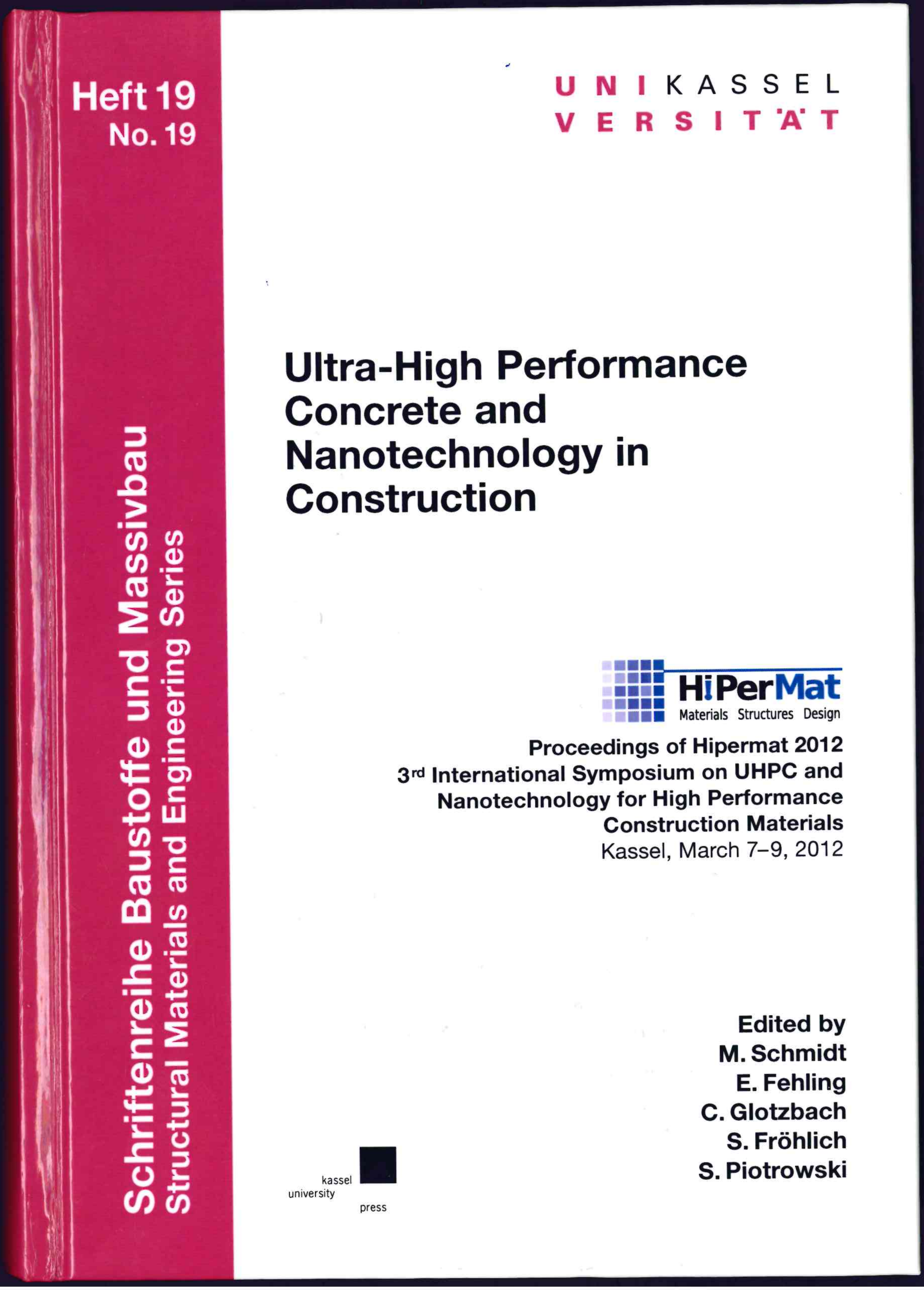


Heft 19
No. 19

Schriftenreihe Baustoffe und Massivbau
Structural Materials and Engineering Series

UNIKASSEL
VERSITÄT

Ultra-High Performance Concrete and Nanotechnology in Construction

HiPerMat
Materials Structures Design

Proceedings of Hipermat 2012
3rd International Symposium on UHPC and Nanotechnology for High Performance Construction Materials
Kassel, March 7–9, 2012

Edited by
M. Schmidt
E. Fehling
C. Glotzbach
S. Fröhlich
S. Piotrowski

kassel
university
press

4 Futher research and acknowledgment

Future work will include the evaluation of more composite samples subjected to 600 and 900 freeze-thaw cycles and slant shear and pull-off tests to evaluate behavior of the bond under different states of stress. The rise of freeze-thaw cycles will assess if the increase of bond strength stabilizes or if there is a turning point from which the bond strength decreases. The slant shear is more sensitive to the surface preparation [1, 2]. The pull-off test can be carried out in situ or in the laboratory giving the opportunity of correlation among the others tests. The authors thank Lafarge North America for their support of the highlighted research activities.

References

[1] Harris, D.K.; Sarkar, J.; Ahlborn, T.M.: Interface Bond Characterization of Ultra High Performance Concrete Overlays. *Transportation Research Board (TRB) 90th Annual Meeting*, Transportation Research Board, Washington, D.C., 2011.

[2] Momayez, A.; Ehsani, M. R.: Comparison of methods for evaluating bond strength between concrete substrate and repair materials. *Cement and Concrete Research* 35 (4), p. 748-757, 2005.

[3] Silfwerbrand, J.: Improving concrete bond in repaired bridge decks. *Concrete International* 12, p. 61-66, 1990.

[4] Beushausen, H.: The influence of concrete substrate preparation on overlay bond strength. *Magazine of Concrete Research* 62, p. 845-852, 2010.

[5] Sprinkel, M. M.: Preparing bridge decks for overlays. *Aberdeen's Concrete Repair Digest* 8, p 242-247, 1997.

[6] Hindo, K. R.: In-place bond testing and surface preparation of concrete. *Concrete International* 12, p. 46-48, 1990.

[7] ICRI Guideline. No. 03732. Selecting and Specifying Concrete Surface Preparation for Sealers, Coatings, and Polymer Overlays. International Concrete Repair Institute, IL., USA, 1997.

[8] Li, S. E.; Geissert D. G.: Freeze-thaw bond durability of rapid-setting concrete repair materials. ACI Materials Journal 96, p. 242-249, 1999.

[9] Geissert, D. G.; Li, S. E.: Splitting prism test method to evaluate concrete-to-concrete bond strength. ACI Materials Journal 96, p. 359-366, 1999.

[10] ASTM C666 / C666M - 03. Standard Test Method for Resistance of Concrete to Rapid Freezing and Thawing. West Conshohocken, PA., 2008.

[11] ASTM C496/C496M. Standard Test Method for Splitting Tensile Strength of Cylindrical Concrete Specimens. West Conshohocken, PA., 2004.

[12] Ramey, G.E.; Strickland, A.M.: An experimental evaluation of rapid-setting patching materials used in the repair of concrete bridges and pavements. Alabama Highway Research, Project 930-103, Part II, pp. 48– 56, 1984.

[13] Wall, J. S.; Shrive, N. G.: Testing of Bond between Fresh and Hardened Concrete. Adhesion Between Polymers and Concrete, Proceedings of an International Symposium, France, 1986.

[14] Graybeal, B.: Material Property Characterization of Ultra High Performance Concrete, FHWA-HRT-06-103, Federal Highway Administration, U.S Department of Transportation, Washington,D.C., 2006.

[15] Michigan Department of Transportation. MDOT Bridge Design Manual. Lansing, MI., 2009.

[16] Julio, E. N. B. S.; Branco, F. A. B.: Concrete-to-concrete bond strength: Influence of an epoxy-based bonding agent on a roughened substrate surface. Magazine of Concrete Research 57, p. 463-468, 2005.

[17] ASTM Standard E965-96. Standard Test Method for Measuring Pavement Macrotexture Depth Using a Volumetric Technique. West Conshohocken, PA., 2006.

[18] Concrete Repair Guide (546R-04). American Concrete Institute. Farmington Hills, MI., 2004.

[19] Sprinkel, M. M; Ozyildirim, C.: Evaluation of high performance concrete overlays placed on route 60 over Lynnhaven inlet in Virginia. VTRC 01-R1. Virginia Transportation Research Council, VA., 2000.

Alkali-Activated Ground Granulated Blast Furnace Slag Binders for High Performance Concretes with Improved Acid Resistance

Ricarda Tänzer[1], Dietmar Stephan[2], Michael Schmidt[1]
1: Institute of Structural Engineering, University of Kassel, Germany
2: Building Materials and Construction Chemistry, Berlin Institute of Technology, Germany

This paper presents the approach from fundamental investigations of alkali-activated GGBFS with different types of alkali silicates as activators to mortars and concretes that can be used for sewage pipes with improved acid resistance. Methods such as flow-table test, compressive strength or scanning electron microscopy and mercury intrusion porosity as well as the examination of the acid resistance are used to characterise the properties of the binders, mortars and concretes in fresh and hardened state. Finally the production of a pipe in laboratory scale is represented.

Keywords: ground granulated blast-furnace slag, alkali silicate binders, sewage pipes

1 Introduction and background

The item "High and Ultra High Performance Concrete" is usually defined by a high compressive strength [1] and dense microstructure. Derived from this, other performance criteria like improved chemical resistance can be mentioned. Currently used concrete pipes that form part of sewer systems are increasingly exposed to aggressive fluids. Concretes based on conventional cements have a restricted resistance especially to acid attack even if they fulfill the structural and strength requirements for HPC or UHPC. Because of that plastic or ceramic materials with a higher acid resistance are preferably used.

Therefore, alternative binders with an improved acid resistant attract more and more attention. One opportunity is based on alkali-activated ground granulated blast-furnace slag (GGBFS) and fly ash, also referred to as "cold ceramics". Activating agents such as alkali salts (carbonates, sulfates), alkali hydroxides or alkali silicates, also known as waterglass, can be used for producing binders which harden at temperatures lower than 100°C and also provide a high degree of chemical and mechanical resistance.

One requirement for the activator is to attack and dissolve the glass network of the GGBFS or fly ash [2]. The basic mechanism of these reactions was described by Glukhovsky [3] in three steps: destroying glass network of the raw material and precipitation; precipitation and condensation as well as condensation and crystallization. According to the CaO-content in the raw materials different reaction products are formed. At high CaO-contents mainly C-S-H and C-A-H phases can be found in the binders. With decreasing CaO-content this proportion is reduced and the proportion of zeolite-like phases is rising [4]. If blast-furnace slag is mixed with solids low or free in calcium such as fly ash or metakaolin, reaction products of both C-S-H and C-A-H phases and an aluminosilicate network are formed [5-8].

In particular, the application of waterglass as activator results in a consistent silicification of the material structure, because of the high amount of silicate in the liquid. This reaction has a significant influence on the pore structure and thus on the impermeability and physical resistance of the binder.

In the following paper the whole development from binder investigations over mortar to the concrete mixing design and finally the production of a pipe in laboratory scale is represented.

2 Materials and methods

Ground granulated blast furnace slag and alkaline activators

The used GGBFS had a glass content of 99.9 wt.-% and a Blaine fineness of 4150 cm²/g. The chemical composition is shown in Table 1.

Table 1: Chemical composition of the industrial GGBFS in wt.-%.

wt.-%	SiO_2	Al_2O_3	FeO	TiO_2	MnO	CaO	MgO	Na_2O	K_2O	S^{2-}
GGBFS	37.4	10.0	0.25	0.80	0.23	38.7	10.3	0.27	0.62	1.14

As alkaline activators several sodium and potassium silicates were used, which differ in their modules (defined as molar ratio SiO_2/Me_2O). Table 2 shows the abbreviations and explanations of the activators used in this investigation. Furthermore, for all binders a water to slag ratio of 0.35 was defined, to allow a comparability of all binders, because of the different solids contents of the waterglasses.

Table 2: Composition of the alkaline activators.

abbreviation		waterglass	molar ratio SiO_2/Me_2O	alkali concentration in mol/kg	solid content
Na-WG-0.5	2 mol/kg Na	sodium waterglass	0.5	2.0	9.2
Na-WG-1.0	2 mol/kg Na	sodium waterglass	1.0	2.0	12.2
Na-WG-2.0	2 mol/kg Na	sodium waterglass	2.0	2.0	18.2
K-WG-0.5	2 mol/kg K	potassium waterglass	0.5	2.0	12.4
K-WG-1.0	2 mol/kg K	potassium waterglass	1.0	2.0	15.4
K-WG-2.0	2 mol/kg K	potassium waterglass	2.0	2.0	21.5

Experimental Investigation

At first sample specimen (2·2·2 cm³) of alkali-activated slags were prepared for investigating the characteristics of the hardened binders. They were kept in moulds at 20 °C and 65 % RH for one day. After demoulding the hardened binders were stored at 20 °C and 100 % RH until testing the compressive strength after 1, 7, 28 and 180 d, respectively. In order to analyze the pore size distribution and microstructure of the binders the hydration of some specimen was stopped by means of vacuum drying 28 d after the preparation. For these investigations a mercury intrusion porosimeter (Poremaster 60 GT, Quantachrome) and a scanning electron microscope (XL 30, Phillips) were used. The setting time of the binders was detected with an automatic Vicat apparatus according to DIN EN 196-3.

The mortars were prepared with a mortar mixer according to DIN EN 196-1. To determine the workability in dependence of the time, the slump was measured in accordance with DIN EN 1015-3 4 minutes after zero time as well as 10, 20, 30 minutes, and if possible 40 minutes after zero time. In addition the acid resistance of mortars were checked. At the age of 28 d, prism (4·4·16 cm³) were exposed to sulfuric acid, nitric acid and lactic acid (each pH-value 4 and 2) and for comparison in water and air. After 14 days, the specimens were removed from the solution, and stored two more days under standard conditions before testing their flexural and compressive strength.

For the concrete two quartz gravels (2/8 and 8/16) were used as aggregates. It was prepared with a concrete mixer ZZ 150 HE by Zyklos company with 150 l of usable volume. First the dry ingredients were pre-mixed to homogenize them for two minutes. Subsequently, the liquid component, consisting of the waterglass K-WG-0.75 and water were added and the concrete was mixed 4 more minutes.

3 Results and discussions

Binder

The compressive strength of the binders in Figure 1 depict several findings. After 1 d, the binders containing waterglasses with low SiO_2/Me_2O-ratios show slightly higher strength compared to the binders containing waterglasses with higher SiO_2/Me_2O-ratios. But from a reaction time of 7 d the strength is increasing with increasing module. This effect becomes more obvious when taking a closer look at the binders with sodium silicates.

High compressive strengths were achieved with potassium waterglasses, in particular K-WG-1.0. This binder reached already after 1 d a strength of nearly 40 N/mm², which increases over time up to 120 N/mm² after 180 d.

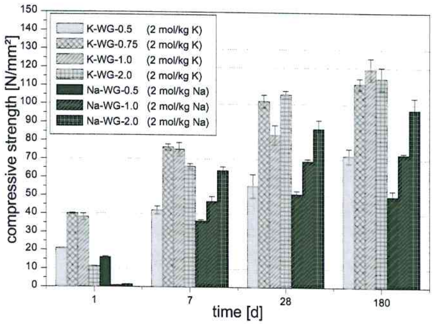


Figure 1: Effect of the SiO_2/Me_2O-ratio of the waterglass activators on the compressive strength of the activated GGBFS.

The porosity of alkali activated binders depend on the modulus of the waterglass used and can be very low. Figure 2 shows the pore size distribution of selected binders with potassium waterglas with moduli of 0.5, 1.0 and 2.0 compared to a hardened cement paste made from CEM I 42.5 R (water to cement ratio 0.35). After 28 d of hydration the hardened cement paste had a broad pore size distribution between 2 and 300 nm with a total porosity of 21.4 vol-%, where of 5.4 vol-% are in the range of gel pores. The total porosities of the alkaline-activated binders are all lower compared to cement paste sample. The majority of this porosity is formed from gel pores. The binder with K-WG-0.5 had the highest porosity with 15.2 vol-%. The lowest porosity had the binder with potassium waterglass with molar SiO_2/Me_2O-ratio of 1.0.

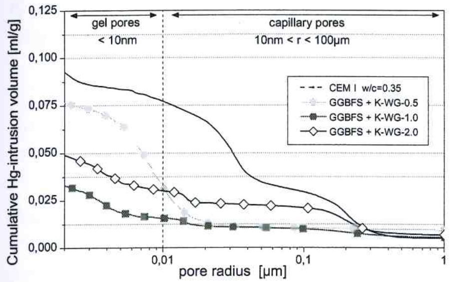


Figure 2: Pore size distribution of alkali-activated GGBFS with different potassium water-glasses as activator compared to a hardened cement paste (CEM I 42.5 R, water to cement ratio= 0.35).

Figure 3: SEM photomicrographs of a binder after 28 d of reaction (GGBFS with K-WG-1.0).

In Figure 3 scanning electron microscopy (SEM) images of the binder with K-WG-1.0 is represented. The selected specimen shows an extremely dense and obviously closed surface without visible pores. It is assumed that gel structures are formed during the hardening process, that cross-linked the slag particles. In contrast to CEM cements no distinct network of capillary pores is formed, which explains the density of the binder [9]. The high density is assumed to have a positive effect on the performance of these binder systems, especially regarding the high mechanical strength and the resistance against chemical attack, caused by the exposition to aggressive liquids and gases.

For the evaluation of the workability times of these alkali-activated binders the setting times were measured twice with an automatic Vicat needle apparatus. Figure 4 presents the setting times of the alkali activated binder pastes with sodium and potassium waterglasses. The clear dependency of the waterglass modulus becomes obvious. With rising SiO_2/Me_2O-ratio the setting times decrease. A possible explanation for this behavior could be a condensation of the colloidal silica oligomers of the waterglass resulting in a stiffening of the binder [9, 10]. The ratio of SiO_2/Me_2O, has a high impact on the resulting setting times, which is shorter with a rising content of SiO_2.

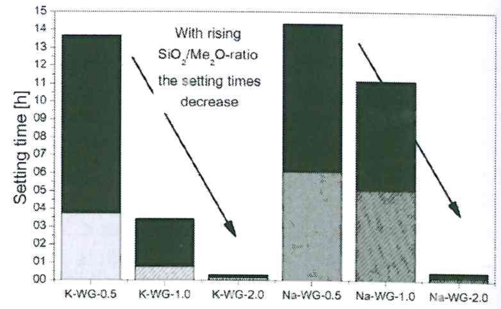


Figure 4: Setting times of alkali activated binders with GGBFS and waterglasses with different molar ratios of SiO_2/Me_2O (black part of the bar: time between the initial set and end set).

Mortar

The consistency and the workability time are important practically relevant properties of mortars and concretes. For practical use, it is specially necessary to influence the consistency, hence not only thin liquid mortar for coatings but also stiff concretes for pipes can be manufactured. For the investigation of consistency and processing time first a mix design for mortar was formulated which consists of GGBFS (Table 1) and a quartz sand 0/2 as well as waterglass and water as the activator. According to the calculation algorithm of Schwanda and Reschke [11, 12] to optimize packing density of broken material, GGBFS (40.8 wt.-%) and quartz sand 0/2 (59.2 wt.-%) were selected, resulting in mixtures with a low content of voids, and hence a maximum space filling of 0.799. The ratio of granulated slag and waterglass was the same as in the binder pastes. The water contents had to be adjusted because of the different solid contents of the waterglasses and the selected water to binder value.

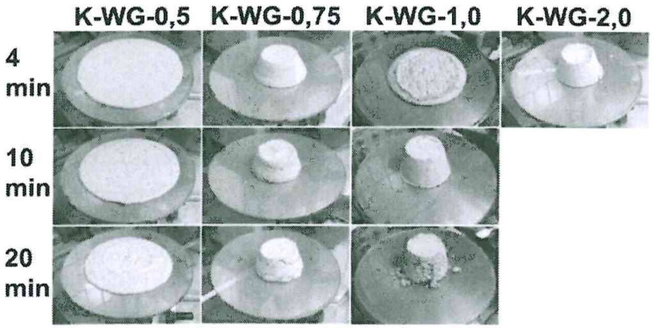


Figure 5: Value of flow table test of different mortars with alkali activated GGBFS (flow table Ø 30 cm).

The mortar with K-WG-0.5 as activator has the softest consistency (see Figure 5), and remains fluid and workable for a certain time after mixing. In contrast to that the mortar with K-WG-1.0 has a soft and fluid consistency at the beginning, but after 20 minutes it began to stiffen very fast resulting in a total loss of workability. The mortar with K-WG-2.0 stiffens even faster and the slump cone could not be filled for a second test after 10 min. Therefore, another activator was required, combining the high slump and long workability of K-WG-0.5 with the high strength of the binder with K-WG-1.0. All the advantages can be combined in the waterglas K-WG-0.75. As can be seen in Figure 1 the compressive strength after 1 d is around the same level like the binder with K-WG-1.0. The mortar with K-WG-0.75 shows a pronounced thixotropic behaviour. The slump is not as fluid as with K-WG-0.5, but the workability of mortar is good. With low mixing energy it is possible to stir up a plastic consistency again and keep it for more than 40 minutes.

This mortar was chosen for testing the acid resistance. Figure 6 on the left side represents the strength (relative to the residual cross-section) of the mortar with GGBFS and K-WG-0.75 after 14 d of storage in various media. The compressive strength of the prism embedded in sulfuric acid (pH=4 and pH=2), nitric acid and lactic acid (each pH=4) are comparable to the strength of the references in air or water. A loss in compressive strength could be observed in consideration of the specimens that have been exposed to nitric acid and lactic acid (pH=2).

On the right side of Figure 6 photomicrographs of two prism after 14 d storage in lactic acid (pH=2) are represented. The mortar above contains alkali-activated GGBFS as a binder, the mortar below is based on Portland cement. The latter is attacked until complete destruction. It was not possible to measure a compressive strength on these deformed specimens. This comparison shows that alkali-activated systems have great potential for acid resistance mortars in the case of sulfuric acid attack, als well as in the case of exposure to organic acids.

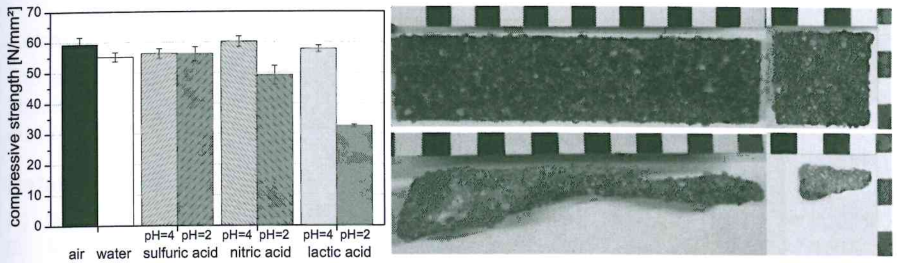


Figure 6: left side: Strength of mortar with K-WG-0.75 activated GGBFS after 14 d storage in various media; right side: Comparison of two prism after 14 d storage in lactic acid (pH=2); above: alkaline-activated mortar with K-WG-0.75, below: cementitious mortar.

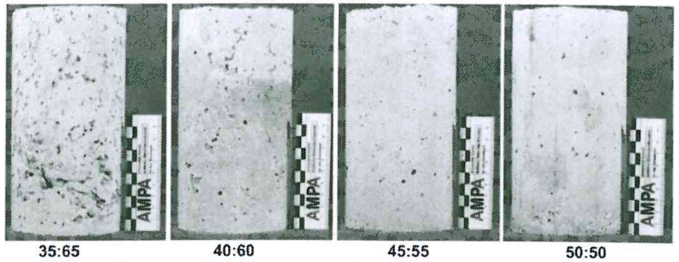
Concrete

The final step was the transfer from mortar to concrete scale and the production of an prototype. For the concrete products industry characteristics such as high green strength, good properties for demoulding and a high dimensional stability are necessary. These properties can be achieved with earth-moist concrete, which has a very stiff consistency and a high proportion of aggregates. The used binder paste or mortar must have a flowable consistency to allow a complete coating of the aggregate. For this reason, the mortar with K-WG-0.75 (water to binder value 0.45) was chosen. In order to achieve an immediate demoulding property, a high dimensional stability and a closed surface of the manufactured cylinders, it was necessary to find the optimum mortar to aggregate proportion. In Table 3 the concrete compostions depending on the ratio of mortar to aggregate are listed.

The specimens from earth-moist concrete (cylinder diameter 20 cm) were produced under load (27.5 kg) while compressing on the vibrating table. The proportion of mortar rises from 35 up to 50 vol-%. It was possible to produce green stable cylinders with high contour accuracy. As illustrated in Figure 7 the surface becomes denser with increasing binder content. Because the specimens with 45 and 50 vol-% do not differ so much, the concrete with a ratio mortar to aggregates of 45 : 55 was used for the prototype pipe for the lower content of waterglass.

Table 3: Concrete composition based on mortar with GGBFS and K-WG-0.75 with different mortar to aggregate ratios (water to binder value 0.45).

		Weight for 1 m³ concrete [kg]			
Ratio Mortar (M) to Aggregates (A) [vol-%]		**M : A 35 : 65**	**M : A 40 : 60**	**M : A 45 : 55**	**M : A 50 : 50**
Mortar	GGBFS	259	296	333	370
	K-WG-0.75	100	114	128	143
	Water	31	35	39	44
	Quartz sand 0-2	375	429	482	536
Aggregates	Gravel 2/8	984	909	833	757
	Gravel 8/16	738	681	625	568
Amount of paste [vol-%] Paste = GGBFS + WG + H_2O		21	24	27	30



35:65 40:60 45:55 50:50

Figure 7: Dimensional stability and surface appearance of concrete specimens with different ratios of mortar to aggregate

At first a formwork was prepared for a 1 m long pipeline with a wall thickness of 5 cm (inner diameter 20 cm, outer diameter 30 cm). After mixing the concrete it was poured in layers in the formwork, which was fixed on a vibrating table. To simulate the industrial manufacturing process the pipe was demoulded immediately. Figure 8 shows the described production process of the pipe demonstrator as well as the finished pipe, a sectional area and the surface of the hardend tube. Due to the mechanical treatment after demoulding a largely non-porous surface could be achieved on the inside and outside of the tube. This rework of the surface is quite commen in concrete factories e.g. in pipe manufacturing.

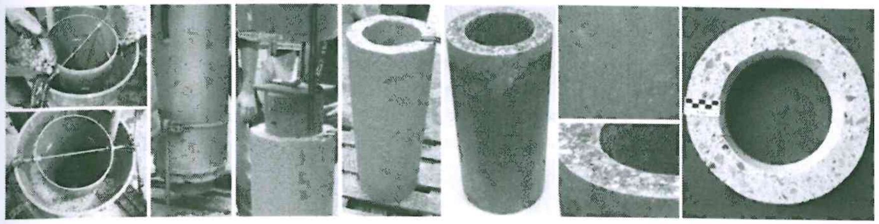


Figure 8: Production process of the pipe demonstrator (filling the formwork and demoulding), the finished pipe (iner diameter 20 cm, wall thickness 5 cm, height 1 m) as well as the sectional area and the surface of the hardend tube.

4 Conclusions

In this paper the development from binder over mortar and concrete to a prototype pipe was represented. Key finding of the investigation is that the specific choice of the waterglass is a dominant control variable to influence the binder, fresh and hardened mortar and concrete properties. With the decision whether a sodium or potassium waterglass is used with a high or low waterglass module (molar ratio SiO_2/Me_2O), the processing properties (consistency and processing time), the solidification and hardening and solid-state properties can be controlled in general. As a consequence mortar and concrete recipes can be developed that are adapted to application requirements. Furthermore, the production of the demonstrator shows that with these binders it is possible to produce concrete which is suitable for the concrete industry and has a good resistance to aggressive external conditions.

Acknowledgements

The authors thank the Bundesministerium für Bildung und Forschung for financial support. Thanks are also expressed to Mr. Ehrenberg (FEhS) and Mr. Krakehl (Woellner) for supply of materials.

References

[1] DAfStb: Sachstandsbericht Ultrahochfester Beton, Heft 561. 1. Auflage, Beuth Verlag, Berlin, (2008).
[2] Shi, C., Krivenko, P. V. and Roy, D.: Alkali-Activated Cements and Concrete. Taylor and Francis, New York, (2006).
[3] Glukhovsky, V. D.: Soil silicates. Their properties, technology and manufacturing and fields of aplication, Doct Tech Sc. Degree thesis, Civil Engineering Institute. Kiev, (1965).
[4] Škvára, F.: Alkali activated material - Geopolymer, Proc. International Conference Alkali Activated Materials (Prague, 2007), pp. 661-676.
[5] Buchwald, A., Hilbig, H. and Kaps, C.: Alkali-activated metakaolin-slag blends - performance and structure in dependence of their composition, Journal of Materials Science, vol. 42, no. 9, pp. 3024-3032 (2007).
[6] Buchwald, A.: Geopolymer binders - Part 1: What are geopolymers?, ZKG International, vol. 60, no. 12, pp. 78-84 (2007).
[7] Yip, C. K., Lukey, G. C. and van Deventer, J. S. J.: The coexistence of geopolymeric gel and calcium silicate hydrate at the early stage of alkaline activation, Cement and Concrete Research, vol. 35, no. 9, pp. 1688-1697 (2005).
[8] Yip, C. K. and van Deventer, J. S. J.: Microanalysis of calcium silicate hydrate gel formed within a geopolymeric binder, Journal of Materials Science, vol. 38, no. 18, pp. 3851-3860 (2003).
[9] Zellmann, H.-D.: Metaphosphat - modifizierte Silikatbinder als Basis säurebeständiger Beschichtungsmaterialien, doctoral thesis, Bauhaus-Universität, (2008).

[10] Goberis, S. and Antonovich, V.: Influence of sodium silicate amount on the setting time and EXO temperature of a complex binder consisting of high-aluminate cement, liquid glass and metallurgical slag, Cement and Concrete Research, vol. 34, no. 10, pp. 1939-1941 (2004).
[11] Schwanda, F.: Der Hohlraumgehalt von Korngemischen, beton, vol. 9, no. 1, pp. 12-17 (1959).
[12] Reschke, T.: Der Einfluss der Granulometrie der Feinstoffe auf die Gefügeentwicklung und die Festigkeit von Beton. Verlag Bau und Technik GmbH, Düsseldorf, (2000).

Part Four

STRUCTURAL BEHAVIOUR

pores are connected leading to a higher measured porosity. This can also be used to explain the trend shown in Fig 7 (c).

5 Conclusions

Our hypothesis that the strength of pervious concrete can be improved by using ultra-high performance matrix has been supported. More research is needed and currently carried out at the University of Connecticut to further improve the mechanical performance of pervious concrete. The following conclusions can be drawn from the current research:

1. The higher the strength of the matrix, the stronger the pervious concrete.
2. Increasing the aggregate to binder ratio of pervious concrete leads to increase of porosity and hydraulic conductivity but lower compressive strength in the range investigated (A/B=2.5 to 3.5). Sufficient matrix should be used to ensure the strength of pervious concrete while excessive matrix should be restricted.
3. With the increase of aggregate size, hydraulic conductivity is increased correspondingly due to the increase of pore size and connectivity.
4. With the combination of the use of ultra-high strength cementitious matrix and an optimum aggregate to binder ratio of 3.5, pervious concrete with high strength of 42.3 MPa and comparable permeability of 2 mm/s can be achieved.

References

[1] Pratt, C.J.; Newman, A.P.; Bond, P.C.: Mineral oil bio-degradation within a permeable pavement: long term observations. *Water Science and Technology* 39, pp. 103-109, 1999.

[2] Park, S.; Tia, M.: An experimental study on the water-purification properties of porous concrete. *Cement and Concrete Research* 34, pp 177-184, 2004.

[3] Schaefer, V.R.; Wang, K.; Sulieman, M.T.; Kevern, J.T.: Mix design development for pervious concrete in cold weather climates. Final reports, *Iowa Department of Transportation. National concrete Pavement Technology Center, Iowa Concrete Paving Association, 2006.*

[4] Yang, J.; Jiang, G.L.: Experimental study on properties of pervious concrete pavement materials. *Cement and Concrete Research 33,* pp 381-386, 2003.

[5] Meininger, R.C.:No-fines pervious concrete for paving. *Concrete International* 10 (8), pp 20-27, 1998.

[6] Ghafoori, N.; Dutta, S.: Laboratory investigation of compacted no-fines concrete for paving materials. *Journal of Materials in Civil Engineering,* 7 (3), pp 183-191, 1995.

[7] ACI 211.3-R02.: Guide for selecting proportiond for no slump concrete. *Manual of Concrete Practice 2004 CD-ROM, American Concrete Institute, Famington Hills.*

[8] Tennis, P.D.; Leming, M.L.; Akers, D.J.: Pervious concrete pavements, EB302, Portland Cement Association, Skokie, Illinoia, 2004.

[9] Lian, C.; Zhuge, Y.: Optimum mix design of enhanced permeable concrete – an experimental investigation. *Construction and Building Materials* 24, pp 2664-2671, 2010.

[10] Chindaprasirt, P.; Hatanaka, S.; Chareerat, T.; Mishima, N.; Yuasa, Y.: Cement paste characteristics and porous concrete properties. *Construction and building materials 22, pp 894-901, 2008.*

[11] Suleiman, M. T.; Kevern, J.; Schaefer, V. R.; Wang, K. : Effect of compaction energy on pervious concrete properties. Submitted to *Concrete technology forum-focus on Pervious Concrete*, National Ready Mix Concrete Association, Nashville, TN, May 23-25, 2006.

[12] Kumar, R.; Bhattacharjee, B.: Porosity, pore size distribution and in situ strength of concrete. Cement and concrete research, 33, pp 155-164, 2003.

[13] Wille, K.; Naaman, A.E.; Parra-Montesinos, G.J.: Ultra high performance concrete with compressive strength exceeding 150 Mpa (22 ksi): A simple way. *ACI Materials Journal 108 (1)*, pp 46-54, 2011.

[14] Wille, K.; Naaman, A.E.; El-Tawil, S.; Parra-Montesinos, G.J.: Ultra-high performance concrete and fiber reinforced concrete: achieving strength and ductility with no heat curing. *Materials and Structures, published online Aug. 27th 2011.*

Sewer pipes and UHPC - Development of an UHPC with earth-moist consistency

Michael Schmidt, Torsten Braun, Heiko Möller
Institute of Structural Engineering, University of Kassel, Germany

Sewer pipes and concrete have been in use since the mid-19th Century for the management of wastewater. Concrete pipes have the advantages of a large variety of possible cross-sectional shapes and they are economically producible and durable. Due to the progressive industrialization of the early to the mid 20th Century and the damaging effect of biogenic sulfuric acid in combination with a low water consumption there will be increasingly higher demands on the sewer pipes. Concrete with proper execution is in general resistant to various external influences, but has weaknesses in its resistance to acids. The protection of the sewage pipes as well as the repairs are usually very complex and expensive and presents challenges to the public sector as a carrier of the sewerage system. When using the fine-grained and slightly moist flowable UHPC in a earth-moist mixture, the acid resistance and hence the durability of concrete pipes can be increased. A UHPC has due to its low w / c ratio practically no capillary porses and its optimized packing density compared with normal concrete allows it to have a much higher structure tightness. Moreover, it is possible to achieve a reduction in the cross-sectional dimensions of the tubes, due to the high compressive strength.

Keywords: earth-moist concrete, concrete pipes

1 UHPC with earth-moist properties

Introduction

Earth-moist concrete after a vibration-press compaction is characterized by high green strength and fast direct stripping. These properties are of particular importance for the concrete products industry as the concrete products can be stripped immediately after the design. The green strength at this time must be designed so that it can hold the proper weight of the concrete products and that the shape stability is guaranteed. To achieve these properties classic earth-moist concrete has a relatively low water-cement ratio of 0.35 to 0.45 and a cement content of between 270 kg/m³ and 350 kg/m³. The paste content is between between 210 and 240 l/m [1]. These small paste content and a relatively high proportion of coarse grain in the recipe are responsible for the stiff consistency of a earth-moist concrete. The paste content, with optimal dosing, in the early hardening stage is primarily responsible for the formation of the green strength. At this stage, the paste content acts as a filler of the cavities formed between the rock grains and as an adhesive of the grain skeleton. With increasing hydration, the paste is increasingly under pressure from compression forces and combines the grain skeleton with each other. In the stage of the hardened concrete the paste is responsible for the formation of a sufficiently pressure-resistant and durable concrete. Thus the paste has two essential functions from a setting time perspective, both of which are essential features for an earth-moist concrete in the early and late stages. With the use of a fine-grain and flowable UHPC paste for the creation of earth-moist concrete, specific characteristics of traditional earth-moist concrete can be improved. This includes a denser and more closed surface that is more resistant to external influences. A further increase in efficiency in the production, transportation and handling of the pipes can be achieved by reducing the wall thickness.

Focal points of the research

The aim of the work performed was to conceive an earth-moist concrete, which contains a high proportion of coarse grain and a binders paste that is based on a UHPC. The characteristics of this earth-moist concrete should, as with the traditional earth-moist concrete also, be a good green strength immediately after stripping. Furthermore, the results were also evaluated based on the parameters of surface integrity and of dimensional stability of the specimen. In order to achieve these conditions, the optimal relationship between the UHPC and the aggregate has been identified using a vibration proctor test developed by the University of Kassel. Following these investigations in the laboratory, the practicality of the formulations was to be documented in a concrete factory with the production of pipe demonstrators with a nominal diameter of DN 300.

Setting the UHPC paste

UHPC formulations developed at the University of Kassel are firstly fine-grain recipes with a maximum particle size of 0.5 mm and the secondly coarse-grained recipes with a maximum particle size of 8 mm. The main differences between these two recipes consist in a lower matrix fraction < 0.125 mm by 35 vol- to 40.5 vol-% and at a much lower cement content of the coarse-grained UHPC formulation [3]. During these investigations, the fine-grained and coarse-grained UHPC formulations were studied for up to a maximum particle size of 0.5 mm, in terms of fresh and hardened mortar characteristics. For the development of an earth-moist UHPC a flowable paste with a slump flow of > 30 cm should be used, and the paste should have very good compressive strength and overall porosity results. The studies were divided in fresh paste investigation with the following characteristics:

- slump flow according to DIN EN 12350 Part 3
- air content according to DIN 12 350 Part 7

and in hardened paste investigations with these characteristics:

- compressive strength after 7 - and 28 days after immersion in water
- Studies on the pore size distribution by the mercury penetration porosimetry.

Table 1: Composition of UHPC paste.

Constitutive materials	Volume [dm³]	Mass [kg]	Density [kg/dm³]
Water	158,0	175,0	1,00
Pore space	15,1	-	-
CEM I 52,5R	209,7	650	3,10
Silica fume	80,5	177,0	2,20
Superplasticizer	28,3	30,0	1,07
Quartz powder fine	122,6	325,0	2,65
Quartz powder gross	49,4	131,0	2,65
Quartz sand 0,125/0,5	133,6	354,0	2,65

Paste levels

An earth-moist concrete in the fresh state corresponds to a weakly cohesive soil [4]. The structural behavior in this early stage is not yet based on the hydration products which are being formed, but there is an interaction between paste and aggregate, which are based on known soil mechanical relationships. The cohesion of the earth-moist concrete is ensured at this point by variables such as internal friction and cohesion, and the load transfer is ensured by the grain skeleton of the rock grains [4, 5, 2, 1]. This grain structure forms a so-called load transfer chain when it comes ideally to a a grain-to-grain contact.

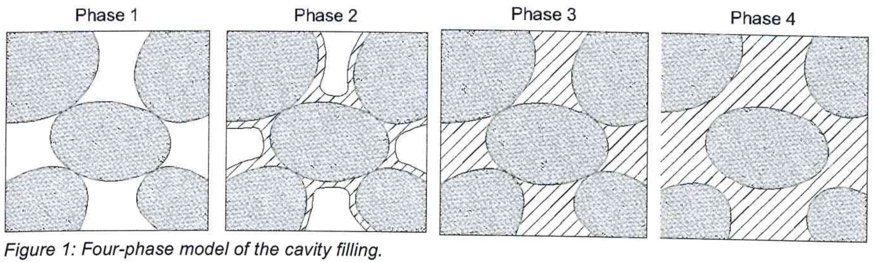


Figure 1: Four-phase model of the cavity filling.

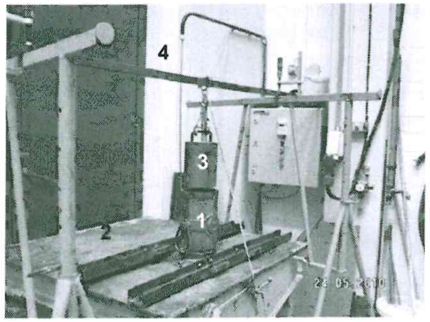
According to [2] an optimal paste/aggregate ratio relationship exists when a grain-to-grain contact exists and when the voids are filled with paste. If the cavities are overfilled or underfilled the green strength and dimensional stability of the removed concrete products is no longer guaranteed. In Figure 1 the four-phase model of the cavitty filling is presented. It describes the increasing degree of filling of the cavities, Phase 3 is characterized by an optimal filling and with a grain-to-grain contact between the aggregate. In order to obtain the optimum filling level of a earth-moist mixture using a UHPC paste, the vibration proctor test was used. In this method the paste/aggregate ratio is graded and compressed under a steady vibration-press compaction. Through the gradual approach the paste content increases with each examination step whilst the aggregate content is decreased. This makes it possible to determine the optimal paste content of a slightly moist mixture.

Vibration proctor investigation

The proctor test [6] is a method, used in geotechnical engineering, to determine the ability of a soil compaction. With a sweeping consolidation a connection between the dry density and different water levels of the soil is created using a constant compaction work. In [2] an additional development step was created for the vibration proctor test modeled after the Proctor experiment for the use of an earth-moist sample. The apparatus consists of a steel cylinder mold (height: 300 mm, diameter 150 mm) and a load weight, which creates a constant surcharge stress of 0.016 N/mm ². The surcharge stress prevents movements of gross aggregate in the earth-moist aggregates in the sample slightly moist. The test set is fixed firmly on a vibrating table and with incipient vibrating influence stand there is a compression of the sample. Figure 2 shows the structure of vibration proctor stand. With this method it is possible to determine the maximum achievable dry density of a concrete mixture. This indicates in turn, with which level of paste content the void is completely filled.

The vibration proctor investigations were made with UHPC paste shown in Table 1. As aggregates, a gravel- (unbroken), basalt- (broken) and a basalt grain size with gap grading were used. The grain size range in each case was 0/16. In accordance with DIN 1045-2, the grain size range "cheap" was used and for the gap grading the gap grading grain size was used.

The mixing of earth-moist concrete was carried out in a compulsion mixer ZZ30 HE from the manufacturer Zyklos with a volume of 20 l at a speed of 60 rev/min with the auxiliary drive and whorl in use. The initial mixing volume was 12 l and increased with the increase of the paste content to about 20 liters. After the end of the mixing time of 10 minutes the earth-moist concrete was filled under vibration influence (60 Hz, amplitude 0.75 mm) flush with the surface in the steel cylinder mold. The load weight was placed after the filling and then it was compressed for another minute. The entire filling and compaction time was about 3 minutes.



1 cylinder mold
2 vibrating table
3 load weight
4 auxiliary frame

Figure 2: Experimental setup vibration proctor test.

In Figure 3, the Proctor curve of the three test series are shown. The y-axis shows the dry density and the x-axis shows the respective paste content of the mixture. There is evidence across all three mixtures, that an optimal density is reached at about 35 vol-% paste to 65 vol-% aggregate. It can also be seen that the two basalt mixtures have almost identical patterns and overall a higher dry density than the gravel mix. In the literature it is known that with increasing fine-grain content, the dry densities also increase. The mixing quantities of basalt mixtures were larger than the mixing quantities of the gravel mixture. This is an indication that a higher void content had to be filled between the basalt graining with paste. This in turn increases the overall paste content and therefore the fine-material content of the mixture. The curve of the gravel mixture approaches saturation much more slowly, this indicates a continuous increase in the cavity saturation.

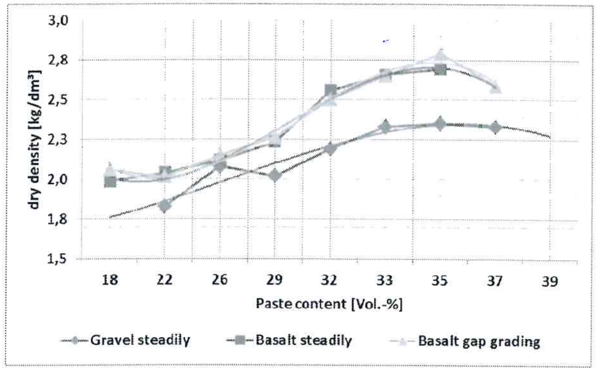
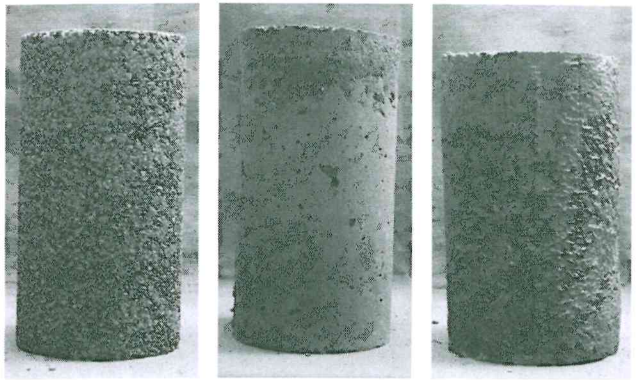


Figure 3: Determination the proctor density with three different grain compositions [7].

Critical to the selection of a suitable composition was not only the best paste/aggregate ratio, instead the surface texture of the specimens should likewise have a unified appearance.

Figure 4 shows an exemplary specimen of gravel mixture after the vibration proctor investigations. The left image shows a test specimen with the paste/aggregate ratio of 26/76, the middle image, a ratio of 35/65 and right ratio of 37/63. In the images of the specimens the phase model of the cavity filling [2] based on constructed surfaces can be seen quite clearly. The left image shows a test with too small a paste content, hence the surface is not closed. The middle image shows an almost unbroken surface, the specimen remained stable in shape after stripping and using the Proctor curve this paste/aggregate ratio has the highest packing density. As for the right-hand specimen there was an over-filling of the cavities, this is very easily recognized by the supersaturated surface as well as the loss of form stability. In conclusion, it shows that with the vibrating proctor test the optimal density of the earth-moist mixture can be detected even with a gradual approach with regards to the paste content.



26/74 35/65 37/63

Figure 4: Specimens with different paste/aggregate ratios, gravel mixture.

2 Preparation of concrete pipes in the plant

Composition / Experimental procedure / production

In a precast concrete plant the earth-moist mixtures, which were previously examined in the laboratory, were put into practice. The plant produces steel reinforced concrete pipes for the wastewater sector in various diameters and lengths up to about 1 m. The earth-moist mixtures are manufactured in a 1.5 m³ synchronous mixer and transported via a conveyor belt to the production plant. The production of the pipes is carried out via a system with a fixed inner part and a movable and removable outer tubular casing. The filling of the formwork is done under vibrating influences, after completion of the filling the pipe is compressed under load. A total of 11 concrete pipes with a nominal diameter of DN 300, length 1100 mm were produced.

In a precast concrete plant the earth-moist mixtures, which were previously examined in the laboratory, were put into practice. The plant produces steel reinforced concrete pipes for the wastewater sector in various diameters and lengths up to about 1 m. The earth-moist mixtures are manufactured in a 1.5 m³ synchronous mixer and transported via a conveyor belt to the production plant. The production of the pipes is carried out via a system with a fixed inner part and a movable and removable outer tubular casing. The filling of the formwork is done under vibrating influences, after completion of the filling the pipe is compressed under load. A total of 11 concrete pipes with a nominal diameter of DN 300, length 1100 mm were produced.

In the practice tests in that plant the same moist mixture from the laboratory tests was used. Furthermore, a second UHPC recipe was used, which contained a different superplasticizer and silica fume. Thus conclusions about the effect of different flow agents could be drawn and this enabled a certain hedge against the possible non-success of a mixture. As the optimal paste/aggregate ratio 35/65 was also used for this second UHPC paste.

For the production of these first tube pipes made out of a earth-moist UHPC principally the following main questions should answered :

- is it possible to create and process an earth-moist UHPC in the factory given the existing mixing and compaction equipment?
- is it still possible to process the earth-moist UHPC for the duration of a production cycle which consists of a total of six tubes and a duration of about 60 minutes?
- Is it possible to obtain a closed surface (blowholes, flaws)?

A volume of 500 l was mixed using a paste/aggregate ratio of 35/65. As aggregate sand 0/2, gravel 2/8 and gravel 8/16 from the available local resources were used. The mixing time in the synchronous mixer was about 10-12 minutes. The ingredients were homogenized for 2 minutes before the water/superplasticizer mixture was added. The fresh concrete temperatures fluctuated between 24.5°C and 25.4°C. The earth-moist concrete was then transported to the pipe manufacturing plant via the conveyor belt system. Overall, the pipe fabrications were very successful, so that 5 pipes DN 300, l = 1100 mm w with bell and spigot were manufactured for each of the two recipes . The figure below shows some of the manufactured concrete pipes in the general view and the detail of the surface.

Figure 5: Manufactured concrete pipes (left) in the view, detail of surface structure UHPC pipe (middle), concrete pipe factory original (right)

The pipemanufacturing with the reformulated recipe was generally speaking a success. However, the optimum paste/aggregate ratio of the laboratory investigations of 35/65 turned out to be a bit too high for the production inside the plant system. The tubes manufactured with this ratio showed within in a shorttime a slight bulge in the middle of the tube. In a second experiment, the paste/aggregate ratio was then decreased to 30/70. These tubes could be very well produced and are shown in Figure 5.

The earth-moist concrete could be used after mixing of about 60 minutes. The surfaces shown in figures 5 indicate that that the earth-moist UHPC exhibited a similar high surface quality as the concrete tubes of the concrete plant. The surfaces of the tubes were almost cavities free except some small spots. A coarse-grained and non-closed structure was formed primarily in the folds of the spigot of those pipes that were produced at a later stage.

Post examinations

Following this production several studies of the concrete pipes were conducted. For this purpose pipes from each recipe as well as original pipes of the concrete plant were sent to the University of Kassel. The original pipes were used to generate some reference values. Several studies on the compressive strength and durability were conducted. As examples the following

figure shows the results for compressive strength according to DIN EN 12390-03 and the crown compressive strength according to DIN EN 1916.

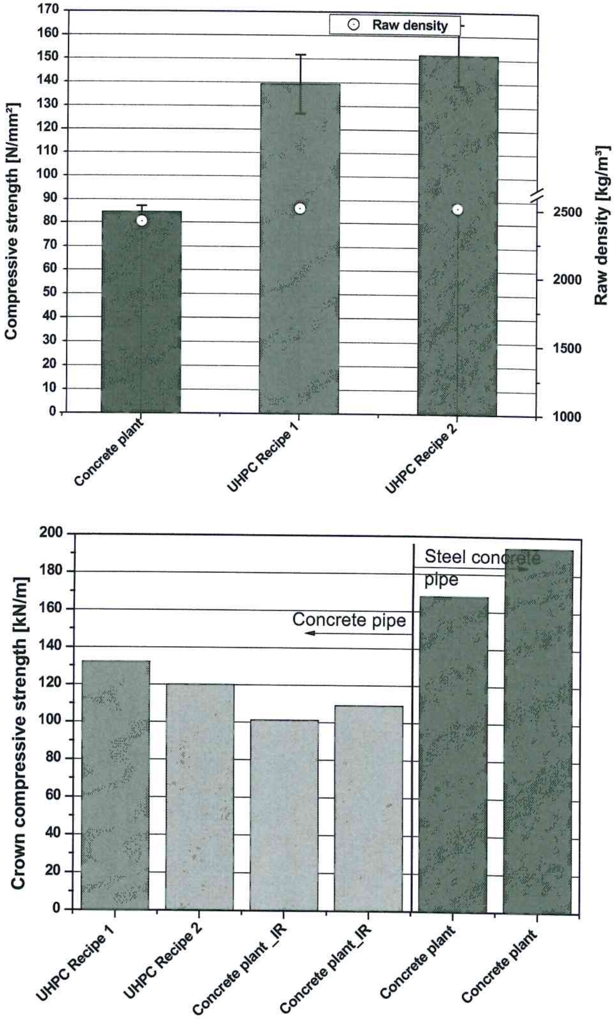


Figure 6: Compressive strength results on cores (above), results of the crown compressive strength (below)

The mixture designation Recipe 1 describes the UHPC paste that has been studied in the lab using the vibration proctor tests. The Recipe 2 is the additional recipe that was made in the concrete plant. In order to determine the compressive strength three cores were drawn from the pipes for each recipe. The ends of the cylinders were grinded so that the height and the diameter were 5 cm. The compressive strengths were determined at an age of > 56 days. The graph shows very clearly the increased strengths of a earth-moist UHPC compared with a normal earth-moist concrete. The right figure shows the results of the crown compressive strength test after 28 days. The earth-moist UHPC pipes as well as two steel reinforced concrete pipes of the concrete plant were examined. The steel reinforced concrete pipes showed as expected, a much higher crushing strength than the concrete pipes. The two results, called concrete plant_IR show the initial cracking during the the crushing test of the steel reinforced concrete pipes. For concrete pipes the break would have occurred after the initial crack and this indicates compared to the moist UHPC pipes an increase in the crown compressive strength compared to concrete pipes made out of ordinary earth-moist concrete.

3 Summary

UHPC is typically a fine-grained, free-flowing concrete for structural applications. Its high strength and especially its much higher density structure virtually without capillary pores can also be used in other application areas. These studies with the use of UHPC in earth-moist mixtures indicate a new possible application in the field of precast concrete products. It is possible to manufacture concrete pipes with a significantly improved mechanical and chemical resistance.

The investigations showed that the optimal paste content a earth-moist mixture can be identified using a vibration proctor test. The difference to the original test procedure was that not the water content was increased gradually in the mixture but instead the UHPC paste was added as a whole in a graded fashion. Due to the dense and compact structure of the UHPC paste very good compressive strength and crushing results were obtained. For further investigations in this area, it would also be possible to reduce the wall thicknesses.

References

[1] Bornemann, R.: Untersuchungen zur Modellierung des Frisch- und Festbetonverhaltens erdfeuchter Betone; *Schriftenreihe Baustoffe und Massivbau*, Universität Kassel, Heft 4, 2005.

[2] Schmidt, M.: Stoffliche und konstruktive Eigenschaften hydraulisch gebundener Tragschichten. *Schriftenreihe der Zementindustrie*, Heft 51, 1991.

[3] Bornemann, R.; Schmidt, M.: Ultra-Hochleistungsbeton UHPC - Herstellung, Eigenschaften und Anwendungsmöglichkeiten. *Beton- und Stahlbetonbau*, 2001, S. 458-467

[4] Wierig, H.J.: Zur Frage der Theorie und Technologie des grünen Betons. *Institut für Baustoffkunde und Materialprüfwesen der Technischen Universität Hannover*, Universität Hannover, Heft 19,1971

[5] Wierig, H. J.: Einige Beziehungen zwischen den Eigenschaften von „grünen" und „jungen" Betonen und denen des Festbetons. *Betontechnische Berichte, Betonverlag Düsseldorf*, 1971, S. 151 – 172

[6] DIN 18127: Proctorversuch – Baugrund, Untersuchung von Bodenproben, *Deutsches Institut für Normung*, 1997

[7] Möller, H.: Konzeption und Untersuchung erdfeuchter Betone mit erhöhten Festigkeiten, *Diplomarbeit FG Werkstoffe des Bauwesens, Uni Kassel*, 2010 *unveröffentlicht*

Development of an Ultra-High Performance Concrete for precast spun concrete columns

Thomas Adam[1], Jianxin Ma[2]

1: Europoles GmbH & Co. KG, Neumarkt i.Opf., Germany
2: Inst. f. Werkstoff- und Konstruktionsentwicklung, Magdeburg, Germany

Strength Class of C100/115 is the present state of art in the field of spun concrete. Consequentially, the next step was the application of concrete above the structural capability of C100/115. Therefore EUROPOLES has started to enhance the compressive strength gradually up to 150 N/mm² during the past years. Due to the different features in compacting (spinning) process the composition and fresh propterties of this UHPC differ necessarily from that of common UHPC The volume fraction of the cementitious paste is much lower. Powders with a Blaine-fineness of about 2500 cm²/g are more favorated than ultrafine powders mostly used in common UHPC. Furthermore the spun UHPC must have a high green strength after spinning. EUROPOLES has produced prototype spun columns and poles. The whole project is undergoing.

Keywords: spun concrete, columns, UHPC

1 Introduction

It is characteristic for spun concrete, that the compaction of the fresh concrete is generated by using centrifugal forces in a rotating mould (*Figure 1*).

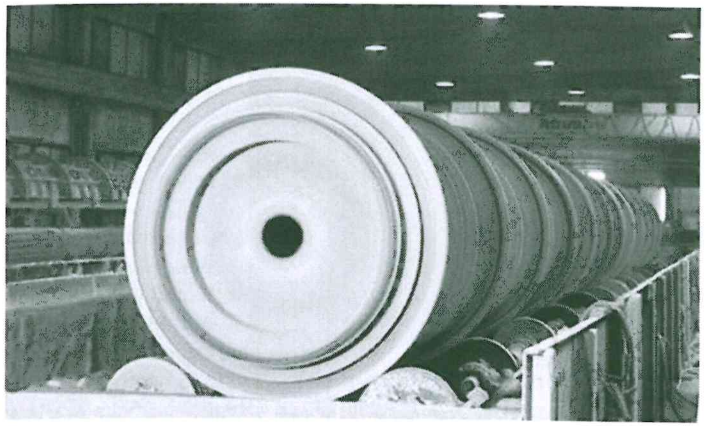


Figure 1: Spinning process.

Thus, the result are rod-shaped elements with a very smooth and dense concrete shell and a circular cavity in the middle of the cross section.

Applications range from light poles, telecommunication and power poles to precast columns for structural use. Logically, an increase in the compressive strength of the concrete benefit the load bearing capacity, especially of elements mainly stressed with normal forces, as columns. During the past years the compressive strength has gradually increased up to C100/115, which is the maximum strength class covered by the DIN-standard [1] and general type approval of EUROPOLES up to now. In order to stay competitive with other concrete columns and steel composite columns further progresses were needed.