Stabilizing highly flowable concrete against segregation and water loss

Dr. Oliver Mazanec
Head of Product Management, Admixture Systems Europe

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PCEs changed the world of construction

PCE technology is basis for modern concrete structures,

but, some additional challenges arose

- Formulation robustness against raw material fluctuations
- Shrinking availability of fly ash (900 Mio/to), slag (350 Mio/to) and sand which are required for stabilizing flowable concrete
- Pronounced usage of inert SCMs, which reduces thixotropy and stability of concrete
- Bleeding, segregation and undesired water loss occurred
Why do we need stabilizers in construction industry?

With increasing fluidity in the mix, the tendency for construction materials to sediment & separate increases!

Severe damage potentials
- Structural: Reduced strength build up
- Aesthetics: Chalking surfaces
- Durability: Increased porosity/capillarity
Construction applications using stabilizers

<table>
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<th>Stabilizers in powder form for …</th>
<th>Stabilizers in liquid or powder form for …</th>
</tr>
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<td><strong>Cement pastes</strong></td>
<td><strong>Mortar and grouts</strong></td>
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<td>Flowable floor screeds</td>
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</table>

- Post-tension grouts
- Self-levelling underlayments (SLU)
- Flowing floor screeds
- Flowable and Self-compacting concrete (SCC)
- Tremie concrete for deep foundations
What causes segregation and bleeding?

Concrete is a suspension of solids (cement, aggregates, sand) in water with a solid volume fraction between 0.4 and 0.8

Reduction of yield point reduces kinetic stabilisation of the cementitious suspension

Yield Stress Model (Yodel)

\[
\tau_0 = \frac{A_0 a^*}{d^2 H^2} \cdot f \sigma^* \cdot \frac{\Phi^2 (\Phi - \Phi_{perc})}{\Phi_m (\Phi_m - \Phi)}
\]

Thixotropy is one key aspect for stable and robust concretes.

Shear phase
Mixing, transport, placement

Time at rest
End of workability and time until setting

Thixotropy
Build up of viscosity and yield stress

viscosity $\eta$ & yield stress $\tau_0$

shear rate

time $t$
How to measure thixotropy of mortar and concrete?

Thixotropy of cement compared to inert limestone powder

**Thixotropy**

- Dynamic & static yield stress (Pa) vs. time at rest $t_p$ (s)
  - CEMENT
  - Limestone powder

**Bleeding**

- Bleeding water (mm) vs. time at rest $t_p$ (min)
  - Limestone powder
  - CEMENT

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* in artificial pore solution

- 50% Cement / CEM I 52,5 N
- 50% Fine Sand
- 0,13% bwoc PCE
- w/c ratio = 0,35

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Origins of cement thixotropy

Thixotropy

Why is cement a thixotropic material?

- Colloidal interaction of cement particles in the dormant period
- Nucleation growths of first nucleation products (e.g. CSH, ettringit)
- Amplifying ongoing hydrates nucleation
- Early hydrates which forms preferentially at the contact points between cement grains

**CEMENT**

- Dynamic & static yield stress (Pa)

<table>
<thead>
<tr>
<th>dynamic &amp; static yield stress (Pa)</th>
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<tbody>
<tr>
<td>100</td>
</tr>
<tr>
<td>80</td>
</tr>
<tr>
<td>60</td>
</tr>
<tr>
<td>40</td>
</tr>
<tr>
<td>20</td>
</tr>
<tr>
<td>0</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>time at rest $t_p$ [s]</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
</tr>
<tr>
<td>30</td>
</tr>
<tr>
<td>60</td>
</tr>
<tr>
<td>90</td>
</tr>
<tr>
<td>120</td>
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</table>

50% Cement (CEM I 52.5 N)
50% Fine Sand
0.13% bwoc PCE
w/c ratio = 0.35

- in artificial pore solution

**Limestone powder**

Addition of C-S-H based accelerator enhances cement thixotropy

Thixotropy

![Graph showing thixotropy over time and yield stress](image)

- CEM + MX-Seed**
- CEMENT
- Limestone powder*

**MasterX-Seed 100: accelerator based on nano C-S-H seeds

Colloidal interaction of cement particles in the dormant period:
- Layer thickness $\delta$ of adsorbed PCE

Nucleation:
- Growth of first nucleation products (e.g. CSH, ettringit)

Amplifying:
- Ongoing hydrates nucleation

Early hydrates which forms preferentially at the contact points between cement grains

Parameters effecting bleeding and segregation of concrete

The rate of sedimentation can be influenced by
- water/cement ratio
- particle size distribution
- paste volume
- cement and SCM type
- admixture type and dosage
- stabilizer or viscosity modifying admixtures (VMA)

Benefits of stabilizer & VMAs
- stabilization of solid particles
  - no sedimentation, no bleeding
- improved robustness
  - tolerates water deviations & raw material deviations
- individual adjustment of rheological properties
  - better control on desired rheology profile
- dosage efficient compared to mineral fillers
  - economic benefit

A wide particle size distribution usually gives a higher stability than narrow due to better particle packing (> $\Phi_m$)
Viscosity Modifying Admixtures - Technology overview

Hydrogen bonding

**Product**
- MasterMatrix SDC 100

**Mode of action**
- Water soluble polymer
- Hydrogen bonding of water

**Properties**
- Imparts no shear-thinning
- High water retention

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Self Association

**Product**
- MasterMatrix SCC 210

**Mode of action**
- Water soluble polymer
- Forms complex molecular aggregates and polymer entanglement

**Properties**
- Imparts highly shear-thinning
- Slightly water retention

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Aggregation/Flocculation

**Product**
- Polyarcylamids

**Mode of action**
- Water soluble polymer
- Flocculation of solid particles

**Properties**
- Imparts no shear-thinning
- Low water retention
Rheological profile of stabilizers in aqueous salt solution

**Self Association**

*Highly shear-thinning*: Easy mixing and pumping and excellent stabilization of coarse particles at rest

**Hydrogen Bonding**

*No shear-thinning*: Excellent water retention at high static pressure
Rheological profile of stabilizers in aqueous salt solution

- **Self association**: (highly shear thinning)
- **Hydrogen bonding**: (no shear thinning)

**Graphical Representation**

- **Log apparent viscosity (Pa·s)** vs. **Log shear rate (s⁻¹)**

**Rheometer**

Anton Paar, Type MCR 302 equipped with coaxial cylinder

**Rotational test**: (apparent viscosity)

**Time (s)**

- **0**
- **300**

- **Apparent viscosity ( Pa·s)**
  - **0**
  - **500**
Apparent viscosity for various VMAs as function of shear rate (aqueous pore solution)

Self Association: imparts highly shear-thinning which increases with concentration

Hydrogen Bonding: imparts no shear-thinning at low concentration and weak shear-thinning at high concentration
Mechanism of shear thinning
Creep recovery test

Stock solutions were prepared by dispersing dry samples for 12 h in distilled water

Mechanism of shear thinning
Critical aggregation concentration $c^*$

$c^*$: Self Association (SA) $\ll$ Hydrogen Bonding (HB)

**Distilled water**

- **Self Association (SA)**
  - no self association
  - $c^* \leq 0.12 \text{ g·L}^{-1}$
  - self association
  - $c^* \geq 0.12 \text{ g·L}^{-1}$

- **Hydrogen Bonding (HB)**
  - no polymer interaction
  - no polymer interaction

$c^*$: critical aggregation concentration
Effect of concentration on apparent viscosity at high shear rate vs. zero shear viscosity

Comparison zero shear vs. apparent viscosities

- Self Association (SA)
  - reduced dosage demands
  - increased viscosity
  - shear thinning

- Hydrogen Bonding (HB)
  - higher dosage demands
  - solely increase of viscosity

@ Typical industrial dosages

Typical industrial dosages

Cg/L⁻¹ (active polymer)
Link between concrete handling and rheological measurements

- Slump flow = yield stress
- Funnel flow = viscosity

- Test
  - Segregation
  - Visibility limit
  - Finishing / placement
  - Pumping
  - Mixing / high pressure

- Log viscosity (Pa·s) vs. log shear rate (s⁻¹)
  - Self Association
  - Hydrogen bonding

Aiad, I.: CCR, 2003, p. 1229-1234
Stabilizing self compacting concrete against bleeding and sedimentation

![Diagram showing viscosity vs. shear rate]

- **Self Association** (shear thinning)
- **Hydrogen bonding** (no shear thinning)
How to find the right superplasticizer and stabilizer dosage?

Example: SCC (target consistency: $a \geq 70$ cm)

- Flow value
- Superplasticizer dosage
- Particle surface covering with PCE
- SCC
- PCE saturation (mixture without stabilizer)
- Optimal SP dosage
- $\geq 75$ cm
- 70 cm
- + Stabilizer

no flow

optimal flow
no sedimentation

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Stabilizing of self compacting concrete with low paste volume ($V_{Paste} = 318 \text{ l/m}^3$)

- **C35/45 (Precast)**
- 350 kg/m$^3$ CEM I 52.5 N
- 100 kg/m$^3$ Limestone powder

- W/c ratio = 0.49

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**Stabilizing of self compacting concrete with low paste volume**

![Graph showing slump flow a (mm) vs. time (min) for different stabilizers](image)

- **w/o stabilizer**
  - (1.2% PCE + 1.1% SR)
- **0.2 g/L Self Association stabilizer**
  - (1.4% PCE + 1.3% SR)

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**Graph showing $t_{500}$-time (s)**

- **w/o stabilizer**
  - (1.2% PCE + 1.1% SR)
- **0.2 g/L Self Association stabilizer**
  - (1.4% PCE + 1.3% SR)

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**Notes**

- *PCE = MasterGlenium ACE 430
- **SR = R&D Product

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Stabilizing of self compacting concrete with low paste volume

w/o Stabilizer

Strong bleeding and sedimentation!

with Self Association stabilizer (0,2 g/L = 35 g/m³)

No separation, robust concrete!
Stabilizing tremie concrete for deep foundations against water loss

Shear rate in application

log viscosity (Pa·s)

log shear rate (s⁻¹)

Self Association (shear thinning)

Hydrogen bonding (no shear thinning)
Deep foundations (piles and diaphragm walls)
Example: Drilling with steel casing

Inserting the steel casing for the upper section of the drilled pile (ensures stable collar)
Excavation with drilling bucket. Stabilization of the borehole wall with steel pipe
Installation of the reinforcement cage
Concreting the pile with the pouring tube. Concreting from base of the hole.
Removal of the steel casing using the drill rig

Drilled piles: \( h = 5 - 30 \) m
High static pressure
- Water is pressed out
- Stabilizer with good water retention properties is required

Concrete requirements
- C40/50, 360 kg/m³ CEM III, w/c = 0.45
- Slump flow \( a = 600 \) mm, \( \geq 6 \) h
- Bleed water control static
- Bleed water control under pressure

High static load
Water is pressed out
Test set-up to determine water filtrared from pressurized fresh concrete based on standard testing for drilling fluids in accordance with API RP 13B-1.

Extreme high share rate / γ

Bauer filter press

Best EFFC/DFI Best Practice Guide to Tremie Concrete for Deep Foundations, 2016
Water retention of different stabilizer in tremie concrete for deep foundations

300 kg/m³ CEM III A 42,5 N
100 kg/m³ Fly ash
w/c ratio = 0.68

Slump Flow
acc. to DIN EN 206
a = 600 ± 50 mm (6 hours)

Hydrogen Bonding results in increased viscosity at high shear rates which improves water retention under pressure

*Hydrogen Bonding for Deep Foundation Concrete: research product, product launch is scheduled for 2019
Conclusions

- The high dispersing power of can PCEs lead to a higher sensitivity of the concrete mix against bleeding and segregation.

- The right balance between high fluidity and high segregation resistance can be obtained by a proper rheological behaviour (yield point, thixotropy and viscosity).

- **Self assembling stabilizers** induce a shear thinning behaviour in the concrete mix which help to stabilize against sedimentation that happens at low shear rate (e.g. Self Compacting Concrete and Underwater Concrete).

- **Hydrogen bonding stabilizers** have constant properties at different shear rates which is beneficial to stabilize against water loss under high pressure (e.g. Tremie Concrete for deep foundations).