J. Reiners, C. Müller, Research Institute of the Cement Industry, Duesseldorf,
J. Penttilä, R. Breitenbücher, Ruhr-Universität Bochum, Bochum, Germany

SUMMARY

Associated with the trend towards softer concretes it is now often found that significant changes in the fresh concrete properties occur unexpectedly and unpredictably in longterm construction projects in spite of using the same concrete composition. In a joint research project between the Research Institute of the Cement Industry and the Chair of Building Materials Technology in the Institute for Structural Civil Engineering at Ruhr-University Bochum criteria were worked out for designing concrete mix formulations. The intention is that these criteria should be fulfilled to prevent the occurrence of undesirable fresh concrete behaviour and so that the inadvertent influence on the fresh concrete properties caused by material- and production-induced fluctuations in the concrete constituents is as small as possible.

ZUSAMMENFASSUNG

Einhergehend mit der Entwicklung zu weicheren Betonen wird derzeit immer wieder beobachtet, dass sich Frischbetoneigenschaften bei länger andauernden Bauvorhaben trotz gleicher Betonzusammensetzung unerwartet bzw. unvorhersehbar signifikant verändern. In einem gemeinsamen Forschungsprojekt des Forschungsinstituts der Zementindustrie mit der Ruhr-Universität Bochum, Institut für konstruktiven Ingenieurbau, Lehrstuhl für Baustofftechnik, wurden Kriterien für den Entwurf von Betonzusammensetzungen erarbeitet, die erfüllt sein sollten, damit kein unerwünschtes Frischbetonverhalten auftritt und die ungewollte Beeinflussung der Frischbetoneigenschaften durch material- und produktionsbedingte Schwankungen der Betonausgangsstoffe möglichst gering ist.

(Translation by Robin B.C. Baker)

Achieving the intended concrete properties in modern 5-material systems of varied concrete constituents

Erreichen projektierter Betoneigenschaften im modernen 5-Stoff-System diverser Betonausgangsstoffe

1 Introduction and research objective

In recent years the onward development of admixtures for plasticizing concrete – especially superplasticizers based on PCE (polycarboxylate ether) – has led increasingly to the use of concretes with soft consistencies. These concretes are easier to place and compact, which makes it possible to accelerate the job sequences and reduce costs [1].

Associated with the trend towards softer concretes it is often found that significant, unexpected and unpredictable changes in the fresh concrete properties occur in construction projects that extend over fairly long periods in spite of the use of the same concrete composition and the same constituents. Deviations from previous behaviour occur for apparently inexplicable reasons with concretes that had previously been processed many times without any problems. These deviations include changed consistency, secretion of water (bleeding), sedimentation and accelerated or retarded strength development [2, 3].

The research project was intended to identify the most important influencing parameters that are responsible for undesirable changes in the fresh concrete properties. The intention was also to work out criteria for the design of concrete compositions so that no unwanted fresh concrete behaviour occurs and to minimize the susceptibility to fluctuations caused by materials or production. In the research project the term "robust" was applied to those concrete compositions in which the fresh concrete properties did not change unexpectedly and significantly either as a consequence of the usual influencing factors found in concrete production or as a consequence of fluctuations in the constituents that normally occur in practice due to the production process.

2 Investigations

2.1 Working step 1: Investigation of concrete compositions with respect to their tendency towards undesirable fresh concrete properties

The first step was to produce concretes with paste contents of approx. 245 l/m^3 to approx. 300 l/m^3. The term "paste content" includes cement, admixtures, the flour-fines content of the aggregate (particle size 0 to 0.125 mm) and water. The concretes had equivalent water/cement ratios between 0.45 and 0.65. Four different superplasticizers were used to achieve the target consistency (flow table spread of 55 cm immediately after the end of mixing). The following concrete properties were determined in order to classify the concretes with respect to their tendency towards undesirable fresh concrete properties with specific influencing parameters (temperature, grading curve and mixing time):

- Flow table spread as specified in DIN EN 12350-5 [4] at different times after production of the concrete (0, 45 and 90 min)
- End of the workability time as specified in the DAfStb guidelines for concrete with extended workability times (retarded concrete) [5]
- Water secretion by determining the quantity of bleed water ("bucket method") in accordance with the DVB code of practice "Special methods for testing fresh concrete" [6]
- Tendency to sedimentation (sedimentation test following the "Self-compacting concrete" guidelines issued by the DAfStb [7]
- Air content of the fresh concrete (pressure equalization method as specified in DIN EN 12350-7 [8])

A virtually linear relationship was often observed between the quantity of mixing water and the quantity of bleed water measured by the bucket method (› Fig. 1). Quantities of bleed water that sometimes significantly exceeded the reference value of 0.3 vol. % given in the DVB code of practice for structural concretes occurred regularly with the concretes with water contents > 170 l/m^3 that were examined. However, most of these concretes appeared visually stable on the flow table and exhibited good cohesion. On the other hand, low levels of water and paste combined with high addition levels of superplasticizer led to concretes that exhibited segregation phenomena on the

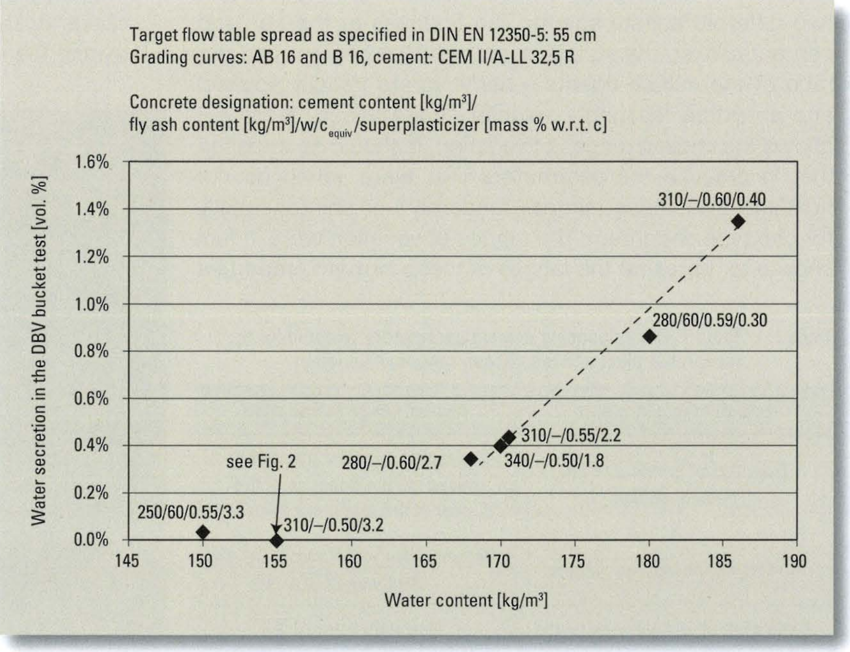

Figure 1: Water secretion in the DBV bucket test relative to the water content in the concrete (fresh concrete temperature approx. 20 °, superplasticizer based on PCE-lignin)

flow table, especially the sedimentation of cement slurry (❱ Fig. 2). Most of these concretes did not exhibit any water secretion in the DBV bucket test or sedimentation of coarse aggregate in the sedimentation test, or any other measurable fresh concrete properties that would cast doubt on their suitability.

2.2 Influence of the material properties of the concrete constituents on the uniformity of the fresh concrete properties

2.2.1 General

The second working step was to investigate how parameters on which the concrete producer generally has little or no influence can affect the fresh concrete properties. The focus was on the way that the variability of the material properties of the concrete constituents affected the uniformity of the characteristic fresh concrete properties. Concretes that had been evaluated as "sensitive" on the basis of the results from the first working step were selected for the subsequent investigations. These concrete compositions had already exhibited a tendency towards one or more undesirable properties or had shown a visual tendency towards secretion of cement slurry but could still be evaluated as suitable for practical use.

The following variation parameters were considered:

- Fluctuations of the properties of the cements used
- Fluctuations of the properties of the superplasticizers used
- Fluctuations in the particle size composition of the aggregate (0 to 2 mm)
- Tolerances when adding the concrete constituents

2.2.2 Alteration of the cement properties

The effects of altering the cement properties were investigated by using different laboratory cements with defined properties. This had the advantage that known factors that affect cement properties could be varied selectively and their influence on the fresh concrete properties observed. The laboratory cements were produced by grinding Portland cement clinker and mixing the ground Portland cement clinker with other ground main cement constituents and two different sulfate agents. The fineness of the Portland cement clinker, the sulfate content of the cement and the ratio of the sulfate agents – hemihydrate (readily soluble) and anhydrite (sparingly soluble) –were varied. ❱ Table 1 shows the chosen ranges of variation. It should be stressed that in practice the parameters that were varied do not fluctuate over these ranges "randomly" or unintentionally for one type of cement. The ranges of variation were in fact chosen to represent the ranges of these cement properties as control variables for achieving standard cement properties over long production periods in order to investigate the effects on the properties of fresh concretes with different compositions.

Table 1: Table 1: The influencing cement parameters selected for the research project and the chosen ranges of variation

Influencing parameter	Chosen range of variation
Fineness of grinding of the cement clinker	Variation by ± 400 cm^2/g Blaine, based on the fineness of the clinker in the two plant cements
Sulfate content of the cement	Variation from 2.5 mass % SO_3 to 3.0 mass % SO_3
Ratio of the hemihydrate sulfate agent (readily soluble) to anhydrite (sparingly soluble)	Variation from 25 % anhydrite/75 % hemihydrate to 75 % anhydrite/25 % hemihydrate

Pastes were produced from the laboratory cements and water (w/c = 0.35) and their shear resistances were investigated in the Schleibinger NT Viscomat for comparative observation of the properties of the laboratory cements. A standard profile that is often used in the VDZ was employed as the test profile for the Viscomat. The vessel that contains the cement paste is rotated for five minutes each at 60 rpm, 80 rpm, 100 rpm, 80 rpm and 60 rpm. ❱ Fig. 3 shows the measured shear resistances for the Portland-slag cements produced in the laboratory.

The results of the investigations carried out on the cement pastes showed that

- a variation of the sulfate content within the chosen limits had only a very slight influence on the shear resistance of the cement pastes in the Viscomat.
- in most cases a variation in the fineness of grinding of the clinker within the chosen limits had only a slight influence on the shear resistance of the cement pastes. In a small proportion of the comparative investigations a greater fineness of grinding of the cement clinker led to a somewhat higher shear resistance.
- as expected, the ratio of the sulfate agents had a significant influence on the shear resistance of the cement pastes: a larger proportion of hemihydrate meant that sulfate was available more rapidly in the pore solution and the shear resistance after production of the cement paste was higher than with the other cements.

It was formulated as a requirement for "robust" cements that the dependencies observed for cement paste should also be applicable to the fresh concrete properties and that the concretes should therefore react "as expected". For robust concretes this would mean that

- the properties of the fresh concretes investigated change only slightly when the fineness of grinding of the cement clinker or the sulfate content of the cement are altered (within the range of fluctuation investigated), and

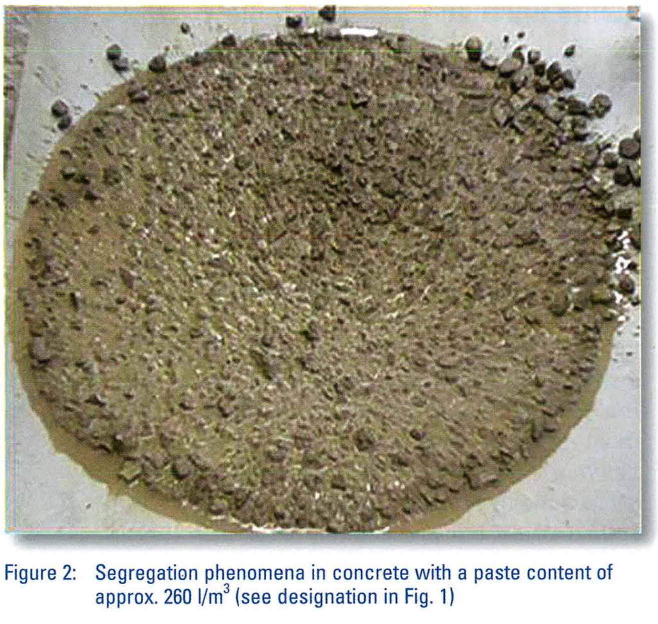

Figure 2: Segregation phenomena in concrete with a paste content of approx. 260 l/m^3 (see designation in Fig. 1)

- a change in the ratio of the sulfate agents from HH/AH = 25 %/75 % to HH/AH = 75 %/25 % can result in more rapid stiffening of the fresh concrete.

This was checked on concretes with different paste contents.

When the above-mentioned properties were altered in the laboratory a concrete with a paste content of approx. 265 l/m^3 that had been classified as "sensitive" in the first working step sometimes exhibited unplanned re-plasticizing and great differences in the quantity of water secreted in the DBV bucket test (› Fig. 4).

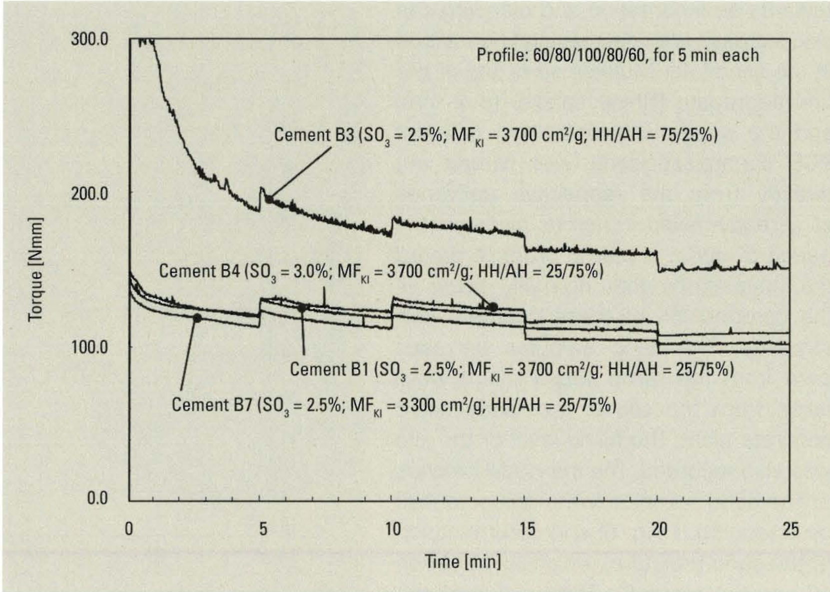

Figure 3: Shear resistance of Portland-slag cement pastes (w/c = 0.35) in the viscometer (MF_{KL}: fineness of grinding of the cement clinker)

On the other hand, the flow table spread of a concrete with a paste content of approx. 300 l/m^3 always behaved in line with expectations during changes in the cement properties (› Fig. 5): a lower flow table spread was only observed when using the cements with HH/AH = 75 %/ 25 % (cement A3), while the flow table spreads of concretes containing the other cements exhibited very similar behaviour. The quantity of water secreted exhibited smaller fluctuations than with the concrete composition containing less paste. The concrete with the higher paste concrete was therefore "more robust" than the concrete with a paste content of only 265 l/m^3.

2.2.3 Fluctuations in the properties of the sand and the superplasticizer

The fine fractions have a particular influence on the properties of the fresh concrete and also of the hardened concrete [9] so even the natural dispersion in the fine particle content of the sand can have an adverse effect on the uniformity of the concrete properties, especially the workability. It was also established in practice that the tendency of the concrete

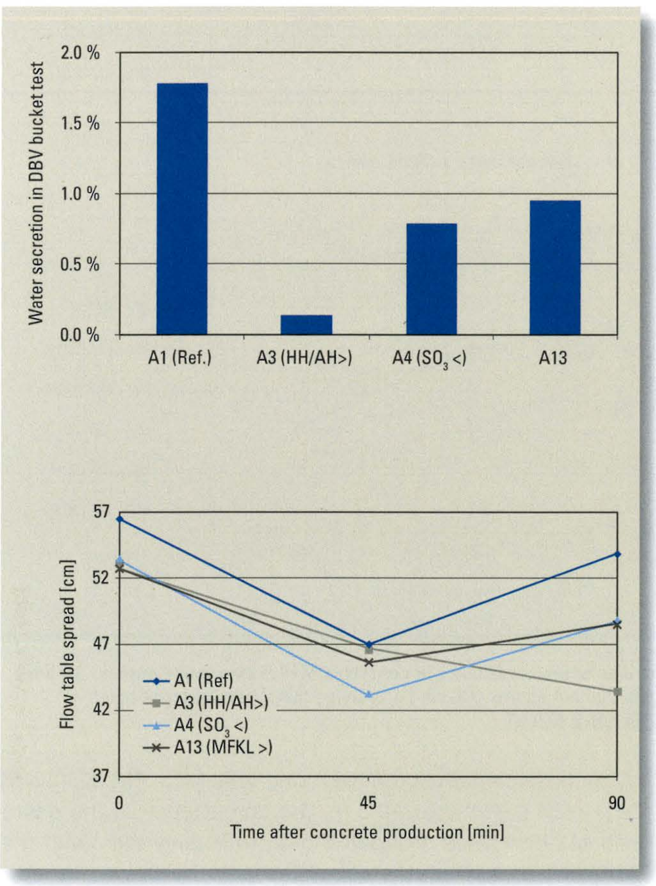

Figure 4: Water secretion and change with time of the consistency and water secretion of concretes with the same composition (paste content approx. 265 l/m3) during laboratory changes to the properties of the cement used (cement content 340 kg/m^3, water content 153 kg/m^3, w/c = 0.45, grading curve AB16, PCE superplasticizer)

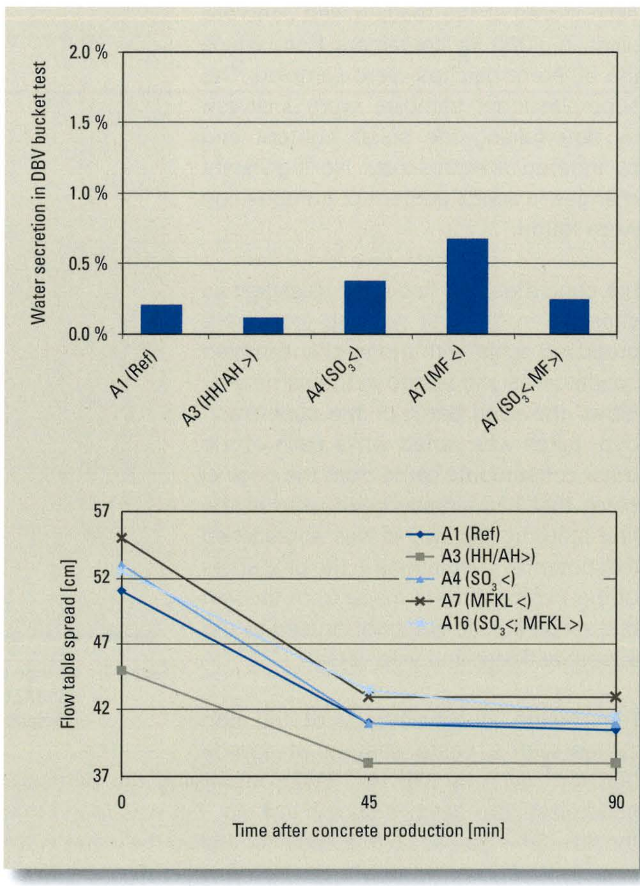

Figure 5: Water secretion and change with time of the consistency and water secretion of concretes with the same composition (paste content approx. 300 l/m^3) during laboratory changes to the properties of the cement used (cement content 340 kg/m^3, fly ash content 51 kg/m^3, water content 167 kg/m^3, w/c_{equiv} = 0.46, grading curve B16, PCE superplasticizer)

towards sedimentation and bleeding can also increase with decreasing fine fraction in the sand [10]. Multiple sampling of the fine aggregate (Rhine sand 0 to 2 mm) and the superplasticizers (two different PCE superplasticizers) was carried out directly from the respective deliveries at a ready-mixed concrete plant over a period of about a year in order to record the fluctuations that normally occur in the composition of these concrete constituents. The sand samples (in each case from the same supply plant) were taken from the silo in the ready-mixed concrete plant; the filling level of the silo was also recorded. The individual batches of the sand samples were characterized by screening (❱ Fig. 6) and determination of the sand moisture, which lay between 1.8 and 6.9 mass %. The k value of the sand batches varied between 1.23 and 1.71. The flour-fines content (< 0.125 mm) lay between 0.91 and 2.57 mass %, and the proportion of fines (< 0.25 mm) lay between 10.2 and 23.1 mass %. In some cases these values therefore differed significantly. No relationship could be detected between these characteristic values and the sand moisture or the filling level in the silo when the samples were taken. The two PCE superplasticizers from one producer that were used were each stored at the ready-mixed concrete plant in 1 000 kg containers from which the different batches were sampled. The superplasticizer samples were analyzed by determining the solids content and by infrared spectroscopy. No significant changes in solids content or composition were found.

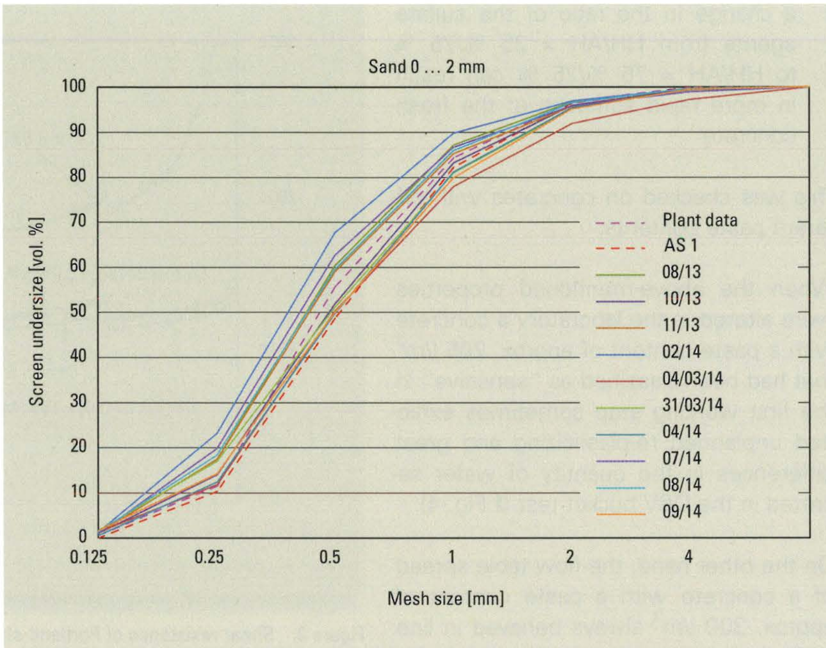

Figure 6: Grading curves of the sand batches

The concretes that had been classified as sensitive in the first working step were produced again with the freshly sampled constituents and tested in the same way. Either the sand batch or the superplasticizer batch was varied while each of the other constituents came from the original batch that had already been used in the first step. In this way it was established that potential fluctuations in the properties of the fresh concrete made from the various sand batches were not caused by the superplasticizer and vice versa.

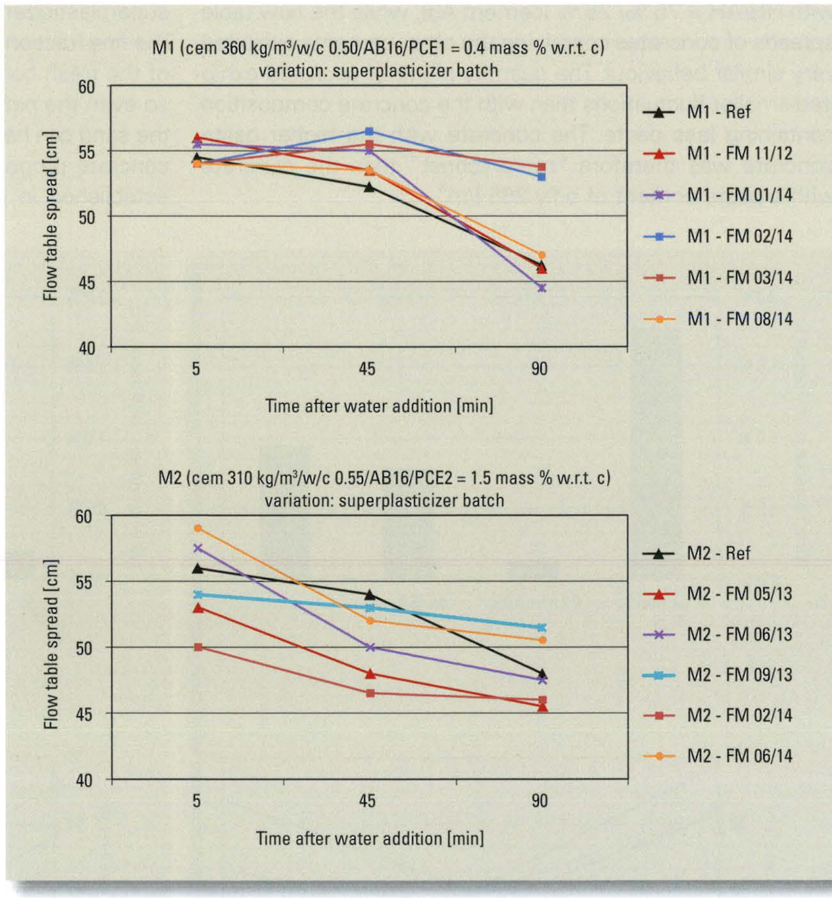

Figure 7: Change with time of the consistency of concretes M1 (paste content approx. 300 l/m^3) and M2 (paste content approx. 275 l/m^3) on varying the superplasticizer batch (cement: CEM II/B-S 42,5 N)

The change in consistency of the concretes with a paste content of approx. 300 l/m^3 (M1) or 275 l/m^3 (M2) on varying the particular superplasticizer batch is shown in ❱ Fig. 7. It was found that the flow table spreads 5 minutes after adding the water were virtually identical for the M1 concretes while they exhibited a range of up to 10 cm with the M2 concretes. The range of the flow table spreads carried on virtually uniformly with time for the M2 concretes but the flow table spreads for the different M1 concrete mixes only differed sharply from one another after 45 min (cf. M1 – FM 11/12 and M1 – FM 02/14). With the exception of the two concretes M1 – FM 02/14 and M1 – FM 03/14 after 90 min, the consistency of the paste-rich M1 concretes changed more predictably than with the M2 concretes when the superplasticizer batch was varied.

❱ Fig. 8 shows that the target starting consistency (flow table spread of about 55 cm) was achieved dependably by almost all the M1 concretes made with sand from the different supply batches. The flow table spread immediately after the end of mixing lay between 52 and 57 cm (exception: concrete M1 – S 10/13) and therefore lay within the permissible tolerance range of ± 3 cm specified in DIN EN 206 and DIN 1045-2. The flow table spread of the M2 concretes at this test time varied slightly more between 51 and 58 cm. The differences between the two concretes (M1 and M2) were noticeable mainly in their stiffening behaviour. The decrease in consistency of the M1 concretes with time was virtually uniform but with the M2 concretes it could only be predicted to a limited extent. About 70 % of the mixes investigated registered a fairly sharp drop in consistency between 5 and 45 min while with the rest of the concrete compositions the loss of consistency took place mainly between 45 and 90 min (e.g. M2 – Ref or M2 – S 31/03/14). This means that the concretes with increased paste content that were investigated also exhibited the expected fresh concrete properties when the concrete constituents were altered and could therefore be classified as "robust" (Figs. 5, 7 and 8).

The flow table spread 90 min after the addition of water and the quantity of bleed water measured in the DBV bucket test are compared in ❯ Fig. 9 with the proportion of fines (< 0.25 mm) in the aggregate. A trend can be seen in which, on average, smaller quantities of bleed water were measured with increasing fines content of the aggregate and at the same time there was a drop in the flow table spread measured 90 min after the addition of water.

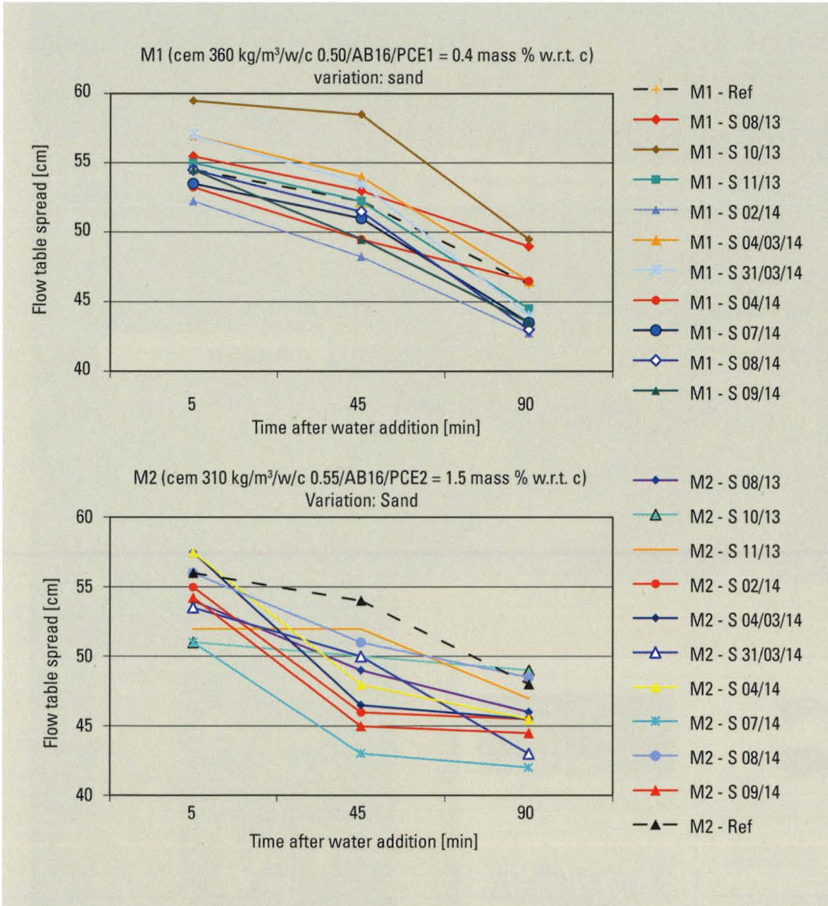

Figure 8: Change with time of the consistency of concretes M1 (paste content approx. 300 l/m³) and M2 (paste content approx. 275 l/m³) on varying the sand batch (cement: CEM II/B-S 42,5 N)

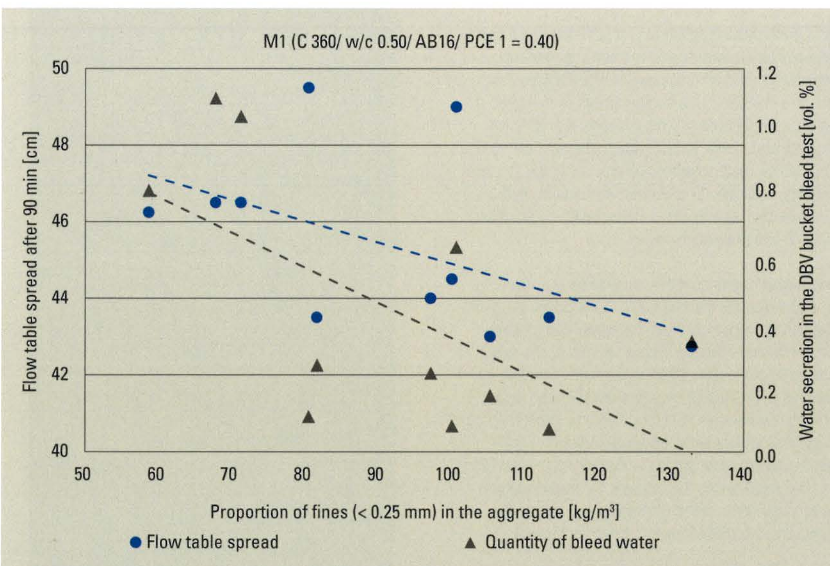

Figure 9: Correlation of the quantity of bleed water and the consistency with the proportion of fines in the aggregate using the example of the M1 mix formulation (cement: CEM II/B-S 42,5 N)

3 Summary

The results of the research project show that with soft concretes containing low levels of paste the occurrence of the following unexpected phenomena must be expected to an increased extent if there is a change in the concrete constituents:

- significant, unpredictable differences in the quantity of water secreted in the DBV bucket test (bleeding)
- uncontrolled re-plasticizing of the concretes, i.e. softer consistencies with advancing time
- unplanned increased air content in the fresh concrete
- accelerated stiffening behaviour

It became apparent that these phenomena can appear not only if there is a change in cement properties, such as may occur in practise, but also when choosing a different batch of the same aggregate or the same superplasticizer used. The occurrence of unexpected changes in fresh concrete properties can be very largely avoided by increasing the paste content.

Certain fluctuations in the properties of the concrete constituents due to normal large-scale production are inevitable, so they must be taken into consideration in the concrete design to ensure predictable fresh concrete properties over long periods. Excessive reduction in the binder and paste content in the concrete, which is supposedly possible through the development of efficient superplasticizers, can be the cause of unexpected fresh concrete properties and less robust concretes.

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