Air Content in Shotcrete: As-Shot Versus As-Batched

By Lihe (John) Zhang

Air-entraining admixtures are added to shotcrete primarily for durability considerations. Freezing-and-thawing resistance is improved by air entrainment.[1-3] It is widely recognized in the shotcrete industry that the air content of the as-batched shotcrete will drop during the shooting process. This is due to the fact that the shotcrete process tends to "knock out" air from the mixture and thus reduce the air content of the in-place shotcrete. The air content in the in-place shotcrete is typically below 6%, regardless of how high the as-batched air content was before shooting. Testing for air content in the hardened shotcrete can be conducted by air voids analysis using the ASTM C457 test procedure. This test is time-consuming and expensive, however, and is thus not often used as a quality control test. Thus, the challenge is to establish the basic criteria for the air content in the in-place shotcrete. This article discusses the requirements for the air content in the shotcrete mixture, both before and after being applied, and then tries to answer a simple question: Do we need to test the air content both before and after shooting?

Measuring the Air Content

An air meter is used to measure the air content of the plastic shotcrete or concrete. Air content measured at the point of discharge from the truck or at the end of the pump hose is referred to as **as-batched air content** (Fig. 1). Air content measured by shooting directly into the air meter base or shot against a wall into a wheelbarrow or even into a basket and then scraped out to fill the air meter is called **as-shot air content**. Sometimes, the terminology of "air content at nozzle" is also used (erroneously) for the as-shot air content.

When an accelerator is used, it can be very difficult to measure the as-shot air content. Shotcrete can reach the initial set in as quickly as 5 minutes or less, and it may not be possible to scrape and fill up the air meter base and conduct the air content test while the shotcrete is still plastic. It is, however, possible to shoot into the air meter base and fill it up, then trim the surface and test for air content within a few minutes. After the test, shotcrete will soon set inside the air meter if it is not cleaned immediately. Therefore, only very experienced testing technicians can handle this type of air content testing without damaging the air meter.

Shotcrete Mixture Design Considerations

A typical air-entrained shotcrete mixture design will have an as-batched air content of 7 to 10% and an as-shot air content of about 3 to 5%. Thus, it is important that the yield calculation in the mixture design use the as-shot air content and not the as-batched air content. Otherwise, the shotcrete supplied will under-yield—that is, the shotcrete contractor will effectively get less material than ordered.

High As-Batched Air Content and Slump-Killer Effect

It is well-recognized in the shotcrete industry that high initial air content in the as-batched shotcrete will increase slump.[4] Considering that the cost of an air-entraining agent (AEA) is much lower than that of high-range water-reducing admixtures, it is typically more economical to add more AEA to increase the slump of the mixture while reducing—but not replacing—the quantity of high-range water-reducing admixtures. As the shotcrete impacts on the wall, about half of the air content is lost and the slump on the wall goes down instantaneously because slump is directly related to air content. This so-called "slump-killer" effect is very beneficial to the shotcrete process. Shotcrete has high slump at discharge into the pump, which makes it easier to pump without blockages and facilitates a good uniform accelerator addition at the nozzle. The instantaneous loss of slump on the wall is good for improved adhesion and thickness of shotcrete buildup without sagging and sloughing.

In some situations, however, such as certain underground shotcrete applications, the "slump-

killer" effect has to be used with caution. In some underground mines or tunnels, shotcrete is supplied to an underground remixer unit through a vertical drop pipe, which can range in length from a few hundred meters to a few thousand meters. The impact at the bottom of the drop pipe tends to knock out about half of the air content from the mixture. This results in the "slump-killer" effect taking place at the wrong location, resulting in too stiff (low slump) a mixture in the remixer unit. Therefore, when a drop pipe is used, it is not recommended to add an AEA to the mixture.

It is also found that in underground shotcrete applications, if the transmixer transportation and delivery is a long-haul process, this might cause a substantial increase in air content when the shotcrete arrives at the application site. Air content could increase to up to 14% or even higher. This will make it difficult to pump the "spongy" shotcrete. It is the author's experience that removal of the air-entraining admixture from the shotcrete mixture design is desirable for underground shotcrete applications. Admixture suppliers have products that can reduce the microair introduced by the AEA, but it is more economical not to use an AEA. Actually, the data in the following project examples show that even without an AEA—by adding a high-range water-reducing admixture **only**—the air content can increase up to 4 to 6% during transportation.

Project Example 1: Testing Air Content during Shotcrete Operations in an Aboveground Application

In one trial mix shooting project, we examined the combined effects of a high-range water-reducing admixture, hydration control admixture, air-entraining admixture, and accelerator on the air content of wet-mix shotcrete. The shotcrete mixture design had an as-batched air content of 7 to 10% and an as-shot air content of 3 to 5%. The as-batched air content was tested at the point of discharge from the concrete truck and at the end of the pump hose. The as-shot air content was tested by shooting into the air meter base and shooting onto a vertical wall made with plywood. It was then scraped off to fill the air meter. The results are listed in Table 1.

When an AEA was added, the as-batched air content went up to 18%. The test results show that the air content at the end of the pump hose is only slightly lower than the air content at the discharge from the truck.

The as-shot air content ranges from 2.5 to 3.1% for the air content tested by shooting directly into the air meter base and ranges from 4.0 to 4.5% when tested by shooting onto a vertical wall and then scraped off to fill the air meter base. It should be noted that when an AEA was used, the air content at the pump was as high as 18%. The as-shot content was 5% when shooting into the air meter base and 5.4% when shooting to the wall and tested in the air meter. This shows that even the high as-batched air content results in less than 5.5% as-shot air content.

When a nonalkali accelerator is added at 8% by mass of cement, the air content does not vary greatly from mixtures without an accelerator. It should also be noted that the addition of a hydration control admixture does not affect either the as-batched or as-shot air content in the non-air-entrained shotcrete mixtures.

Project Example 2: Testing Air Content for an Underground Shotcrete Application

For underground applications, shotcrete is agitated in a transmixer during transportation. With a hydration control admixture, this process

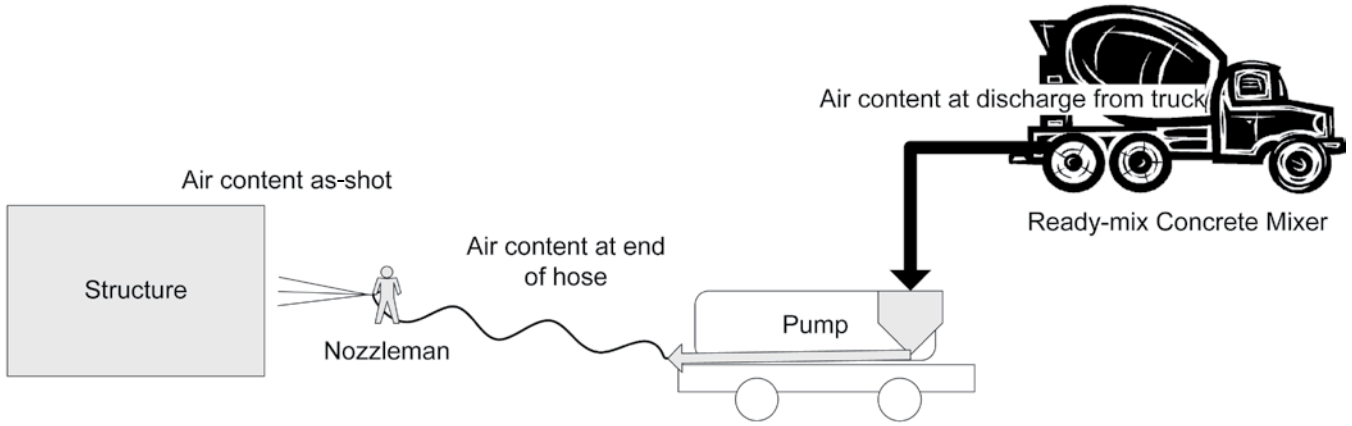

Fig. 1: Sketch of shotcrete process and air content measurement

Table 1: As-Batched Versus As-Shot Air Content for a Trial Shotcrete Project

Material	Trial 1	Trial 2	Trial 3	Trial 4	Trial 5
Water, L/m³ (gal./yd³)	185 (37)	185 (37)	185 (37)	185 (37)	185 (37)
HRWRA, ml	Used as per supplier's recommendation for 175 mm (6.9 in.) slump				
Hydration control admixture, ml	Added to extend set time to 4 hours	None	Added to extend set time to 4 hours	None	None
Air-entraining admixture, ml	None	None	None	Added	None
Accelerator, ml	8% by mass of cement		None	None	None
Slump, mm (in.) at truck	140 (5.5)	90 (3.5)	175 (6.9)	175 (6.9)	220 (8.7)
Slump, mm (in.) at pump hose (no compressed air)	125 (4.9)	75 (3.0)	145 (5.7)	125 (4.9)	220 (8.7)
Air content: before shooting, at truck, %	5.2	5.5	8.0	18.0	9.0
Air content: before shooting, at pump hose discharge, %	4.5	4.6	Not available	18.0	8.5
Air content: after shooting into air meter, %	2.7	3.0	2.5	5.0	3.1
After shooting onto vertical wall, %	4.2	4.0	Not available	5.4	4.5

could last for as long as 72 hours. The air content was tested at discharge from the truck, discharge from the transmixer, and as shot by shooting into the air meter base. Figure 2 shows a sketch of the underground wet-mix shotcrete production, delivery, and application.

Table 2 lists the test results for the as-batched and as-shot air content. It shows that when an AEA is added, the as-batched air content ranges from 9.3 to 12%. After shooting, the as-shot air content ranges from 3.4 to 5.3%. This shows that the as-shot air content is further reduced to less than 5.5%. When no AEA is added, the as-batched air content ranges from 4.1 to 4.3% and the as-shot air content ranges from 1.3 to 3.8%. When a nonalkali accelerator is added at dosages ranging from 4, 6, and 8% by mass of cement, this does not change the as-shot air content significantly.

During the underground shotcrete application, it was noted that when shotcrete was delivered by a transmixer with agitated rotation (for example, 7 rpm agitation for over 2 hours), the air content increased from 11 to 14.5%. This high air content was a concern for pumping, as discussed in the high as-batched air content and slump-killer effect section. Therefore, it is recommended that when long-distance hauling and transportation in a transmixer is required, an AEA should not be used.

Discussion

The two studies reported show that:

1. The as-shot air content is always below 5.5%, regardless of the as-batched air content. Due to the high-velocity impact caused by the shotcreting process, air is driven out of the in-place shotcrete. It should be noted, however, that when an AEA is added, the as-shot air content is always higher than the as-shot air content in a mixture made without an AEA.
2. The as-shot air content tested from the materials scraped from the wall is typically about 1.0 to 1.5% higher than the air content tested from shooting and filling up the air meter base.
3. The use of high as-batched air content with the associated "slump-killer" effect is beneficial to shotcrete pumping and shooting. For underground applications, however, a high as-batched air content might cause pumping problems and the "slump-killer" effect might occur in the wrong place (for example, when a drop line is used). Therefore, it is not recommended to add an AEA for underground appli-

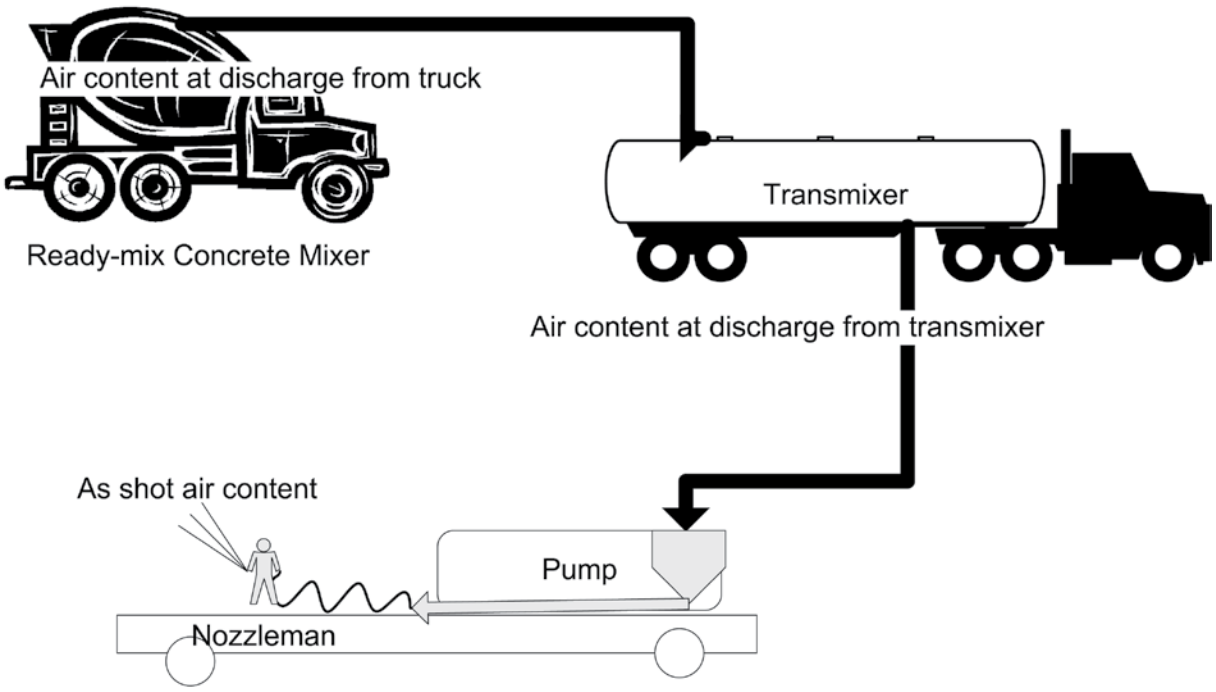

Fig. 2: Sketch of underground shotcrete transportation and application

Table 2: As-Batched Versus As-Shot Air Content for an Underground Shotcrete Project

Material	1	2	3	4	5	6	7	8	9
Water, L/m³ (gal./yd³)	185 (37)	185 (37)	185 (37)	185 (37)	185 (37)	185 (37)	185 (37)	185 (37)	185 (37)
HRWRA, L/m³ (gal./yd³)	1.0 (0.2)	1.0 (0.2)	1.0 (0.2)	1.0 (0.2)	1.0 (0.2)	1.0 (0.2)	1.0 (0.2)	1.0 (0.2)	1.0 (0.2)
Hydration control admixture, L/m³ (gal./yd³)	1.5 (0.3)	1.5 (0.3)	1.5 (0.3)	4.0 (0.81)	4.0 (0.81)	4.0 (0.81)	4.0 (0.81)	4.0 (0.81)	4.0 (0.81)
Air-entraining admixture, L/m³ (gal./yd³)	2 (0.4)	2 (0.4)	2 (0.4)	None					
Accelerator, 0%, 4%, 6% and 8% (by mass of cement)	6	6	6	0	4	6	8	4	6
Slump, mm (in.) at truck	150 (6.0)	275 (10.9)	175 (6.9)	225 (8.9)	225 (8.9)	225 (8.9)	225 (8.9)	125 (4.9)	125 (4.9)
Air content: before shooting, at truck, %	12	11	9.3	4.1	4.1	4.1	4.1	4.3	4.3
Air content: before shooting, at transmixer, %	—	14.5	—	—	—	—	—	—	—
Air content: after shooting to air meter, %	3.4	4.5	5.3	3.0	1.6	1.3	2.3	3.8	3.8

cation, unless there is special consideration (for example, where freezing-and-thawing conditions prevail).

4. The results of the as-batched air content tested at discharge from the truck are very close to the air content tested at the end of the pump hose (before shotcreting). Therefore, it is recommended that the as-batched air content be tested **only** at the point of discharge from the truck.
5. Certain brands of high-range water-reducing admixtures can increase the air content. Depending on the dosage of high-range water-

reducing admixture being added, the as-batched air content can increase by up to 6% or even higher without any AEA being added to the mixture.

6. The addition of a hydration-controlling admixture does not appear to have any significant effect on air content.

Do We Need to Test As-Shot Air Content?

As with conventional concrete, the air content of the as-batched shotcrete at the point of discharge from the truck should be tested as part of the regular quality control operations. In addition, given that a considerable amount of air is "knocked out" of the mixture during the shooting process, it is recommended that for any given mixture and supply/application scenario, a correlation be established between the as-batched and as-shot air contents. If testing shows this correlation to be consistent, testing of the as-shot air contents need only be conducted if there is a change in any of the shotcrete ingredients or proportions or a change in the supply/transportation/application methods or duration.

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