th>Rebound Collected During Interval RSUM₁</th>
<th>Total Shot During Interval SSUM₁</th>
<th>RRR</th>
<th>Accumulated Total Rebound Collected RSUM</th>
<th>Accumulated Total Shot SSUM</th>
<th>Average Rebound RAVE, %</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>8</td>
<td>10</td>
<td>0.8</td>
<td>8</td>
<td>10</td>
<td>80</td>
</tr>
<tr>
<td>2</td>
<td>6</td>
<td>10</td>
<td>0.6</td>
<td>14</td>
<td>20</td>
<td>70</td>
</tr>
<tr>
<td>3</td>
<td>1</td>
<td>10</td>
<td>0.1</td>
<td>15</td>
<td>30</td>
<td>50</td>
</tr>
<tr>
<td>4</td>
<td>1</td>
<td>10</td>
<td>0.1</td>
<td>16</td>
<td>40</td>
<td>40</td>
</tr>
<tr>
<td>5</td>
<td>1</td>
<td>10</td>
<td>0.1</td>
<td>17</td>
<td>50</td>
<td>34</td>
</tr>
<tr>
<td>6</td>
<td>1</td>
<td>10</td>
<td>0.1</td>
<td>18</td>
<td>60</td>
<td>30</td>
</tr>
<tr>
<td>7</td>
<td>1</td>
<td>10</td>
<td>0.1</td>
<td>19</td>
<td>70</td>
<td>27</td>
</tr>
<tr>
<td>8</td>
<td>1</td>
<td>10</td>
<td>0.1</td>
<td>20</td>
<td>80</td>
<td>25</td>
</tr>
</tbody>
</table>
PHYSICAL SIGNIFICANCE OF RRR AND RAVE

When measured properly, Rebound Rate Ratio (RRR) is a true measure of how efficient the shotcrete operation really is at any given instant. To make such measurements, rebound must be measured at frequent intervals (such as in multiple-tarp tests described in the next section) so that the calculated value of RRR closely approximate a true rate. RRR has no value in itself in estimating the amount or cost of rebound losses.

In spite of the fact that RAVE does not reflect the precise physical behavior, a properly-determined RAVE does accurately reflect the total rebound lost which is what the Contractor really needs to know. A properly-determined RAVE or some other parameter based upon RAVE, is the only parameter that can be used when quantities or costs are to be determined. Accordingly, Average Rebound, RAVE, is still a very important parameter but it has limitations never before recognized that must be understood and accounted for as described in later sections.

FIELD TESTING OF REBOUND

DESCRIPTION OF FIELD PROGRAM

General

Rebound tests were conducted by shooting against several blasted rock surfaces and against specially-prepared plywood boards. Generally
the tests were mini-rebound tests planned specifically to give accurate, representative results on rebound in order to evaluate how rebound changed when a given mix or shooting condition was changed.

Large plywood panels were previously prepared by covering them with about 6 in. (15cm) of shotcrete that had hardened. This layer provided a smooth, hard surface (which approximated the hardness of rock) which was similar for all rebound tests. The special panels eliminated any variable that could have resulted from the differences in roughness of blasted rock surfaces. A few tests were shot against blasted rock surfaces for comparison. A sketch of the panel configuration is shown in Fig. 2. The upper and lower foot (30 cm) of the panel were designated nonshooting areas so that the area shot during the rebound test was 6 ft (1.8 m) high by 4 ft (1.2 m) wide.

Rebound was collected on from 1 to 3 individual tarpaulins placed successively on top of each other as shown in Fig. 2. A scheme for making one large tarpaulin out of several smaller ones was devised. Several 4 x 4 ft (1.2 x 1.2m) tarps were made out of heavy waterproof canvas. Grommets along the perimeter of each tarp permitted any number of small tarps to be assembled into a mosaic of the various dimensions possible with the 4-ft (1.2m) module. Most often, the outside dimensions of the tarps were 16 x 16 ft (4.9 x 4.9m); several of these were assembled prior to shooting. Sometimes large plywood panels were placed as wing walls to the panel being shot to ensure no rebound would fall outside the tarps. The mosaic of smaller tarps permitted an evaluation
SHOTCRETE FOR GROUND SUPPORT

3/4" (1.9 cm) plywood panel

6" (15 cm) previously applied hard shotcrete

4-6" (10-15 cm) shotcrete applied during test

Nozzle

Rebound collected on each of up to 3 tarps

Extent of rebound approx. 4' (1.2 m)

FIG. 2 PHYSICAL LAYOUT FOR MULTIPLE-TARP REBOUND TESTS
of the geometrical distribution of rebound (distance from the wall, etc.). Their small size also made weighing of rebound faster, easier, and more accurate. The tarps with rebound on them were merely hung individually by their corners on a spring scale.

**Single-Tarp Test**

Before shooting began, a clean tarpaulin was assembled and placed on the ground in front of the rebound panel. Care was taken that the tarp was large enough to recover essentially all the rebound. At the beginning of shooting of every batch, the nozzleman shot at a practice panel until the proper water content was achieved. He then usually shot the rebound panel for about 3 to 5 minutes. Precise times of each stage of shooting were recorded. In some cases the entire mix was shot at the rebound panel.

**Multiple-Tarp Test**

Initial preparations for the multiple-tarp test were the same as those for the single-tarp test except that one or two other mosaics of tarps were assembled and readied so that each could be placed as fast as possible. The nozzleman moved the nozzle quickly over the entire rebound panel until, in his judgement, the panel was coated with a uniform layer just thick enough to get the shotcrete to stick to the surface. This was the end of Phase 1. All the material that rebounded during this time (usually less than 30 seconds) was collected on the
bottom tarp. The nozzle was then pointed away from the rebound panel for a very short time while a second tarp was placed on the ground on top of the rebound collected for the first stage of shooting.

In this manner, the rebound for any stage of shooting was collected separately from that resulting from other stages. Each tarp isolated the rebound collected up to that time from all remaining rebound. As soon as the next tarp was placed (usually in less than 15 seconds), shooting at the rebound panel was resumed. Material was built up on the wall uniformly until the rebound test was either complete or until another tarp was placed. Thus, at the end of each stage, the thickness of shotcrete was approximately uniform all over the rebound panel.

Test Variables

In order to compare different conditions, a series of mixes was shot with different mixes and different shooting conditions. The mixes included conventional, steel fiber, and regulated-set cement mixes with varying percentages of coarse aggregate and varying cement contents. Shooting conditions included a wide range of accelerator dosages, air pressures, MDR, temperature of nozzle water, different nozzle types, and total thickness shot.

Documentation of Results and Supplementary Studies

Rebound was also studied by many other supplementary measures. A high-speed stop action camera was used to look carefully at the details of each particle impacting and rebounding etc. Also, samples
of the dry mix, the material on the wall and the material in the rebound pile were collected and subjected to analysis for grain size, cement content, water content, etc. All rates, pressures, weights, and procedures were documented continually and in detail.

TEST RESULTS

General

The basic results are summarized in this section. The details are contained in the basic report (Parker, et al, 1975). The field test program was planned to make comparisons of various factors believed to affect rebound such as temperature, cement content, amount of coarse aggregate etc. No other factor exerted as great an influence on the rebound results than the thickness of the fresh shotcrete layer on the wall. Many comparative field rebound tests were conducted in a manner that direct comparisons should have been easy. Most of the tests were shot to a thickness of between 2-1/2 and 4 inches (6.3-10 cm), yet the thickness effect still created difficulties with the comparisons in terms of RAVE. A further complication was that the tests were conducted during the winter and, though they were done underground, the air temperatures were sometimes near freezing. Nevertheless, some tentative conclusions were made after very careful study to ensure the results were appropriate and these conclusions are described briefly below. It should be recognized that these comparative results are for a specific range of conditions and that the magnitudes of rebound and, except
for the thickness effect, perhaps even the trends between different parameters could change significantly for other conditions.

**Effect of Thickness on RRR and RAVE**

**Multiple Tarp Test.** Rebound for one conventional mix was collected in three separate tarps as shown in Fig. 2. The results are summarized in Table 2 and are presented graphically in Fig. 3. The ordinate of the bar graphs in Fig. 3 represents the Rebound Rate Ratio (RRR) calculated for each tarp.

**TABLE 2**

RESULTS OF THREE-TARP REBOUND TEST

<table>
<thead>
<tr>
<th>Tarp</th>
<th>Thickness at completion of collection on tarp in. (cm)</th>
<th>Weight of rebound on tarp lb (kg)</th>
<th>Rebound ratio RRR</th>
<th>Average rebound RAVE, %</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.3 (0.8)</td>
<td>121 (54.1)</td>
<td>.56</td>
<td>56%</td>
</tr>
<tr>
<td>2</td>
<td>2.5 (6.2)</td>
<td>72 (32.5)</td>
<td>.10</td>
<td>21.3%</td>
</tr>
<tr>
<td>3</td>
<td>4.2 (10.7)</td>
<td>82 (37.0)</td>
<td>.13</td>
<td>18.3%</td>
</tr>
</tbody>
</table>

It can be seen that the losses during the establishment of the cushion, 0.3 in. (0.76 cm) thick, were extremely high (RRR > 0.6). Once the initial critical thickness was established, the Rebound Rate Ratio decreased and stabilized at 0.10 to 0.13 for the remainder of shooting. The nozzleman had been instructed to shoot only to the initial critical thickness and it appears that he was correct in his estimate. During
The build-up of this initial critical thickness, the amount of rebound collected was 44 percent of the total material eventually collected during the shooting of the entire thickness. However, this initial critical thickness corresponded to only 7 percent of the total thickness shot.

The data in Fig. 3 represents one continuous test. If the rebound test had been stopped arbitrarily when the layer was 1 in. (2.5 cm) thick, an Average Rebound of 39 percent would have been reported. If the test would have been stopped when the layer was 2, 3, or 4 in. (5, 7.6, or 10 cm) thick, the Average Rebound values reported would have
been 25, 20, and 19 percent respectively. This rebound test is experimental proof that the average rebound as reported by industry may depend as much or more on the thickness shot as it depends upon the mix and shooting conditions.

**Thickness of Initial Critical Layer.** The sharp reduction in RRR after the initial critical thickness was established was confirmed in 6 separate multiple-tarp tests. When multiple-tarp tests were conducted, the nozzleman was instructed to shoot the first stage until the initial critical thickness had been established uniformly over the rebound test panel. The data permit an evaluation of the range of thicknesses the nozzleman shot as representative of the initial critical thickness. These data indicate a range from 0.1 to 0.4 in. (2.5 to 10.2 mm). The results of a high-speed photographic study of the operation tend to confirm that the critical thickness for these conditions was on the low end of this range.

**Experimental Evaluation of RAVE Versus Thickness.** Figure 4 is a plot of Average Rebound (RAVE) versus total thickness for all tests including single-tarp tests. All tests for which thickness was less than 1 in. (2.5 cm) resulted in Average Rebound (RAVE) greater than 45%; tests with thicknesses between 2 and 4 in. (5 and 10 cm) thick generally resulted in a RAVE value between 15 to 35 percent. A good correlation between RAVE and thickness is shown by the approximate curve
drawn through the test data. Data points generally stray no more than 5 percentage points from the curve.

It should be noted that the data shown in Fig. 4 were obtained for rebound tests on 27 different mixes shot under very different conditions. They include cement contents ranging from 7-1/2 to 10-1/2 bags per cubic yard (420 to 585 kg/m³), water-cement ratios ranging from .26 to .41, nozzle-water temperatures ranging from 45 to 120°F (7 to 48°C), variations in coarse aggregate, different nozzles, fibrous and
non-fibrous mixes. Yet, the final thickness of the in-place shotcrete overshadows the significance of any other variables.

Effect of Mix Design and Shooting Conditions

Cement Type, Cement Content, Accelerator Dosage, and of Steel Fibers. A new type of cement, Regulated-set cement, was compared against conventional Type 1 cement. The Regulated-set cement does not need accelerators to achieve a fast strength gain but sometimes needs to be shot with hot nozzle water to achieve a faster set. The comparative results were erratic, some mixes with Regulated-set cement had higher rebound, some had lower rebound. However, the lowest average rebound measured (RAVE = 12.2%) was a rich mix of Regulated-set cement shot with very hot water.

Minor changes in cement content of about 100 pounds per cubic yard (76 Kg/m³) did not change RAVE and it appeared that other conditions were more important. Meager data are believed to confirm the hypothesis that increased accelerator dosage should reduce rebound up to an optimum dosage. Above the optimum, increased dosage makes the shotcrete stiffen so fast that the fresh shotcrete is less receptive to embedment of incoming particles to the extent that rebound increases rather than decreases.

The presence of steel fibers in the mix did not seem to have an important effect on RAVE although some of the Phase 2 RRR values for fiber mixes were quite low. The effect of fiber on mixes is complicated.
It has been concluded from these and other tests that the mere presence of fibers in a mix does not affect rebound appreciably but if the mix or shooting conditions can be improved as a result of using fibers there is a chance that rebound can be reduced significantly.

**Water Content.** The effect of water content on rebound was only indirectly evaluated in these tests. It is believed that the mix and shooting conditions determine a fairly narrow range between too dry and too wet and the nozzleman must shoot within this range. He can, however, by adjusting the water content within this range reduce rebound significantly by shooting at the wettest stable consistency which is at the highest water content at which the shotcrete does not slump on the wall.

It should be noted that there is a difference between water content and consistency. High cement contents require a higher water content to obtain the same consistency. Consistency and not the absolute water content or water-cement ratio, is the important parameter for rebound, other conditions being equal. A wetter consistency generally results in lower rebound up to the wettest stable consistency. Shotcrete begins to slough above the wettest stable consistency, thus increasing the rebound.

**Temperature.** The low ambient temperatures had a significant effect on the results in several ways. The temperature of the cement, water, aggregate and accelerator was low enough that the normal accelerator dosages of 3% by weight of cement used in most tests was essentially
ineffective. On cold days a dosage of about 5% appeared to be close to the necessary dosage for early-strength gain. Yet the temperatures of materials and environment could not have been very important since similar mixes that were shot on various days when the air temperature ranged from freezing to 60°F (15.5°C) resulted in a measured RAVE that ranged only from 16 to 20 percent. It was concluded that low temperatures caused slightly higher rebound values but that the effect of material and environmental temperatures was not as great as other parameters.

On several tests, the nozzle water was heated to overcome cold temperatures or to evaluate the effect of nozzle water temperature. One special series was conducted using Regulated-set cement with water temperatures of 60, 80, 100, and 120°F (15.5, 26.6, 37.8, 48°C). Increasing the nozzle water temperature from 60 to 120°F (15.5 to 48°C) reduced the average rebound, RAVE, from 19.4 to 12.2%. Higher nozzle water temperatures increase the rate of hydration that begins once water comes in contact with the cement, thereby producing a more cohesive material in the shotcrete air stream. Up to some optimum value, increased nozzle water temperatures should reduce rebound. It is reasonable to assume that, if the water temperature is too high, the hydration process will be over-accelerated or become too active, thereby producing shotcrete that stiffens so fast that the material on the wall is not receptive to embedment of incoming material.
Nozzle Type. Two types of nozzles were tested. Most tests were shot with a conventional, straight-through type nozzle body with a short 18 in (7.2 cm) straight hose tip. Some mixes were shot with a homemade "long nozzle" consisting of the same nozzle body but with a 14 ft long (4.3 m) hose tip. No specific valid test results are available to compare the two nozzle types. However, observations of the airstream made during the shooting process and detailed studies of airstream pictures with a high-speed camera indicate much better mixing of ingredients and a more uniform mixture resulted when the long nozzle was used. Better mixing of the ingredients coming from the nozzle indicates an airstream consistency which sticks to the wall more readily and embeds incoming particles more easily, therefore, produces less rebound. In this respect, the long nozzle should tend to reduce the average percentage of rebound and produce a more homogeneous material in the wall. In fact, the long nozzle was found to be superior to the short nozzle in every way compared, including strength.

Type and Hardness of Wall. Mixes were shot against bare plywood panels, previously shotcreted surfaces, smooth rock walls and irregular rock walls. The results were inconclusive but it is not believed that the hardness of the wall has much effect on the average rebound (RAVE). It appeared that during Phase 1, harder surfaces made the particles rebound farther away. In theory, it should take longer to establish the initial critical thickness on a harder wall but no field data seemed to confirm this. It was observed, however, that, once the initial
critical thickness was established, the hardness of the wall had no
effect on rebound because during Phase 2, rebound is affected not by
the hardness of the wall but by the consistency of the fresh shotcrete
on the wall.

SIGNIFICANCE OF PREVIOUSLY-REPORTED REBOUND DATA

Average rebound has been shown to be so highly dependent upon the
thickness of the layer being shot that previously-reported rebound data
on coarse-aggregate shotcrete have limited or restricted value unless
they were properly documented. This does not mean that all previous
data are unreliable or useless. It merely implies that previously repor­
ted data may have an unknown bias due to the thickness effect and the
data must be evaluated carefully before being used. Naturally, data
on comparative studies of similar rebound tests with different condi­
tions of shooting are less likely to be prone to bias from this thick­
ness effect.

Very few results reported in the literature are documented with
the actual thickness shot during rebound tests. Most merely report
an average value of rebound; sometimes a specified thickness is given
or a wide range of thickness shot. Few reports give details such as
percentage of time shooting overhead, etc. The few reported values
of rebound that also have a corresponding thickness have been plotted in Fig. 5. Some of the reports have been confirmed by personal communications with the investigator to determine the details of the rebound tests.

Also shown in the figure is the range of RAVE values obtained from the tests on this project. This range should be expected to be lower than other results since the tests were conducted on regular vertical walls. The results from other projects often included some overhead shooting.
There is a great variety of conditions represented by the plotted results and considerable scatter may be expected. They include fine and coarse aggregate, wet-and dry-mix, wall- and overhead-shooting, etc. Nevertheless, there is a general tendency for this documented field data to show a decrease of RAVE with thickness that can be seen in the figure.

The general tendencies for rebound are illustrated schematically in Figure 6. Average rebound should follow the general RAVE-versus-thickness type curve but the specific location of the curve depends upon the conditions. Generally, the curves should shift upward for the conditions shown in the figure. If sufficient well-documented data becomes available in the future, bands or envelopes might be determined showing typical ranges for specific shooting conditions. For instance, a typical range for coarse aggregate dry-mix shotcrete might be differentiated from a band representing coarse-aggregate wet-mix shotcrete. Separate bands might be differentiated for fine versus coarse aggregate. The data are too speculative and too sparse to permit such an interpretation at this time, but there is promise in the future if a standard method of reporting rebound data can be implemented.

PROPOSED STANDARD REBOUND TEST

Because of the dominant effect of the final layer thickness on the measured value of Average Rebound, a standard rebound test has been proposed in order that the relative influence of parameters affecting
rebound can be investigated. Such a test can be used during preconstruction testing to evaluate the effect of variations in mix or shooting conditions on rebound. In addition, it can be used for quality control and proficiency checks on the crew during construction. If adopted throughout the industry, such a standard rebound test would permit correlation of rebound information between jobs. Ultimately, data would be collected that could be used to determine typical ranges of RAVE and RRR values that might be expected with each of the various types of shotcrete (wet-mix, dry-mix, coarse or fine aggregate, etc.). Such a standard test should include a standard thickness to which rebound tests should be shot and reported.
A thickness of 4 in (10 cm) is the recommended thickness for comparative evaluations of coarse-aggregate shotcrete. This is a metric equivalent of a commonly used thickness of shotcrete linings used for temporary support. More importantly, it is a thickness at which RAVE is not changing rapidly since 4 in. (10 cm) is out on the near-horizontal portion of the RAVE curve as illustrated in Fig. 4. There is too much chance for error if rebound collection stops when the slope of the curve is still quite steep. Shooting all tests to this standard thickness should be adequate for rebound tests for evaluations of mix design or shooting conditions on rebound or for publishing results. Though the rebound behavior for wet-mix shotcrete may be different, rebound tests on wet-mix shotcrete should also be shot to the standard thickness to permit correlations with dry-mix shotcrete.

Based upon the experimental evidence collected in this study, it is believed that once the initial critical thickness is established (Phase 1), RRR during subsequent shooting (Phase 2) is approximately constant. This observation will be used to propose the following simple method to determine RRR for both Phase 1 and Phase 2 and to determine RAVE for the final thickness. With this information, a contractor can determine if changes in the mix design or shooting conditions will reduce the losses during Phase 1 or Phase 2 or both. The effects of even small changes in mix or shooting conditions should be able to be detected in the RRR values. Very little extra work is required to separate the losses during Phase 1 from those during Phase 2 since both proposed tests can be done in one brief shooting.
Details of the test with lists of equipment and dimensions of boards and tarps are given by Mahar, Parker, Wuellner (1975). The simple, two-part standard rebound test consists of shooting two special plywood panels without interruption. The second test panel is optional if RRR is not desired. The two test boards are separated sufficiently with divider panels so that rebound from each board can be collected independently on separate tarps. Wing walls inclined at an angle of $45^\circ$ are provided on the top and sides of each test board. The first board to be shot has wing walls extending out to the standard thickness of 4 in (10 cm). The board should be shot so that the surface of shotcrete is as uniform as possible at a thickness of 4 inches. The weight of the rebound on the tarps from this test is RSUM. After the rebound is weighed, the tarps should be replaced and the shotcrete on the test panel scraped off onto the tarps. Usually it falls off on impact if the board is pushed over on to the tarps. The weight of this shotcrete on the board is YSUM. Since $SSUM = RSUM + YSUM$, everything is known to calculate average rebound, RAVE. No preweighing of ingredients or measurements of MDR are necessary although they should be determined as part of documentation for the tests. Since $RAVE = RSUM/SSUM$, the average rebound can be calculated by the formula:

$$Rave\ For\ Standard\ 4\ Inch\ Thickness \quad = \quad \frac{RSUM}{RSUM + YSUM}$$
The optional rebound test is shot immediately after the first board by quickly directing the nozzle to the second test board without interrupting shooting. The wing walls on this board extend out only 1/2 in. (1 cm.). As soon as the second board is uniformly covered to a thickness of 1/2 inch (usually in less than a minute), the nozzle is directed away and the test is over.

Since the rebound from the second test board was collected separately and on a different tarp from the first, the weight of the rebound on the second tarp is $RSUM_1$. The weight of shotcrete on the boards is $YSUM_1$ and it can be measured by the same procedure as with the first board. The rebound value calculated from this test is the average rebound for a 1/2 inch (1 cm) thick layer but it approximates the average RRR for Phase 1.

$$\text{Average RRR for Phase 1} = \frac{RSUM_1}{RSUM_1 + YSUM_1}$$

Assuming that RRR is more or less constant during Phase 2, the following calculation gives an approximation of RRR during Phase 2.

$$\text{RRR for Phase 2} = \frac{RSUM - RSUM_1}{(RSUM + YSUM) - (RSUM_1 + YSUM_1)} = \frac{RSUM - RSUM_1}{SSUM - SSUM_1}$$
It is very important that procedures be standardized and that each test be well documented with such measurements as MDR, accelerator dosage, mix design, shotcrete equipment, temperatures, etc. The standardized procedures and suggested documentation are given in Mahar, Parker, Wuellner (1975).

These standard rebound tests are primarily useful in comparisons as is the case with any standard test such as ASTM tests. By use of these tests, comparisons between projects can be made reliably. However, when the actual project losses are desired, the project conditions must be simulated. The standard test can be modified to estimate actual project losses more accurately, a test board could be set up overhead so that rebound losses that result from shooting the crown can be estimated. If mesh is used, it should be included in the rebound test.

Since the average rebound curve of dry-mix, coarse aggregate shotcrete changes with thickness, a better estimate of project rebound losses can be made by conducting the tests to the same thickness as placed in an average lift used during routine production shooting. (Since there are Phase 1 losses at the beginning of each lift, it is the thickness of each separate layer that determines the rebound.) Similar tests could be made on actual rock surfaces but a specific predetermined area should be shot to a specific thickness that is representative of the lift thickness or the results will be invalid.
Any volumetric term such as cubic yard or cubic meter has a limited or restricted usefulness in tunnel shotcrete work because material is usually batched by weight, and overbreak and rebound losses must be considered. Most tunnel specifications require a minimum thickness that must be placed on the wall. This thickness, perhaps modified by an average amount of overbreak, over a specified area of the tunnel is the average volume that must be placed. The volume can be converted to a weight in-place by multiplying by the unit weight of the material in place. The relationships between the thickness and amount of material which must be shot are derived in Parker, et al (1975). The weight of material that must be shot exceeds the in-place weight (or equivalent volume) by the parameter Overshoot Factor, OSF, defined as follows:

\[
\text{Overshoot Factor} = \text{OSF} = \frac{1}{1 - \text{RAVE}}
\]

It is important to recognize that the RAVE should be measured or estimated for a specific thickness that includes the estimated amount of overbreak and any tendency to shoot thicker or thinner than specified. Kobler (1966) states that 1.6 to 1.7 cu yd (1.2 to 1.3 cu m) of dry mix is required to produce 1 cu yd (0.8 cu m) of coarse aggregate
shotcrete in-place underground. His "Overshoot Factors" would be 1.6 to 1.7. Hendricks (1969) reports a factor of 1.5 for dry-mix coarse aggregate shotcrete.

Any numerical economic evaluation of rebound should be based upon RAVE data adjusted by the Overshoot Factor; interpretations based on unadjusted numerical values of RAVE will give the wrong impression unless converted to actual weight shot or adjusted by the Overshoot Factor.

CONCLUSIONS

Rebound has great economic importance and it deserves much more attention by owners, engineers, and contractors. Technical and economic aspects of rebound can be viewed from an entirely new perspective. A better understanding of the effect of various parameters was obtained through the field tests and analyses. The single parameter that had the greatest and most significant effect on the test value of rebound in this study was the total thickness shot. The effects of the high rebound losses that occur when first shooting against a hard surface are far more pronounced and more far-reaching than previously believed. Thin linings have a high average rebound; average rebound reduces with increased thickness shot. These effects can even make a rebound test inapplicable to the very project for which it was intended. Also,
previously reported values of rebound have limited value for correlation with other tests unless documented by the thickness shot. A proposed standard rebound test, incorporating a standard thickness, should be conducted if comparisons are to be made between projects or if rebound is to be reported. If actual project losses are desired, the test must simulate actual production conditions. The test can be modified to simulate conditions such as mesh, overhead shooting etc. Most important, however, is for the test to be conducted to the same thickness as routinely placed in an average lift. Only then will the test be representative of project conditions.

ACKNOWLEDGEMENTS

This research was supported by the Federal Railroad Administration, U.S. Department of Transportation through Contract No. DOT FR 30022. The study was part of a much larger project being conducted by the Civil Engineering Department of the University of Illinois at Urbana-Champaign for the sponsor under the overall direction of Dr. S.L. Paul. The field program was made possible by the special efforts and interest shown by Mr. Frank L. Lynch, Washington Metropolitan Area Transit Authority, Mr. J.S. Bhore, Granite Construction Company, and Dr. E.J. Cording, University of Illinois. Mr. James W. Mahar enriched the study through his parallel efforts on other shotcrete research for this contract and his direct contributions both in the field and during subsequent phases of the study. Mr. Jan A. Blanck supervised all the field work for A.A.