Effect of Mixing and Placement Methods on Fresh and Hardened Ultra High Performance Concrete (UHPC)

Summary:
In order to achieve sufficient ductility and fire resistance, ultra high strength concrete (UHPC) is produced with w/b-ratios near 0.25 and silica fume contents up to 30 wt.% w.r.t. cement. Between 1.0 and 3.5 vol.% steel fibres and up to 0.65 vol.% PP fibres are added to the mix. This necessitates high mixing energies for UHPC. For example, the specific mixing energy for a UHPC made with 2.5 vol.% steel fibres and 0.3 vol.% PP fibres was 5.81 kW/h. Air bubbles with diameters between 0.1 and 1 mm formed in this highly viscous mortar leading to loss of strength of the hardened concrete.

In this contribution practical methods to reduce the air content of hardened UHPC are introduced and their advantages und disadvantages discussed. Usually, UHPC is produced by compacted a highly fluid concrete with internal or external vibrators so that as much air as possible is removed. This can cause fibre orientation or even sedimentation of the fibres. Tests showed that when the concrete was placed by pumping the fresh concrete temperature increased from 20°C to 40°C while the air content decreased by as much as 2 vol.% Air removal from the fresh concrete by pressure reduction down to 50 or 70 mbar within a closed mixing system was found to be an effective, but technologically complicated method.

Keywords: ultra high strength concrete, mixing energy, mixing procedure, evacuation, air void content, steel fibres, PP fibres

1 Introduction
The research at the cbm of the TU Munich on ultra high strength concrete began towards the end of the 1990s when the new generation of super plasticizers based on polycarboxylates had not yet reached their current effectiveness. The production of UHPC requires intensive mixing of concrete with the following characteristics:
Maximum aggregate size < 1mm
Low w/c ratio
High silica fume contents > 25 wt.% w.r.t. cement
Steel fibre contents between 2.5 and 3.5 vol.%

This led to the introduction of air bubbles which even after prolonged vibration could only be partially removed.

This publication reports on the research results and experience with regard to the reduction of the air bubble content of UHPC using appropriate mixing technology, mixing procedures and placement methods. The work focuses the development of suitable procedures for practical application.

2 Mixing Technology - Effect of Mixer Type on the Fresh Concrete Properties

2.1 General Remarks
Conventional mixer types can be used to produce UHPC in the laboratory or in precast concrete plants. However, a reduction in compressive strength due to enhanced air void content must be accepted if unsuitable mixing and placement procedures are used.

2.2 Compulsory Mixer (Volume 75 l)
The laboratory mixes were made with a 75 l ZZ 75 HE mixer manufactured by Zyklos. The eccentrically mounted turning and dividing paddles, which were very near the bottom of the drum, as well as the drum wall scraper resulted in three dimensional turning of the mix, see Fig. 1. The mixer speed was between 2 and 3 m/s so that the super plasticizer was evenly blended into the mix. Toward the end of mixing (approximately 7 min) the fresh UHPC had a very sticky consistency so that lumps of fresh concrete stuck to the paddles lowering the efficiency of mixing. Due to the sticky consistency the air void content of the fresh concrete was approximately 4.3 vol.%. The fresh concrete temperature was between 20 and 23 °C.

Figure 1: Mixing method of ZZ 75 HE (Zyklos; Mix volume 75 l)
2.3 Ring Mixer (Volume 1000 l)

In order to produce a UHPC strut (cross section 40×40 cm²) 400 l of fresh concrete were prepared with a 1000 l ring mixer at a precast concrete plant. The ring mixer had three star-shaped satellites driven by a multiple-stage planetary gear which rotated around the vertical axis, Fig. 2. The speed of mixing was between 1 and 2 m/s. The high shear forces applied by this technique yield an intensive mixing and highly effective distribution of the cement in the mix. After a mixing time of approximately 12 minutes the air void content of the fresh concrete was 3.2 vol.% at 19°C.

Figure 2: Ring mixer (mix volume 1000 l)

2.4 R-Intensive Mixer with Vacuum Periphery

The following requirements are placed on the mixer for UHPC production:

- Short mixing duration
- Homogeneous blending of small quantities of additives and admixtures
- Homogenization of materials having different densities

These requirements and the practice-relevant volume (up to 7 m³) appeared to be fulfilled by the R-intensive mixer produced by Eirich, Fig. 3.
Due to the optimum combination of drive and geometry which enables high mixt speeds of up to 40 m/s (opposed currents) and the tilt of the drum this mixer produces optimum homogenization of materials with large differences in density. The vacuum accessory permits evacuation down to pressures of 50 mbar in a closed system. Depending on the required performance the turning geometry can be varied. While the star turner is mainly used to homogenize the dry materials, the rod turner is used to distribute water and super plasticizer and homogenize the final mix.

3 Effect of Air Voids on the Fresh Concrete Properties

During mixing air bubbles find their way into the mix. This effect increases with poor workability and stickiness of the fresh concrete. Air voids with a diameter of 0.1 to 1 mm are similar to the aggregate size and are effectively defects in the concrete which can initiate cracks at high loads.

Usually, UHPC is produced at a fluid consistency similar to self-compacting concrete so that the air void content can be reduced to roughly 2 to 2.5 vol.%. Since the density of the steel fibres is three times higher than the density of fresh concrete, soft consistencies lead to sedimentation of the steel fibres. On the other hand, PP fibres are very fine (φ < 20 μm) which causes stiffening and reduces air removal from the fresh concrete.
Earlier, when the mixing procedure had not been fully optimized and the super plasticizer was less efficient, the air void content of the fresh concrete was above 4 vol.% on account of the sticky consistency. By using the vacuum accessory with pressure of 50 mbar during the last mixing phase it was, despite of the sticky consistency, possible to reduce the air content to values below 1 vol.%. This resulted in an increase in concrete density and correspondingly compressive strength from 150 to 230 N/mm$^2$, Fig. 4.

![Figure 4: Effect of pressure in the mixer on density and compressive strength of samples](image)

4  Optimization of Mixing Procedure

The following mixing procedure which is divided into 6 steps (Fig. 5) is the result of extensive optimization investigations with the R-intensive mixer in the laboratory. The procedure proved to be effective for the production of UHPC with high fibre contents. A mix speed of 8 to 9 m/s was found to be sufficient and was used for all the mixing steps.

- **Step 1:** Homogenization of all dry materials (excluding steel fibres) in under 1.5 min
- **Step 2:** Addition of water and wetting of the surface of the materials within 1.5 min. Half of the super plasticizer is added with the water in order to avoid agglomeration of the silica fume
- **Step 3:** Sufficient contact duration between the cement and the water is necessary to improve the effectiveness of the remaining super plasticizer. This is provided by a 2 minute break. According to \(^1\) the addition of super plasticizer at the beginning of the dormant period gives the best liquidation and good stiffness behaviour. This could be confirmed by the present investigations.
- **Step 4:** Continuous addition of steel fibres over 1.5 minutes. The fibres can be added in Step 1 to reduce the total mixing time
Step 5: Addition and blending in of the remaining super plasticizer 5 minutes after the first contact between water and cement

Step 6: Finally, the system is evacuated to 50 mbar to remove air from the fresh concrete. (1.5 min)

Figure 5: Optimized mixing procedure for fresh concrete preparation with the R08 VAC (Charge: 110 kg)

The parameters shown in Fig. 5 for the rotational speed of the turner and the power applied were measured during the preparation of an UHPC with a fibre cocktail comprising 2.5 vol.% steel fibres and 0.33 vol.% PP fibres.

A specific mixing energy totalling 5.81 kWh/t (Plate: 2.15 kWh/t; Turner: 3.66 kWh/t) was needed for the whole procedure. The necessary mixing time for other types of mixers can be derived from this. Thus a mixing time of 12 min results for a compulsory mixer with a specific mixing energy of 30kW/t. Since thorough mixing is achieved at high degrees of drum filling, the ratio between mixing energy and mixer capacity should be as high as possible.

An even colour of the mix was observed after mixing the dry materials such as quartz sand, cement, silica fume and PP fibres for one minute. In step 2 the mixing power increased to 7.7 kW due to the increase of the cohesive forces on wetting the surfaces. It then fell significantly once the water had been evenly distributed, see Fig. 5.

When the mixer was switched on after the 2 minute break in step 4 the highest power was measured at 9 kW. This can be explained by agglomeration due to the start of cement hydration. The fresh concrete had a porridge-like consistency during this mixing phase which enabled a
high input of mixing energy. This yielded a good distribution of the steel individual fibres during the subsequent addition of steel fibres to the mix. After homogenization and attainment of a constant power of 7 kW, the remaining super plasticizer was added 5 minutes after the first contact between water and cement. A fluid consistency at a power of 4.3 kW followed.

In the final step of the mixing procedure, air was almost completely removed from the homogeneous, fluid fresh concrete by application of a pressure of 50 mbar. The pressure was chosen so that the water loss from the fresh concrete was minimized. Moreover, the pressure in industrial scale mixers can only be roughly set to this level. In order to minimize further addition of air bubbles, the rotational speed was reduced.

The mixing procedures for the compulsory and ring mixers were adapted from the optimum mixing procedure for the R-intensive mixer. Somewhat more than half of the super plasticizer was added 5 min following the first contact between water and cement to enhance the effectiveness of the super plasticizer and produce better setting behaviour.

Table 1: Mixing times and steps for the compulsory mixer (75 l)

<table>
<thead>
<tr>
<th>Zeit [min] Beginn - Ende</th>
<th>Handlung</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dry homogenisation or quartz sand and silica fume over 1 min</td>
<td></td>
</tr>
<tr>
<td>0 – 1.0</td>
<td>Addition of water</td>
</tr>
<tr>
<td>1.0 – 1.75</td>
<td>Addition of mixture of cement and quartz powder</td>
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<tr>
<td>1.75 – 2.5</td>
<td>Addition of 40% super plasticizer within 15 s followed by homogenization</td>
</tr>
<tr>
<td>2.5 – 6.0</td>
<td>Break</td>
</tr>
<tr>
<td>6.0 – 7.0</td>
<td>Addition of remaining (60%) super plasticizer and homogenisation</td>
</tr>
<tr>
<td>6.0 – 8.0</td>
<td>Continuous addition of steel fibres</td>
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</tbody>
</table>

Owing to the controlling system it is not possible to pause the ring mixer (1000 l). The second addition of super plasticizer followed nevertheless 5 minutes after the first contact between water and cement. This was preceded by an extended homogenization period. The total mixing time was 12 min on account of the time needed to handle the large quantities of material.
In both cases, as opposed to the R-intensive mixer, it was not possible to achieve a porridge-like consistency after first addition of the super plasticizer. The reason for this was the low mixing energy which led to lower fresh concrete temperatures of 19 to 23° compared with 28 to 30°C for the R-intensive mixer.

5 Measures to Reduce the Air Content of Concrete Components

5.1 Conventional Methods

5.1.1 Adjustment of a Fluid, Self-Compacting Consistency

The removal of air from UHPC is usually improved by a suitable choice of super plasticizer, cement and silica fume in combination with an optimized mix composition and mixing procedure. A fluid almost self-compacting consistency can be obtained.

Based on extensive investigations with the R-intensive mixer without use of the vacuum accessory, fresh concrete with a spread of 26 to 28 cm proved to be optimal regarding workability, air removal and stability, Fig. 4.

Figure 6: Effect of mortar flow (no hits, mortar cone according to DIN 1060 T.3 (D/d/h = 100/70/60 mm) of fibre-free ultra high strength fresh concrete on the air content of the samples (Compaction 60 s at 70 Hz with formwork fixed to compaction table)
The data in Fig. 6 are the result of statistical evaluation of roughly 30 samples per mix. The 5% fractile value for the air void content is in good agreement with the minimum value measured confirming the use of a sufficient number of samples.

Spreads below 26 cm led to higher air void contents, but resulted in a lower scatter in bending and post-fracture behaviour \[v\]. This effect is very important in practice and must according to \[^2\]\ be determined at a realistic scale during the design of concrete components. The reason for the higher scatter at softer consistency lies in the poor joint between fibre and matrix as well as the different fibre orientation - and even sedimentation - due to the particular placement method and form geometry. Sedimentation of fibres was observed in the laboratory for spreads of 28 to 30 cm and more.

5.1.2 Concrete Placement by Pumping

To reduce the air content, the fresh concrete was pumped into the formwork with a spiral pump with an operating pressure of 25 bars. During pumping the air content of the fresh concrete was reduced on average from 1.3 vol.% to 2.9 vol.%.

The degree of air removal depended on the length of the pipe. On account of the viscous consistency friction resulted, depending on pipe length and concrete quantity, in an increase in fresh concrete temperature from initially 20 to 23°C to roughly 40°C at the end of the pipe.

5.1.3 Air Removal by Vibration

It was not possible to effectively remove air from the concrete for the test struts (cross section 40/40 cm) using the table vibrator at the precast concrete plant. Cores taken from the stuts contained air void as large as 4 mm. It was observed that the air voids introduced during mixing did not rise up through the fresh concrete. This behaviour was obviously caused by the use of an inappropriate combination of vibration frequency and amplitude for the UHPC.

According to the recommendations of Bresson \[^3\]\ the vibration speed at w/c ratios below 0.3 should be about 0.2 m/s. Fig. 7 indicates which equipment is able to provide this high vibration speed.
Furthermore, as well as the properties of the cement paste the aggregate size affects the optimum vibration frequency. According to [4] the best compaction is reached when the vibration frequency corresponds to the resonant frequency of the mean grain size. Thus in the case of a mean grain diameter of <1 mm a frequency of 200 Hz should be chosen giving an acceleration of 100 to 120 m/s² and an amplitude of 0.12 to 0.15 mm. On comparing these values with the data in Fig. 7 it can be seen that such vibrators are not usual in concrete construction.

5.2 Complete Air Removal from Fresh Concrete with Vacuum Accessory

As already mentioned in Section 4, it was possible to reduce the air content of the fresh concrete to values under 1 vol.% irrespective of the steel fibre content (up to 10 vol.%) through the application of pressures of 50 to 70 mbar in the closed mixing system of the R-intensive mixer Fig. 5. The spread of these mixes was between 22.6 and 30.8 cm. To avoid orientation or sedimentation of the fibres the concrete was not vibrated. The post-fracture behaviour of the samples in a displacement-controlled bending test has already been published in [5].

![Figure 7: Characteristic values for the vibration and modes of concrete vibration](image)
Figure 5: Density of samples as a function of steel fibre content

The air content of fresh concretes with 0.33 or 0.65 vol.% fine PP fibres ($\varnothing = 16 \mu m$) added to improve fire resistance were as much as 2.0 vol.% after evacuation. This significantly higher air content was attributed to the fineness of the PP fibres. However, this value is well below the values in the literature for UHPC made with PP fibres in conventional mixers.

6 Conclusions and Recommendations

It is certain that in the near future UHPC will be manufactured exclusively in precast concrete plants. With regard to the practical use of UHPC technology two cases must be considered:

Since the use of UHPC is still at the beginning it may be assumed that UHPC will, at first, find a small number of applications and be produced in a well-equipped precast plant using the available equipment there. In this case a high level of expertise and experience with UHPC is especially important. An optimum combination of the conventional methods described in Section 5.1 to reduce the air content should be chosen. Quality control (monitoring variations the materials etc.) is necessary to avoid production errors. The mixing times should be adapted to the efficiency of the mixer according to Section 4. The production of UHPC with high contents of steel fibres (> 3.0 vol.%) or with PP fibres to improve fire resistance (0.3 to 0.65 vol.%) is very difficult. Conventional mixing methods are expected to result in void contents of 3 to 4 vol.% for cocktail mixes with steel and PP fibres. A highly fluid consistency (spread >30 cm) should be avoided since it will cause a large scatter in the post-fracture behaviour.
An economically viable solution for precast concrete plants lies in the production of large numbers of UHPC components which make the investment in the special vacuum mixing technology worthwhile. The R23 Vac. has a mix volume of 3 m$^3$ and is suitable for the production of precast concrete. Evacuation down to pressures of 50 to 70 mbar during the last mixing step can yield workable fresh concrete with an acceptable consistency (spread 24 to 27 cm) and an air bubble content below 1 vol.%. The following advantages for the production would be gained:

- Low sensitivity of the hardened concrete properties with respect to quality variation of the mix components on account of the low air void content
- Highly homogeneous concrete microstructure throughout the concrete member
- Good post-fracture behaviour due to an even distribution of fibres.


