WHY IS RHEOLOGY IMPORTANT FOR SHOTCRETE AND HOW IT CAN BE IMPROVED

by
Ezgi Yurdakul, PhD

Better Concrete Conference
Ames, IA

What is shotcrete?

Shotcrete (aka sprayed concrete) is **concrete** placed by a high velocity pneumatic projection from a nozzle.

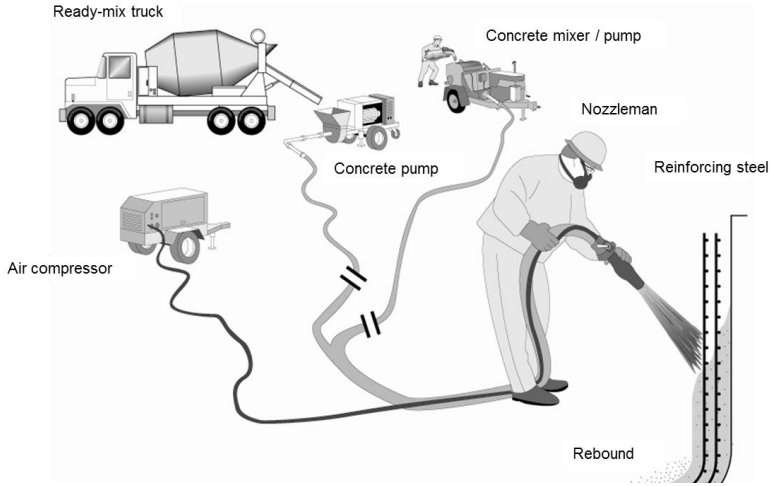
There are two types of process:

- **Dry-mix process:** The dry material is conveyed through a hose in an air stream at high velocity. Water is added at the nozzle to produce a plastic material which is compacted by impact on the receiving surface.

- **Wet-mix process:** Wet-mix is shotcrete in which the ingredients, including water, are mixed before introduction into the delivery hose.

Advantages of shotcrete

- Used for mining and tunneling applications for both temporary and permanent support
- Provides high early strength
- Increases safety of underground opening
- Flexibility to reach areas where ready-mix trucks can't get in



Manual spraying

Robotic-arm spraying

What does the industry want to have?

The ideal mix should have the following characteristics:

- Optimum flowability and viscosity to balance pumpability and sprayability
- Very high early strength
- High bond strength
- Low rebound rate
- Low sagging
- High durability

Rheology of shotcrete

Wet-mix shotcrete requires a **complex and conflicting rheological performance** to satisfy both pumpability and sprayability needs

Pumpability

- High flowability
- High cohesion (to prevent segregation under pressure)

Sprayability

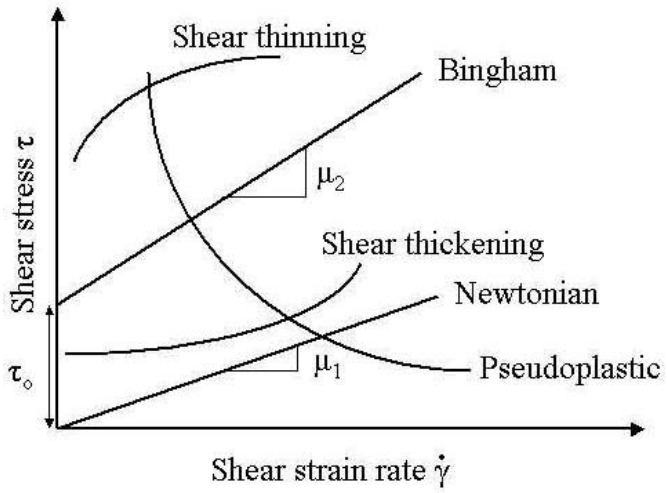
- Low flowability (to prevent sagging and increase build-up thickness)
- Moderate plasticity (to aid with better dispersion of accelerator, allow proper compaction, and reduce rebound so the incoming material hits to a soft substrate)
- High cohesion (so material sticks to itself and provide resistance against sliding under its own weight)
- High stickiness (so material sticks to the sprayed surface, increases bond, and prevents fall outs)

When pumpability increases, sprayability decreases

Limitations of slump test

The demand on the rheological behavior of shotcrete is too complicated to be oversimplified by judging based on slump test.

≠



It is possible to have two mixes with the **exact same slump** values but with **completely different rheological properties** as a result of different cementitious materials and the advancements in chemical admixture technology.

Desired rheological characteristics

Shotcrete must be as plastic as possible so that the sprayed aggregates can be embedded in the fresh concrete[1]. Therefore, although aggregates are the ones that rebounds, paste rheology is the factor that determines the rebound rate.

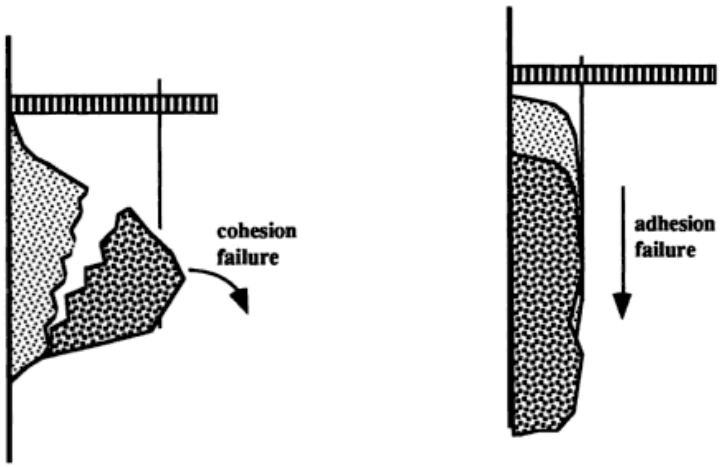
[1]Pfeuffer, M., and Kusterle, W. (2001). "Rheology and rebound behaviour of dry-mix shotcrete." Cement and Concrete Research, Vol. 31, pp. 1619–1625.

Rheology required for sprayability

- Sprayability is the efficiency of a mix at sticking to the applied surface (**adhesion**) and to itself (**cohesion**).

- Rebound occurs as a result of the larger aggregate particles segregating from the mix after hitting the receiving surface at high velocities and subsequently bouncing off.

- When a **soft cushion like cement paste is formed to encapsulate aggregates**, the rebound rate becomes lower in the subsequent layers.



Rheology required for rebound reduction

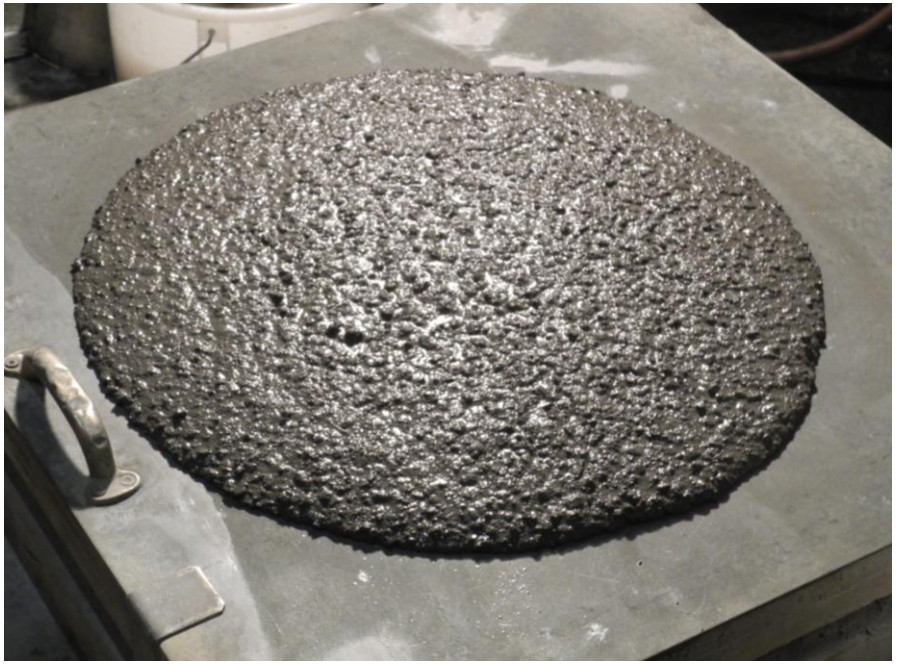
The quality of paste is important for evaluating the rebound:

- **Stickiness:** adhesion to substrate surface that allow large build-up thickness
- **Cohesiveness:** adhesion to itself to resist against the segregation of the mix which is critical for shotcrete
- **Yield stress and viscosity:** essential to resist against sagging on vertical walls

Rheology required for pumpability

Pumpability is the stability and mobility of a mix under pressure

Highly flowable mixes are prone to sagging if they do not possess a certain degree of **viscosity and yield strength** which helps material to resist the effect of gravity.



Rheology required for build-up thickness

“Sticky” mixes are desirable for the shotcrete process as they allow larger build-up thicknesses on walls and overhead applications.

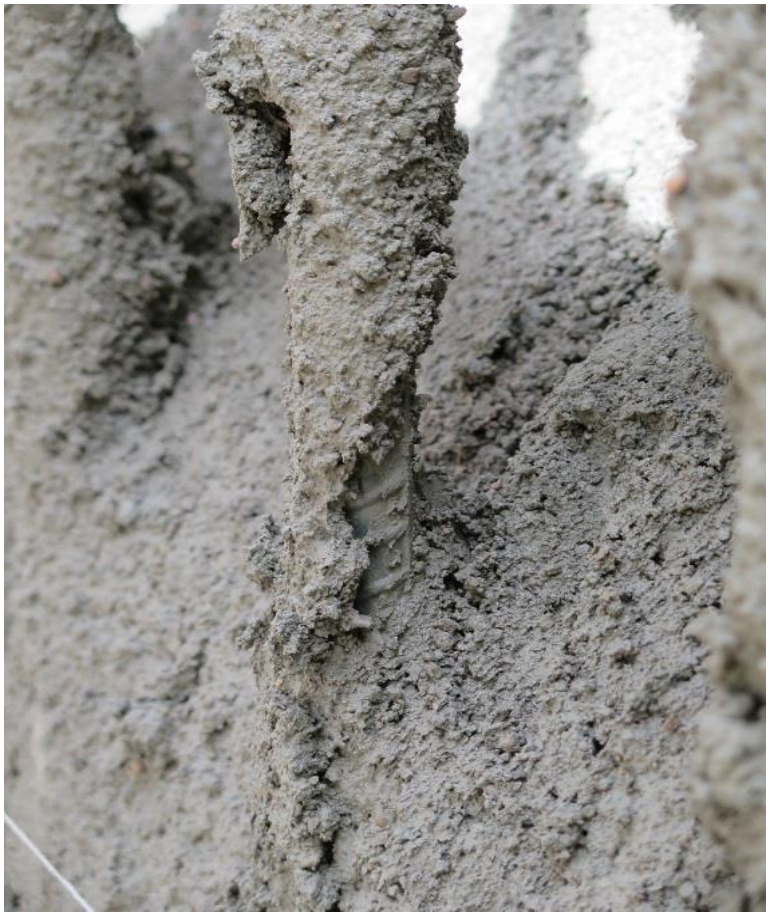
“Stickiness” also contributes to enhancing:

- ✓ Safety
- ✓ Productivity
- ✓ Cost-efficiency

Rheology required for consolidation

If mixes have a lack of cohesion and are not fluid enough, voids will occur within the shadow areas behind the reinforcement

Poor consolidation causes poor coating of the rebar and high porosity of the concrete causing a **reduction in strength and durability**.



How is rheology of shotcrete being addressed?

The following changes are made to the mix to improve its rheology:

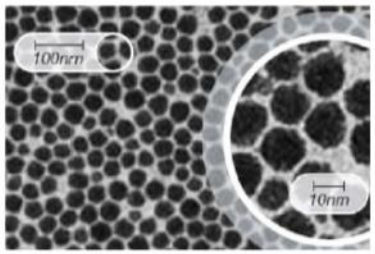
- Increase binder content
- Use silica fume
- Use rheology control admixtures
- Use viscosity modifying admixtures
- Use superplasticizers
- Use air-entraining agents
- Use accelerators
- Optimize sand/total aggregate ratio
- Optimize aggregate size and gradation
- Optimize w/cm

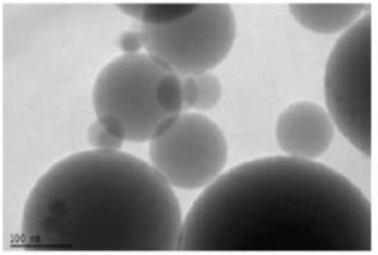
Pozzolanic-based rheology control agent

Composition

- Pozzolanic-based rheology controlling admixture
- Liquid dispersion of discrete, uniformly distributed nanometric particles of amorphous silica
- Non-porous, spherical, and non-aggregated
- In a stable colloidal aqueous dispersion

Properties



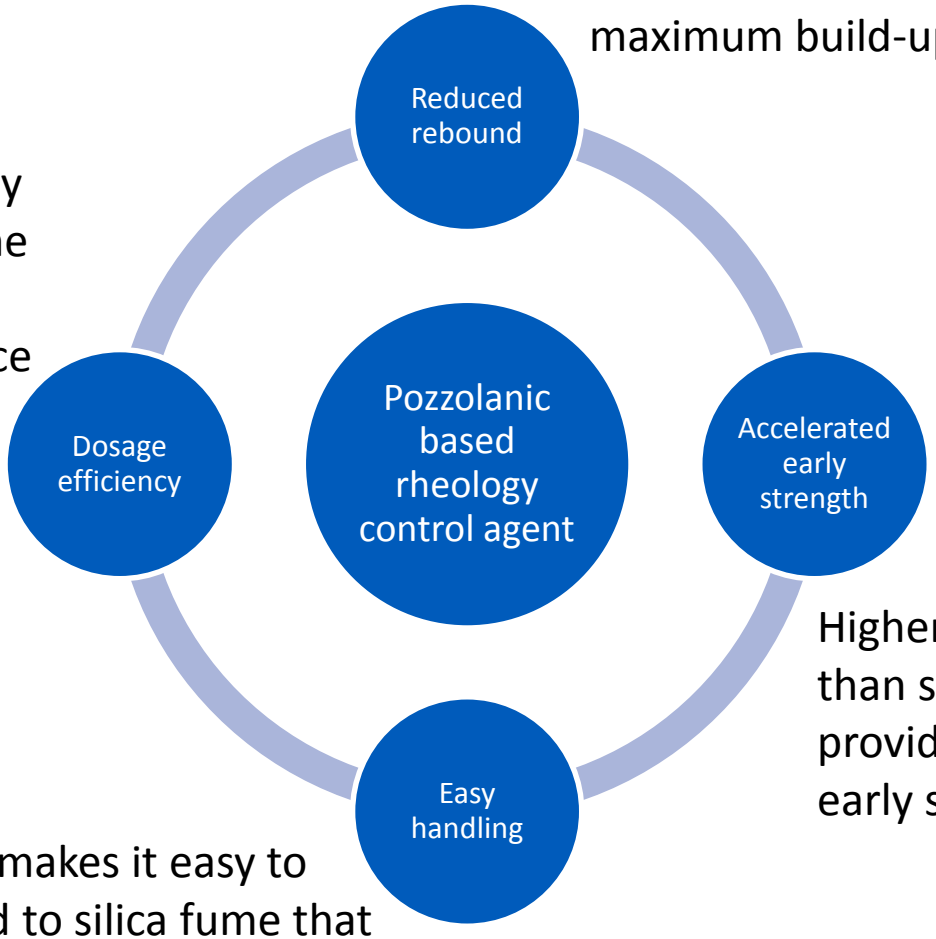


RHEOLOGY CONTROL AGENT	SILICA FUME
Nanometric	Micrometric
Engineered Material	Industrial Waste
Pure and Amorphous	Containing Impurities
Liquid	Powder
Robust	Variable Quality
Easy to use	Difficult to Handle
Commonly used dosage	**Commonly used dosage**
0.6%-0.8% of total binder content	**5%-8% of total binder content**

Benefits

Increases cohesiveness therefore, improves sprayability/ pumpability, reduces rebound and increases maximum build-up thickness.

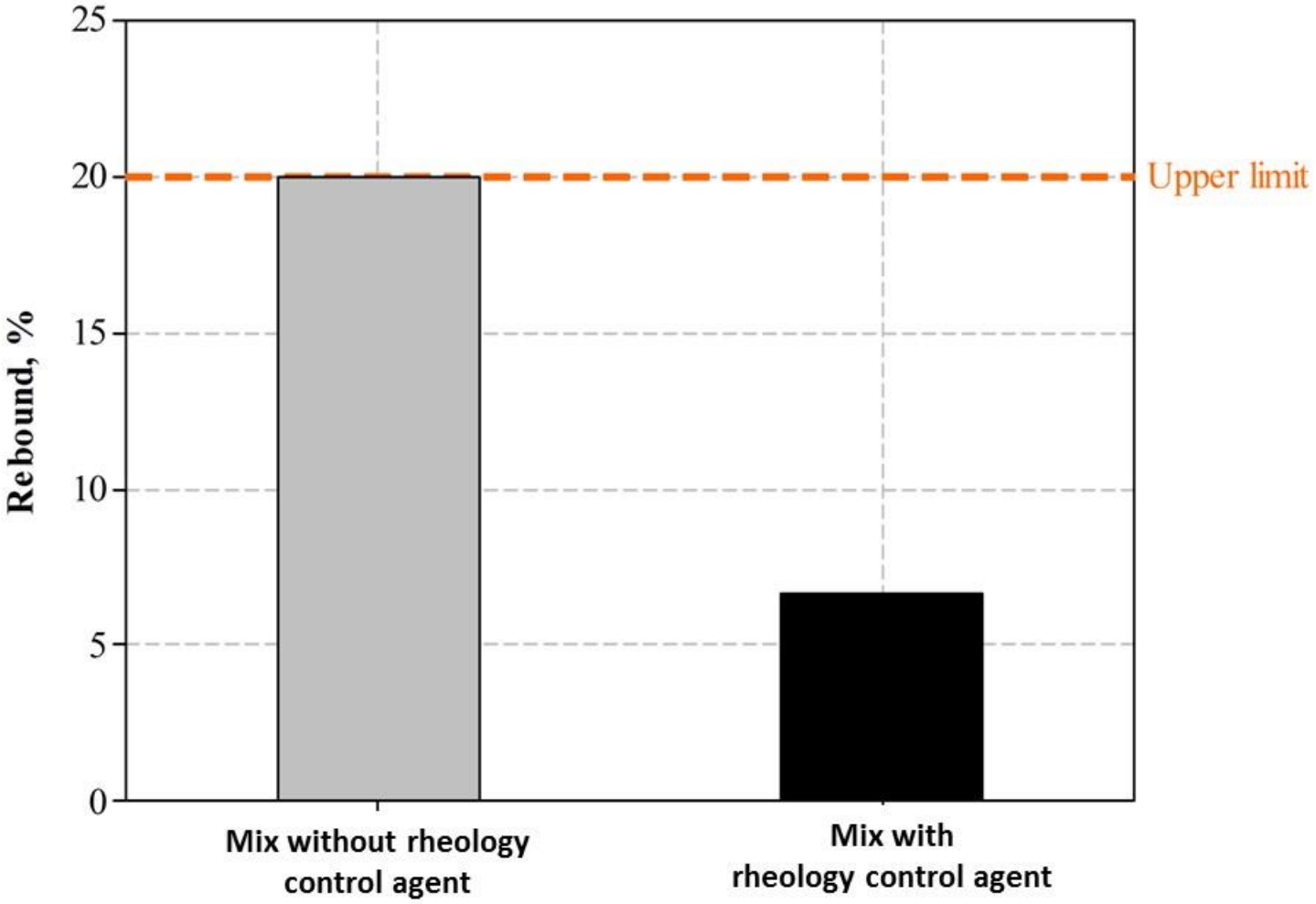
Requires approximately 1/10th of the silica fume dosage to provide equivalent performance



Higher pozzolanic activity than silica fume, therefore it provides faster and higher early strength

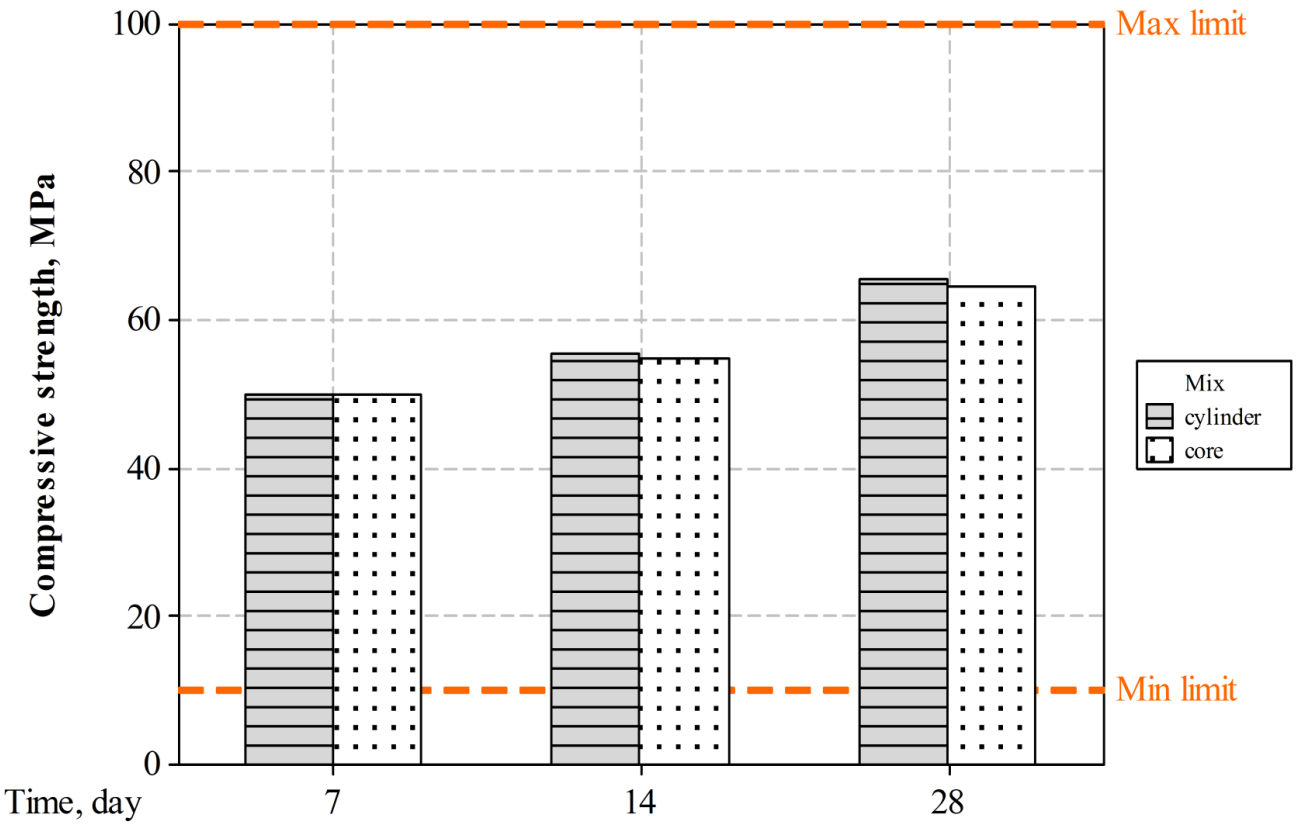
It is liquid which makes it easy to handle compared to silica fume that is in powder form.

Reduced rebound



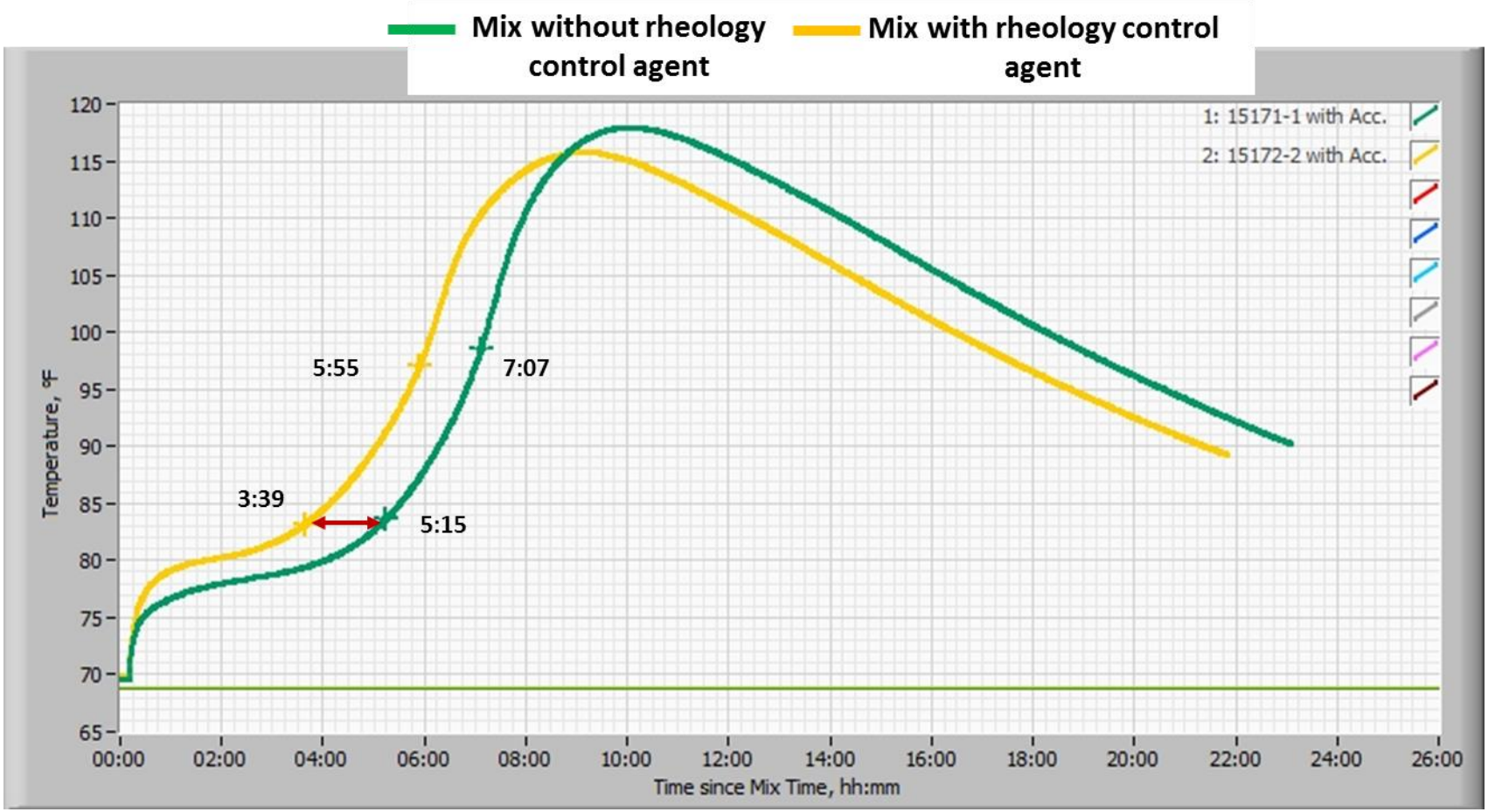
Mix with rheology control agent, rebound reduced from 20% to 5%

Improved compaction



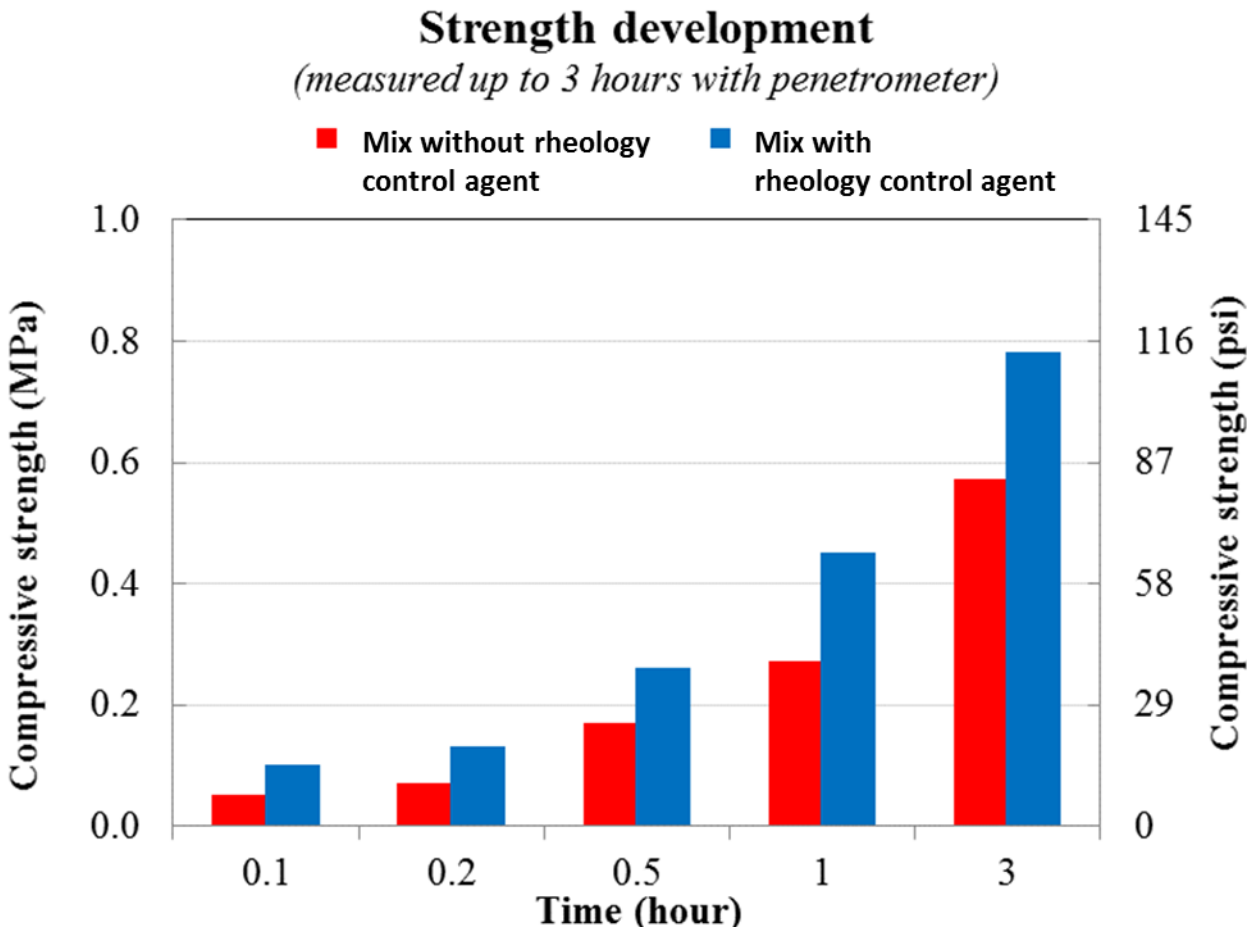
No difference was observed in cylinder vs core strength due to rheology control agent improving the rheology and consolidation

Reduced cycle times



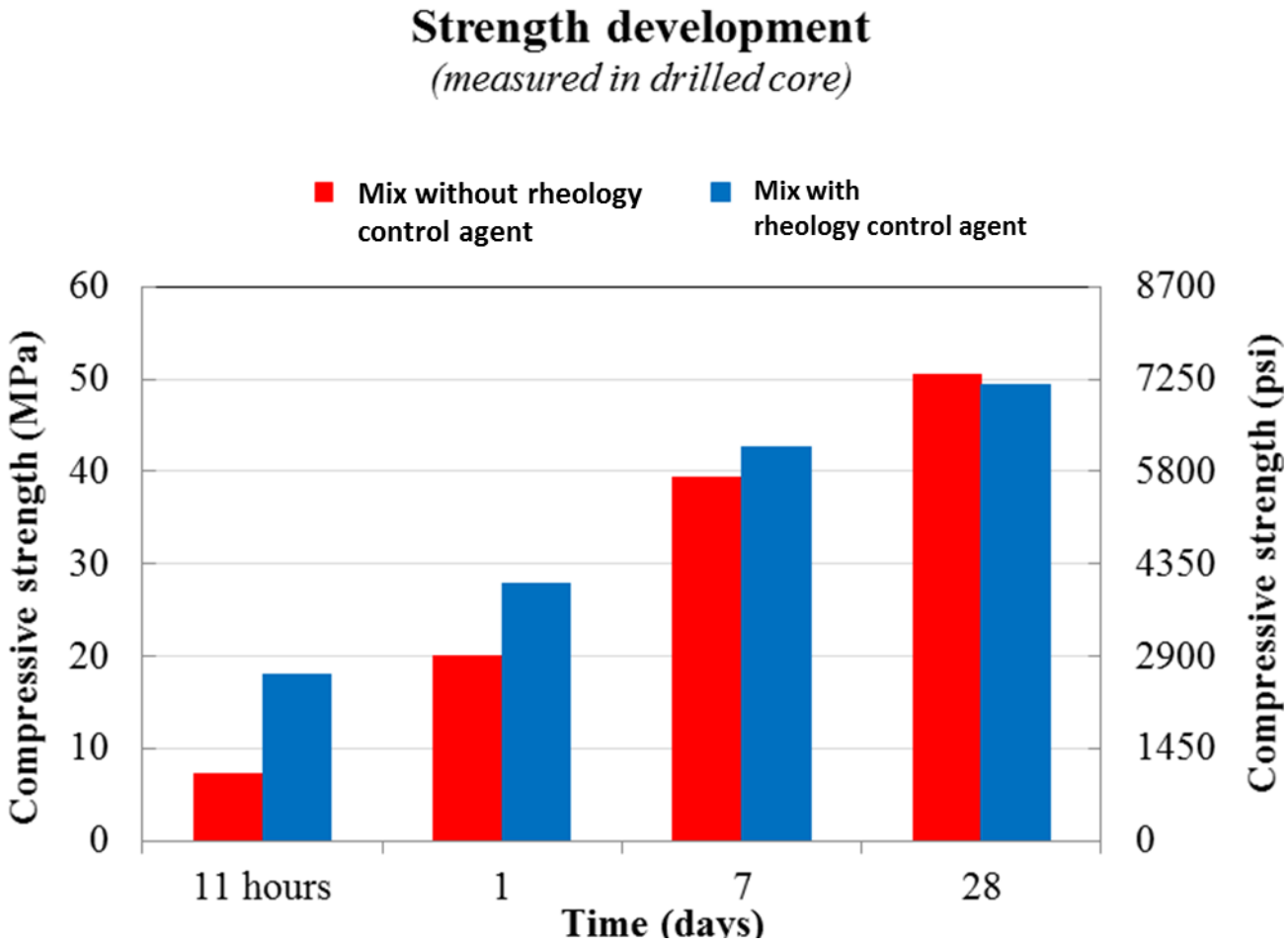
Mix with rheology control agent reaches initial and final set 1 to 3 hours faster than the silica fume mix

Faster early strength



Mix with rheology control agent provides much faster early strength

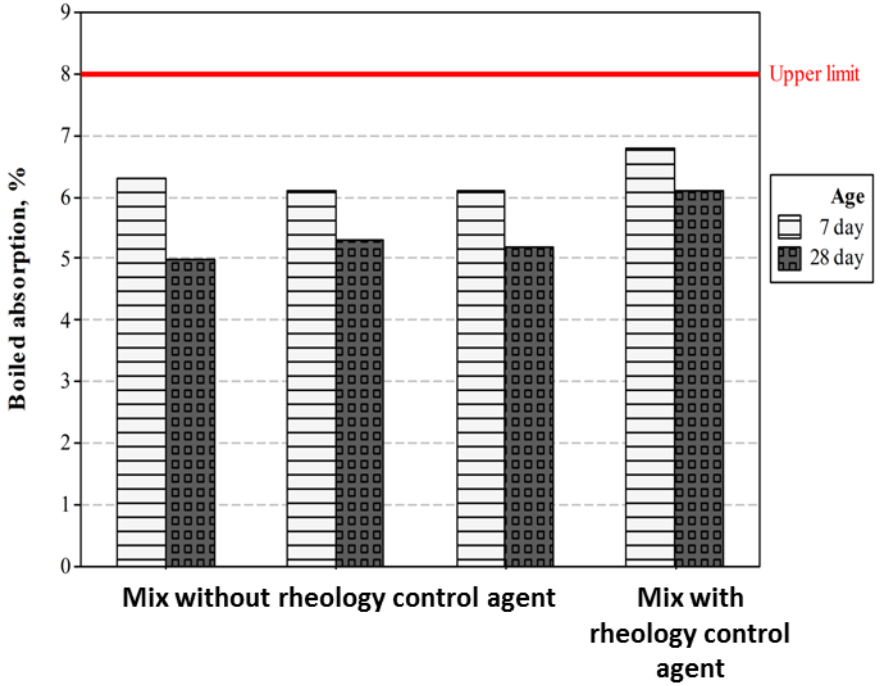
High long term strength



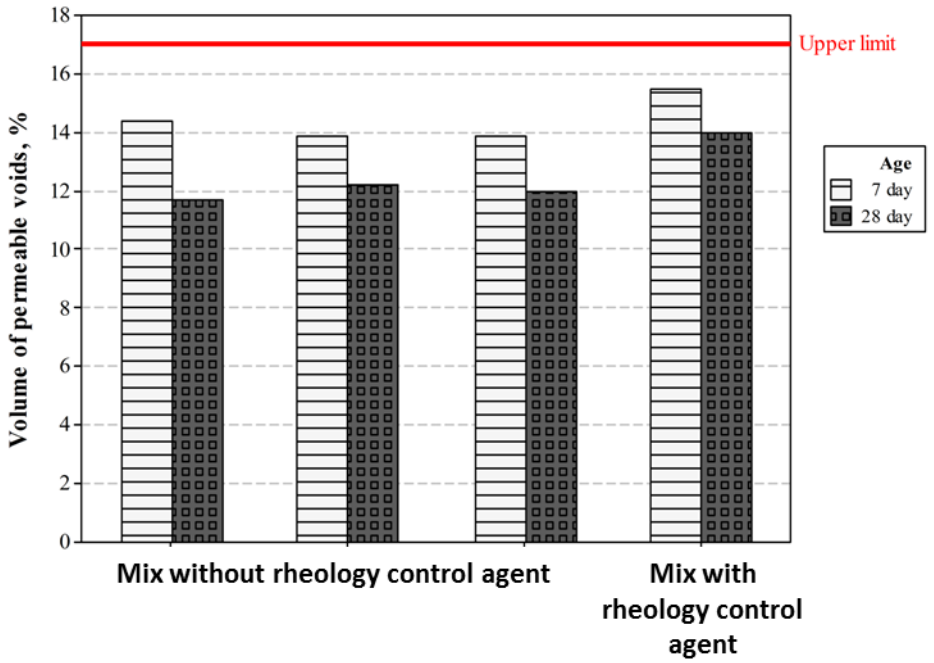
Mix with rheology control agent provides faster early strength without compromising final strength

High durability

Boiled absorption



Permeable voids



Mix with rheology control agent provided low permeability due to its filler effect improving the microstructure

Conclusions

- There is a very delicate balance between the mix constituents and their impact on shotcrete performance.

- It is ideal to maintain the highest possible fluidity (lowest yield strength) while providing the desired viscosity, cohesiveness, and “stickiness” to satisfy all needs.

- The addition of rheology control agent optimize the mix and help achieving that delicate balance by improving the shotcreting process as an application and shotcrete performance as a material.

Questions?

gcp applied technologies