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**БЕТОН УЛЬТРАВЫСОКИХ ТЕХНОЛОГИЙ (УНПС) –
БОЛЬШЕ, ЧЕМ ПРОСТО ВЫСОКАЯ ПРОЧНОСТЬ**

Бетон ультравысоких технологий (сокращенно УНПС) – это бетон, известный своими чрезмерными прочностью на сжатие, долговечностью и высокой морозостойкостью. Благодаря высокой химической стойкости УНПС за счет плотной микроструктуры, существует идея использования его для производства газонепроницаемых стеновых панелей для вакуумной теплоизоляции. Использование небольшого количества воды и большого количества цемента обеспечивает очень низкие коэффициенты водоцементного отношения: от 0,25 до 0,14. Сочетание суперпластификаторов и сверхтонких частиц расширяет диапазон размеров частиц и способствует заполнению пространства между зернами цемента, что приводит к высокой плотности упаковки конструкции, делая УНПС еще более прочными и долговечными. В статье приведены некоторые результаты исследований использования УНПС для строительства multifunctional стеновых панелей и его влияния на новые системы вакуумной теплоизоляции, а также возможности энергосбережения.

Ключевые слова: бетон ультравысоких технологий, проницаемость, плотная микроструктура, вакуум, изоляция, multifunctional стеновые панели, энергосбережение, производство теплоизоляции, долговечность.

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**ULTRA HIGH PERFORMANCE CONCRETE –
MORE THAN JUST ENORMOUS STRENGTH**

Ultra-High Performance Concrete, abbreviated as UHPC is a concrete that is known for its outrageous compressive strength, durability and its highly frost and de-icing resistance. Being highly chemical resistant, due to its characterizing dense microstructure, leads to the idea of gas impermeable wall elements used for vacuum based heat insulation. Using a very low amount of water and a high amount of cement ensures very low water cement ratios from 0.25 down to 0.14. Combining that with superplasticisers and sub micrometer fines to extend the particles size range and allowing the hollow spaces in between the cement grains to get filled up, the concrete results into a high density packing structure, which makes the UHPC more worthy than just strong and durable. This paper shows some of the research results in using UHPC for the construction of multifunctional wall elements and its influence on new vacuum heat insulated systems and energy saving opportunities.

Keywords: ultra-high performance concrete, permeability, dense-microstructure, vacuum, insulation, multifunctional wall-elements, energy-saving, opaque heat production, durability.

Introduction

Reducing the demand on heating energy for buildings is one of the major tasks of sustainable energy usage and climate protection. Currently most of the wall – and insulating systems are accomplished by conventional insulating materials, e.g. mineral fibers, polystyrene foams or polyurethane foams. Disadvantages of those systems are primarily the large insulation diameters that are needed for an average insulation quality and the resulting amount of space that is lost throughout its construction. In addition to that, conventional insulating materials aren't capable to realize any heavy load-bearing tasks, due to their low abilities in compressive strength. Therefore those materials are always bound to a load-bearing structure, which again influences the wall diameters and building costs dramatically. Considering that minimizing the wall diameters while maintaining the same structural abilities, clarifies that the only way to achieve a sufficient insulation is to establish a vacuum inside the wall. The element in question is an innovative construction that uses the same open-pored, microporous insulation for pivotal material like VIP elements (vacuum insulated panels), but instead of the conventional impermeable aluminum layer it uses a statically effective surrounding of UHPC concrete. With this it would be possible to establish a solid, viable exterior wall that could be reduced in its diameter while having the same abilities in heat insulation. So the major task of our research was to develop a concrete that was nearly impermeable to gas, having a compressive strength that compensates a diameter loss by half.

1. Concrete optimization And Strength

For a minimum of gas permeability, regarding to the research paper of [1], the usage of higher amounts of microsilica is decisively recommended. Microsilica, which is an extra fine silicic acid, basically works as filler between the cement grains. Because of its dewatering effect, microsilica displaces the water between the cement grains, working like a condenser within the fresh concrete. With a specific surface of 100.000 cm²/g according to blaine it is the perfect fine to extend the particles size range and allowing the hollow spaces to get filled up.

Then, to reach an increase in strength and density, the UHPC usually gets heat treated. Common are heating treatments from 50 up to 250 °C lasting seven days at a maximum. The heat treatment over 90 °C up to 150 °C causes an accelerated reaction of the puzzolanic silica fume, which leads to

modification of the hydrate phases, creating at very high temperatures the very hard tobermorite and making the concrete stronger and dense. Due to the composition of UHPCs the viscosity is quite distinctive, making it hard to vent the concrete. This specific characteristic makes it necessary to increase the mixing times by close to all UHPCs.

Also it is recommended to stick to the exact mixing regime, while adding the superplasticizers as late as possible. Due to the dry cement powder, most of the superplasticizer molecules are absorbed within the very early hydration process, if the superplasticizer is thrown in too early, causing a bad result in liquefying the paste. Adding the superplasticizer as late as possible gives the cement powder the opportunity to first absorb the already added water and building up early hydration products. The superplasticizer then is set on early hydrated agglomerates causing them to break loose into tiny pieces filling up hollow spaces, causing a dense structure. The superplasticizer also is not buried by early hydration products, giving its side chains the opportunity to increase the liquefying effect by keeping the distance between new hydration products [3].

But even with using superplasticizers, to get a UHPC to reach self-compacting circumstances, the vibrating process should not be necessarily relinquished [2].

Considering that another focus of the research was on using a local compound cement with a lower amount of microsilica, due to cost and transport specifications, the concrete curing was probably the most significant part to get a decisively increase in density and strength within the hardened concrete. For that instance three different ways of common curing strategies, shown in fig. 1, were compared with each other, dividing those in unshaken and shaken samples as well.

After compaction, the concrete was cured in moulds at room temperature (20 °C) for exactly 24 hours. Thereafter they were demoulded and one third of the samples were put into water-storage (20 °C), curing 26 days until they were taken out for 48 hours of standard storage at 20 °C and 65 % rel. humidity. One third of the samples were heat treated at 90 °C for 48 hours with a heat rate of 10 K/h after demoulding.

Fig. 1. Compressive strength vs storage conditions

After heat treating the samples were put into water-storage (20 °C), curing 2 days until they were taken out for 22 days of standard storage at 20°C and 65 % rel. humidity. The last samples were cured by standard storage. at 20 °C and 65 % rel. humidity. As seen in fig. 1, a low increase in strength has been observed throughout the combined heating and watering process, while shaking the samples made the significant difference. Because of the very low water cement ratios and the dense packing structure, formally achieved throughout the usage of sub micrometer fines, the entire porosity (air voids, capillary voids and gel voids) compared to a normal concrete,

decreases dramatically. Still the high viscosity of the UHPCs can cause air bubbles to get stuck in the mixture, causing an immense loss in strength and density. The increase in strength throughout the combination of heat – and water curing on the other hand can be explained, regarding to a study of the University of Kassel [5], in the following way. The single grains within the cement paste are surrounded by water during the mixing process. With the combination of water and cement, both react to cement gel, which in turn is the total of all sub micrometer particles that have a diameter of approx. a thousandth of the original cement grain. Between those particles often remain little gaps, which we call gel voids. Looking at the first phase of hydration in detail, the cement grain will be surrounded by a very thin layer of cement gel, after the first water contact. In further progress of the hydration, additional water has to first get through the already surrounding cement gel, to solubilize the remaining cement grain. At this point parts of the new formed cement gel immediately drop out in the redundant space during the solution process. The rest of the cement gel diffuses to the outside, dropping out within the boundary layer between water and cement gel. During the hydration process only a certain part of the tempering water will chemically ligated, producing the necessary cement gel. Some of the water stays within the cement voids, practically being organized interlayer water, located directly with the calcium silicate hydrate (CSH). Right at this point the combined heating and watering process catches in. Because of the initial heating up to 90 °C, the pore water can be evaporated. Thereby the not entirely hydrated cement grain is exposed again, being ready for a new hydration as soon as it's getting contact to water (second step: water curing). At this point it needs to be said, that a heating over 90 °C as well as a faster increase in temperature than 10K/h can lead to a very quick evaporation, causing huge amounts of pressure or the emergence of micro-cracks.

2. Construction and Simulation of the Wall Elements

In relation to the simulation for deformation behavior and based on the concrete test results of the cube samples (compressive strength and E-modulus) the following parameters got more and more into focus.

- Concentration
- E-modulus
- Poisson's ratio

- Compressive strength
- Dimensions
- Bearing conditions
- Net dimensions of finite element module

Fig. 2. Parameter study of the Poisson's ratio

As a result, several parameter studies by use of the software ANSYS 13® were implemented. Referring to that, a parameter study with a varying Poisson's ratio exemplarily is shown in fig. 2. The dimensions of the specimen were chosen to meet the standard of common precast components for exterior walls. As a defined workload, the atmospheric pressure at sea level, with 101.325 Pa, was set all-around the specimen.

In later simulations, the Poisson's ratio was set to a constant value of 0.18. In additional test it was observed, that the parameter concentration not necessarily had an influence on the deformation of

the specimen. To achieve a simulation that was as realistic as possible, the net dimensions of the FE-module were rarefied till no changes in values were observed anymore. For the bearing condition this meant to analyze the most common ways of bearing.

- External Grounding: – admitting a direction oriented shift of the specimen
- Grounded bearing: – extensively grounding at the bottom of the specimen

Within the context of this simulation tests, an additional extrapolation of the maximum deformation for a possible exterior wall was done. The results of those simulations, exemplarily shown in fig. 3 and 4, showed that the maximum deformation increases by using an external grounding. This is based on the all surrounding workload (atmospheric pressure) used on the specimen, which deforms the holding side as well.

Fig. 3. Load schedule of total deformation using grounded bearing

Fig. 4. Deformation of total deformation using grounded bearing

For the grounded bearing, an extensively grounding at the bottom of the specimen, however, the bottom can't be deformed for that reason. Therefore this results in a lower deformation for the whole specimen. Furthermore it was observed that the total deformation increases very quickly with bigger dimensions of the specimen. Already with a dimension 2.0 m/ 3.0 m/ 0.08 m a value was reached that the vacuum chamber got inoperative. Considering that additional loads like snow, wind and live loads haven't even been taken into account so far, lead to the use of frame bars within the vacuum chamber, that exclude the atmospheric pressures each other. Based on the results from the simulation test and parameter studies, a real live prototype was build (fig. 5 and 6), reaching a measured compressive strength of 154 MPa after curing, holding a vacuum of 5.0×10^{-2} mbar.

Fig. 5. CAD of the real life prototype

Fig. 6. Segment of a real life prototype

3. Vacuum Insulation

Regarding to statements for the behavior of thermoconductivity in gases of the University in Jena [4], considering the mean velocity according to Maxwell-Boltzmann, the thermo-conductivity can be evaluated as follows:

$$\lambda = \frac{1}{3} \cdot \Lambda \cdot v \cdot n \cdot C_v / Na. \quad (1)$$

It can be seen, that the thermoconductivity can't depend on the gas pressure, because the particle number n in fact is proportional to the pressure, as in

$$p = n \cdot k \cdot T, \quad (2)$$

but the mean free path Λ is inversely proportional to the pressure, as in

$$\Lambda = \frac{k \cdot T}{\pi \cdot \sqrt{2} \cdot (2 \cdot r)^2 \cdot p}. \quad (3)$$

Therefore the product of mean free path and particle number can't be depending on the gas pressure anymore (table 1).

Table 1

Dependence of Mean free Path and gas pressure

p in [mbar]	T in [K]	n in [m ⁻³]	Λ in [m]	v in [m/s]	λ in W/(mK)
1,00E+03	273,15	2,65E+25	8,98893E-08 ~ 1,00E-07	446,8466117	4,23E-04
1,00E+02	273,15	2,65E+24	8,98893E-07 ~ 1,00E-06	446,8466117	4,23E-04
1,00E+01	273,15	2,65E+23	8,98893E-06 ~ 1,00E-05	446,8466117	4,23E-04
1,00E+00	273,15	2,65E+22	8,98893E-05 ~ 1,00E-04	446,8466117	4,23E-04
1,00E-01	273,15	2,65E+21	0,000898893 ~ 1,00E-03	446,8466117	4,23E-04
1,00E-02	273,15	2,65E+20	0,008988927 ~ 1,00E-02	446,8466117	4,23E-04
1,00E-03	273,15	2,65E+19	0,089889267 ~ 1,00E-01	446,8466117	4,23E-04
1,00E-04	273,15	2,65E+18	0,898892671 ~ 1,00E+00	446,8466117	4,23E-04

But coming from practical experience, it is well known, the thermoconductivity definitely changes while lowering the gas pressure (e.g. evacuated tube collector and vacuum jug). But within the crossovers from viscous flow to Knudsen regime ($\Lambda \approx d$), the ratio between the mean free path and the component dimensions is essential. As long as the mean free path is smaller than dimension of the evacuated area, the thermoconductivity surely is not depending on the surrounding pressure. But as the mean free path

reaches the dimension of the evacuated area, the path that the particles can move is limited by the dimension of the evacuated area. In this case the mean free path can be seen as an absolute term, while the thermoconductivity is depending on the particle number, which again can be controlled by pressure (table 2).

Table 2

Dependence of Mean free Path and gas pressure taking account
of the Dimensions

p in [mbar]	T in [K]	n in [m ⁻³]	Λ in [m]	v in [m/s]	λ in W/(mK)
1,00E+03	273,15	2,65E+25	8,98893E-08 ~ 1,00E-07	446,8466117	4,23E-04
1,00E+02	273,15	2,65E+24	8,98893E-07 ~ 1,00E-06	446,8466117	4,23E-04
1,00E+01	273,15	2,65E+23	8,98893E-06 ~ 1,00E-05	446,8466117	4,23E-04
1,00E+00	273,15	2,65E+22	8,98893E-05 ~ 1,00E-04	446,8466117	4,23E-04
1,00E-01	273,15	2,65E+21	8,98893E-05 ~ 1,00E-04	446,8466117	4,23E-05
1,00E-02	273,15	2,65E+20	8,98893E-05 ~ 1,00E-04	446,8466117	4,23E-06
1,00E-03	273,15	2,65E+19	8,98893E-05 ~ 1,00E-04	446,8466117	4,23E-07
1,00E-04	273,15	2,65E+18	8,98893E-05 ~ 1,00E-04	446,8466117	4,23E-08

With a decreased pressure of 100 Pa and the use of open-pored, microporous insulation inside the evacuated area, realizing a minimization of the mean free path, it was possible to establish a decrease of the thermoconductivity by half. Considering a stable active vacuum it is possible to lower the insulation diameters by half using that technique. Combined with the diameter loss in construction reached by using UHPC, the target of lowering the wall diameter by half without losing any benefits, the target of this research was achieved.

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