Accelerators are commonly used in both the wet and dry process Shotcrete to impart accelerated setting and accelerated strength gain.

It is not the purpose of this paper to discuss why accelerated strength gain and setting time are of advantage in ground support, but rather to explain what these accelerators are and how they perform.

Shotcrete accelerators are composed of either soluble inorganic aluminates, carbonates, silicates, or combinations of these chemicals or proprietary organic chemicals. These four classes of chemicals act differently on the cement/water reaction.

The early reactions of Portland Cement and water may be described schematically as shown in Figure 1 and 2. Reaction of the tricalcium aluminate and water, as shown in Figure 1, can be considered to take place usually within approximately two hours. The rate of reaction of the tricalcium aluminate is controlled or retarded by the formation of ettringite which precipitates on the tricalcium aluminate thereby inhibiting the rate of reaction.

The reaction of tricalcium silicate (Figure 2) is also inhibited by the precipitation of lime and hydrates. It may be considered that the rate of early stiffening is controlled by the tricalcium aluminate, and the rate of early strength gain by the reaction of the tricalcium aluminate.

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Fig. 1. Schematic Representation of the Reaction of Tricalcium Aluminate and Water (Reaction Mechanics of Organic Admixtures with Hydrating Cement Compounds, J.F. Young)

Fig. 2. Schematic Representation of the Reaction of Tricalcium Silicate and Water (Reaction Mechanics of Organic Admixtures with Hydrating Cement Compounds, J.F. Young)
Action of Accelerators and the Cement/Water Reaction

The soluble aluminates -- when used in Shotcrete, or more correctly with Portland Cement -- will offset the balance shown in Figure 1. This occurs because the soluble aluminates combine with the gypsum, preventing the formation of ettringite around the cement grain. This will allow the tricalcium aluminate to flash set, providing the early stiffening desired in many Shotcrete applications.

The soluble carbonates mainly influence the reaction of the tricalcium silicate and water. The soluble carbonates will accelerate early strength gain but tend to have little effect on initial set. Actually, the soluble carbonates tend to retard the effect of the soluble aluminates on initial set. Since proportions of C₃A and C₃S will vary depending on the source of the cement, the percentage of aluminate and carbonate in the accelerator should be varied to suit the particular cement composition. Figure 3 illustrates the effect on setting time and strength of carbonates and aluminates.

Generally speaking, the formulator will manufacture a Shotcrete accelerator to fit the average cement composition as shown in Figure 4. However, this is an average, and the cement used in a particular mixture may vary tremendously from the average, as shown in Figure 5. This is an excellent cement, but the compound composition is such that a Shotcrete accelerator which is compatible with an average cement would be incompatible with this cement. Therefore, compatibility tests should be made before the job starts with the cement to be used. Both the carbonates and aluminates will decrease ultimate strength of Portland-Cement mixtures.
Fig. 3. Effect of Carbonates and Aluminates on the Setting Time of Shotcrete

Fig. 4. Average Compound Composition of Present-Day Portland Cement (Technology of Cement and Concrete, Blanks and Kennedy)

Fig. 5. Compound Composition of Cement Used at Morie Colorado Project
Fig. 6. Setting Time of Shotcretes
The soluble silicates induce quick-setting by precipitating as calcium silicate. Although inducing very early set, the silicates will reduce ultimate strengths significantly by their interference on the cement/water reaction.

The organic accelerators accelerate the cement/water reaction by solubilizing the lime and ettringite which normally precipitates on the cement constituents thereby allowing the cement/water reaction to proceed unretarded. The organic accelerators generally produce no strength penalty, as they do not change the basic cement/water reaction. They only allow the reaction to proceed at an uninhibited rate.

Figure 6 shows the typical setting time characteristics of Shotcrete accelerated with a conventional carbonate/aluminate accelerator and with an organic accelerator. Note that the conventional accelerator induces early set, but strength gain after set is slow. The organic accelerator induces early set and also induces accelerated early strength. Figure 7 indicates the typical 28-day strengths obtained with conventional and organic accelerators. The strength penalty imparted by the carbonate/aluminate accelerators is very typical, and can be expected when using these accelerators.

The preceding data refers mainly to the dry-process Shotcrete. With wet-process Shotcrete, premature stiffening can be induced by the accelerators mentioned, but accelerated early strength is generally not obtained due to the fact that the cement constituents have already reacted with water at the time the accelerators are added. The reaction being partially complete, it cannot be accelerated significantly.
Fig. 7. Compressive Strength of Shotcrete Cubes

Compressive Strength Shotcrete Cubes
Testwell Laboratories
Contractor: Gunite Masonry
Cement: Atlas Type I (Northampton)
3-inch sawed cubes
Age: 29 days
Each test average of 7-12 cubes
1. Plain
2. 1/3 gal organic accelerator
3. 1/2 gal organic accelerator
4. 3/4 gal organic accelerator
5. 3% conventional accelerator
Three Factors Influencing the Performance of Shotcrete Accelerators

Among the numerous outside forces affecting accelerator performance, three are of particular significance:

1. **Prehydration** - If the cement constituents react with water prior to the addition of the accelerator or, for that matter, prior to the addition of any admixture, the performance of the admixtures will be affected significantly. Both setting time and strength gain will be retarded by prehydration. Figure 8 shows the effect of delayed addition of the admixture (or prehydration of cement) on setting time. Note that setting time will be increased as the delay time is increased.

   If wet aggregate is left to lie in contact with the cement, the cement will start to hydrate. Any cement which reacts with the water will not be affected by the accelerator. This delay time will be significant even if it is as short as 5 minutes. Where fast set is desired, the cement should be kept dry until immediately before use. One cannot expect to accelerate a reaction which has already been started or completed.

   Figure 9 illustrates the effect of prehydration on 1-day and 28-day compressive strengths. Note that even if only 0.75% of the cement has reacted, strength will be affected both at early ages and at later ages. In this test series, strength dropped from 5,000 psi to 3,000 psi due to this small quantity of hydrated cement. More important, this strength penalty was also evident at one day, a strength/age relationship important for underground support.

   In the wet process, prehydration takes place in all instances, and strength and setting time will be affected accordingly.
Fig. 8. Effect of Delay Time of Addition of an Admixture (prehydration of cement) (Reaction Mechanics of Organic Admixtures with Hydrating Cement Compounds, J.F. Young)

Fig. 9. Effect of Prehydration on Compressive Strength (Prehydration and Strength Development of Portland Cement, Theisen K. and Johansen V., The Ceramic Bulletin, Vol.5A/No.9, 1975)
Fig. 10. Effect of Temperature on the Setting Time of 3 Brands of Cement (Properties and Uses of Initially Retarded Concrete, Tuthill L. and Cordon W., Journal of the American Concrete Institute, Vol. 27/No. 3, November, 1955)
2. Temperature - Temperature will affect setting time and strength development of all cement mixtures. Figure 10 illustrates the effect of temperature on setting time as measured by penetration resistance. Note that the difference in setting time between 50°F and 100°F is a factor of 5. If these mixtures were accelerated with the same quantity of accelerator, this relationship would still hold true.

The affect of temperature on setting time may give the impression that an accelerator is not performing. In reality, however, it is the change in temperature that is actually controlling the setting time.

3. Cement - Cements from different sources will exhibit different setting times. See Figure 11. A given accelerator, at a given proportion, may accelerate the set of the Shotcrete 50%. However, a change in cement to a slow-setting type may offset the acceleration induced by the accelerator.

Cements will vary in their strength-producing qualities. Figure 12 indicates the performance of 5 different cements, sampled at 2-week intervals. Note the great variations in strength produced by a given cement. The variation in strength will be present whether or not an accelerator were used.

Accelerators and Rebound

It has been reported that rebound is increased by the use of accelerators. And it also has been reported that rebound has been decreased by the use of accelerators. Where very careful measurements are made, and the Shotcretes have identical compositions, the quantity of rebound is not changed by the use of accelerators.
Fig. 11. Setting Times of Cement from Different Sources
(Early-Setting Behavior of Concrete, Loughborough, M.T., Ontario Hydro Research Quarterly, Vol. 15, No. 4, 1963)
Fig. 12. Relative Strength Levels for Bi-weekly Samples of Cement from Individual Sources (Variations in Portland Cement, Walter, Stanton, and Bloem Delmar, Proceedings, Vol. 58, 1958, American Society for Testing and Materials)
There is a tendency when using accelerated Shotcrete to shoot with less than the optimum cement/water ratio. In such instances, higher rebound will be reported. But this higher rebound is caused by a dryer mixture and not the admixture per se.

Conclusion

Shotcrete accelerators are available to accelerate setting time and strength gain. In general the inorganic accelerators will reduce ultimate strength and the organic types will not effect ultimate strength. These accelerators are cement-sensitive therefore they should be pretested with the cement to be used before the operation begins. Accelerators can be formulated to be compatible with most of the cements available on the world market.