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Self-compacting concrete as an economical and efficient alternative for the rehabilitation of structures and structural members

The aim of this research project was to establish prerequisites for the use of self-compacting concrete (SCC) as an economical and efficient method for the rehabilitation of structures and structural components as well as a material for use in general construction. The proposal of developing a robust, controlled, and economical SCC required cooperation between the Technische Universität Berlin (TU Berlin, Department of Building Materials and Material Testing), a construction firm (BWE Ingenieurbau, Neustrelitz), and a supplier of testing technology (Projekt Elektronik Mess- und Regelungstechnik GmbH, Berlin) within a joint project.

The goal was to be reached by rationalizing the conceptual processing steps of SCC and the consequent enhancements for the construction material: precision and robustness. This requires a simple rheological test methodology. Part of the project was to develop a test method for the laboratory as well as in-situ applications in order to perform suitability- and quality tests of concrete.

Instead of developing a universal SCC of high complexity for internal structural components, this research project aimed towards developing a low-cost-concrete. To allow for sustained design with limited resource consumption, inorganic secondary substances were used in the course of the project. Various rock powders were selected that accumulate from dedusting in crushing and sieving plants. Larger quantities of rock powders may be added to SCC compared to conventional concrete. Rock powders of the Mitteldeutsche-Hartstein-Industrie AG and the Readymix AG were tested. Results from laboratory tests were to be applied in practical applications. As such, construction personnel should learn about the convenient handling of SCC. Practical applications served the testing of SCC.

Due to the intention of utilizing a concrete with finely ground secondary substances, an SCC of the powder type seemed appropriate. The mix design of SCC is primarily linked to the rheological properties of the fresh concrete. As a result, the relative quantities of constituent materials cannot be evaluated based on the same volumetric design approach used for conventional concrete. This work proposes one possible methodology for the mix design of SCC.

In the design approach, the relative volumetric concentration of coarse dispergents should be limited to a value of 0.5. As a result, 70 % of the viscous matrix forms a movable coating around the coarse aggregates. Hence, the flow properties are not affected by friction forces between individual aggregates. The mortar matrix must be capable of carrying the aggregates during both concrete placement and curing inside the formwork. If the matrix has a sufficiently low yield stress, the entire system can level out under gravity. In practical applications, the yield stress may be reduced by addition of a highly efficient superplasticizer on polycarboxylatether base. The matrix viscosity may be reduced by using concrete admixtures with high water retention, such that the SCC can deaerate and self-compact during flow. To prevent separation of the concrete constituents, the viscosity of the mortar matrix must be sufficiently high. In general, the viscosity of SCC matrices is higher compared to that of a conventional concrete.

The viscosity of the mortar matrix is adjusted by using inorganic finely ground substances. Results of this work show that a water-powder volume ratio less than 0.31 will result in a matrix with sufficient stability. Cements with a high fineness are preferred for increasing the stability. If the powder contains only cement or if it is composed using a reactive filler, the resulting SCC will show strengths similar to those of high-strength concrete. For SCC of the powder type, properties of the hardened concrete are affected by the filler-cement volume ratio, the cement type, and the filler type in particular. Replacing the binder with inert rock powders has shown to result in SCC of normal strength. If the water-cement ratio is evaluated based on water retention capability, density of solid constituents and reduction factor, the concrete strength may be assessed as a function of the filler-cement ratio using the modified curve of Walz. Beforehand, the water retention capability of each powder combination and the density of the constituent powders must be determined. The reduction factor may be taken as 0.85. Considering the required minimum cement content, the rock powders used in this investigation yielded a filler-cement volume ratio of 1.

To obtain a sufficient level of deaeration and compactability, powders with a high specific surface area larger than 15 m^2/cm^3 appeared particularly suitable. For rock powders, this translates to a mass-related surface area of 5 m^2/g, which is roughly 6 times larger compared to that of fly ash. The fine rock powders also showed a positive effect on robustness of the mortar matrix. Mixing inaccuracies and variations of aggregate moisture content, which may lead to changes in the concrete water content, will rarely result in concrete separation when using fine rock powders. However, a high surface area in combination with a narrow grain size distribution was found to be a disadvantage, as it resulted in a significant increase in superplasticizer demand. Large quantities of superplasticizer present unnecessary expenses for self-compaction. The superplasticizer demand was particularly low for SCC using the selected basalt powder with a large surface area.

In the course of this research project, various physical properties of the rock powders were assessed and discussed. The following physical properties represent meaningful criteria for the appropriateness of finely ground admixtures in SCC: the specific surface area according to the procedure of Brunauer, Emmett and Teller (BET), the parameters of the RRSB-function, which linearizes the grain net of Rosin, Rammler, Sperling and Bennett, as well as the water retention capability according to Okamura. For powder combinations using cement and finely ground admixtures, latter value should lie between 1 and 1.2.

During mix design as well as suitability- and quality testing, the rheological properties of SCC must be monitored. Given the fact that fresh concrete is a non-Newtonian medium, its rheological behavior may not be described using the conventional single-point-measurements. Instead, rheological methodologies are needed to describe the shear-stress-dependent flow behavior of concrete and, if necessary, point out the proper adjustments in order to obtain self-compacting properties. An essential result of this work is a novice rheological measurement principle for SCC.

The measurement principle, developed at the TU Berlin, was converted into a rheometer by the Projekt Elektronik GmbH. It is capable of measuring coarse-dispersive flowable mortar- and concrete suspensions. The measurement principle is comparable to the falling-ball-viscometer. Unlike the viscometer, the novice measurement principle utilizes a numerical procedure to evaluate the flow curve from the velocity of a vertically accelerating sphere. As such, the testing device can be classified as a falling-ball-rheometer. Fluids with a high chemical and physical stability are used to test the principle. Correlation of test results with flow curves obtained from a rotation-rheometer of the Searle-type proves the correctness of the analysis as well as the approaches for correcting side- and end-effects. An algorithm was developed to evaluate the apparent flow curve of structurally-viscous media. The software KF-RHEO that was implemented for the falling-ball-rheometer allows representation, documentation, and archiving of test results on a laptop computer. The falling-ball-rheometer was designed such that shear-velocities between 5 and 15 s^{-1} can be measured. The prototype has a capacity of about 25 liters.

The Bingham-law represents the most frequently applied model for cement paste, mortar and concrete. It was shown that the measured apparent flow curves of mortars and concretes could be approximated using the Bingham model. Relative values for plastic viscosity and yield stress were obtained using this model. The range of application of the developed prototype is limited to flowable, homogeneous mortars and concretes for which the method yielded plastic viscosities between 5 and 120 Pas and a yield stresses between -600 and 100 Pa. This includes self-compacting mortars and concretes. The plastic viscosity of self-compacting mortars using rock powders was between 6 and 24 Pas with a yield stress between -86 and -8 Pa. For SCC, the plastic viscosity ranged from 30 to 65 Pas. Concretes with sufficient flowability showed yield stresses between -200 and 50 Pas. The test results revealed a distinct correlation between the age of SCC and both its plastic viscosity as well as its yield stress.

Advantages of the falling-ball-rheometer include the short test duration of only a few minutes, easy handling, as well as the immediate and automated documentation of test results. Latter makes the rheometer also suitable for monitoring the concrete quality on-site. To assess the practicability of the rheological test principle, measurements at a concrete pre-cast facility were conducted.

Tests conducted on the hardened concrete yielded a normal-strength SCC with compressive strengths ranging from C 30/37 to C 40/50. Following the optimization of selected SCC mix-designs for the ready-mixed concrete sector, which encompassed laboratory testing as well as results from a Readymix AG mixing plant in Berlin, large-scale tests in cooperation with BWE Ingenieurbau AG were conducted.

The concrete properties of SCC using rock powders were discussed based on porosity and pore size distribution. Porosity represents one of the primary influence factors for impermeability and strength of the hardened concrete. For SCC using rock powder, the porosity corresponded to that of conventional concrete ranging from 12 to 17 vol.-%. For shrinkage, the capillary porosity is crucial. SCC shows a pore size distribution which differs from that of conventional concrete. Using mercury intrusion porosimetry, a characteristic pore size distribution with a predominant peak < 0,1 µm was determined. The shift of the pore size distribution towards smaller pores is due to the transition zone between coarse aggregates and matrix. The use of finely ground, inert admixtures leads to numerous physical effects that result in a denser, stronger and more resistant transition zone. Examination of the activity index and concrete strength confirm this. SCC using Portland cement and rock powder reached compressive strengths of up to 35 % higher than expected according to the curve of Walz. Another important factor is that the low structural stress during processing of SCC prevents internal bleeding, such that no capillary-porous transition zones are formed. However, the pore size distribution of SCC has a negative effect on the sensitivity during curing. For an uncured SCC, a substantial increase of drying shrinkage was noted compared to a conventional reference concrete of identical strength.

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