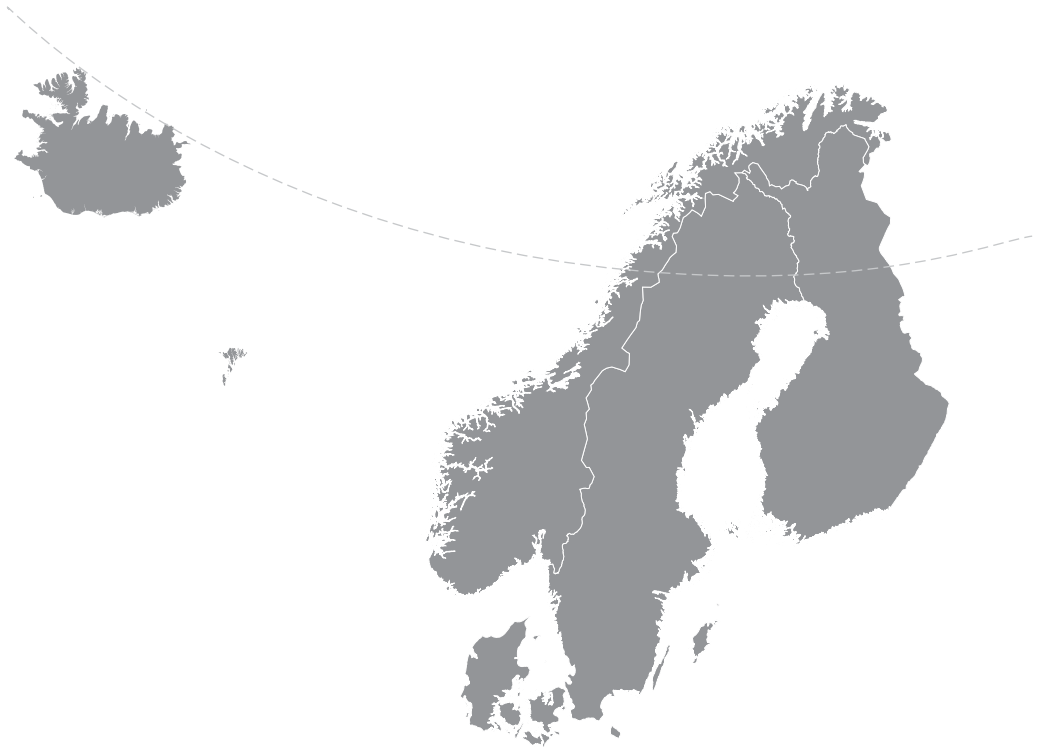


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Preface

Nordic Concrete Research is since 1982 the leading scientific journal concerning concrete research in the five Nordic countries, e.g., Denmark, Finland, Iceland, Norway and Sweden. The content of *Nordic Concrete Research* reflects the major trends in the concrete research.

Nordic Concrete Research is published by the Nordic Concrete Federation that beside the publication activity also organizes the Nordic Concrete Research Symposia that have constituted a continuous series since 1953 in Stockholm. The Symposium circulates between the five countries and takes place every third year. The next will be held in Finland at Hanasaari, the Swedish-Finnish Cultural Centre near Helsinki June 5 – 8, 2011.

The homepage of the Nordic Concrete Federation, www.nordicconcrete.org have now been revised, and the Research Committee will keep it up dated.

Papers presented in the journal are also published on the homepage. For the first half year only the abstracts are published there, thereafter the full paper.

Since 1982, 347 papers have been published in the journal. Since 1994 the abstracts and from 1998 both the abstracts and the full papers can be found on the homepage.

From January the current chairman of the Research Committee, Mr. Klaus Söderlund, will be replaced by Dr. Jussi Mattila.

The actual crisis also put a fingerprint on the journal – only a few authors have been able to present their research in this issue of NCR. Hopefully, this will be a problem which shortly will be overcome – not only for the NCR publication, but for the whole society.

Aalborg, December 2009

Dirch H. Bager

Editor, *Nordic Concrete Research*

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Use of stabilizer/VMA to adjustment of the flow properties of SCC at the Job Site



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Abstract: Successful use of SCC typically places greater demand on logistics of concrete delivery and on control of flow properties at the jobsite than is the case with conventional slump concrete. One poor truck load of SCC or minor stops in concrete delivery can ruin an SCC casting.

Consequently, it is crucial to have means of remedy if concrete is delivered at a jobsite with unacceptable flow properties. One option, if the concrete is segregating at delivery, could be to correct the flow properties at the jobsite by adding stabilizer/VMA before the concrete is poured into the formwork. This approach, although not presently supported by the European concrete standard EN 206-1, has been investigated for typical Danish strength class C30 and C25 concrete using two commercially available stabilizers.



The results indicate that the controlled addition of stabilizer/VMA at the jobsite can be a superior solution to rejecting the concrete or simply ignoring the deficient flow properties and casting the concrete anyway.

Keywords: 4C-Rheometer, SCC, Stabilizer, VMA

1. INTRODUCTION

Successful use of SCC is dependent on a continuous uninterrupted supply of concrete with consistent flow properties to the jobsite. In fact the difficulties in meeting this requirement is in fact one of the major obstacles to a more widespread use of SCC [1, 2]. Currently, SCC only accounts for approximately 1-2 % of the total European concrete production [3]. If the flow properties of delivered SCC differ and trucks are rejected, the casting will be in jeopardy of resulting in multilayer hardened concrete, where individual batches of concrete rest upon each other with a weak porous interfacial zone in between [4]. The weak zone is created when the second layer of concrete is not able to sufficiently break the static yield stress of the first layer, which is needed to obtain “intermixing” of the two layers. The critical maximum allowable resting time of the first layer before the casting of a second layer of concrete depends on the

thixotropic properties (structural build-up with time) of the concrete. The higher the thixotropy the shorter the critical resting time. The risk of multilayered concrete sometimes results in batches of SCC being cast that should in fact have been rejected due to inadequate flow properties, which instead leads to problems with incomplete form filling, segregation, or poor surface quality [5]. In some serious cases it may only take one poor batch of SCC to ruin the structural quality of even very large castings, and leaving no other option than very expensive repairs or perhaps even a complete reconstruction. To avoid segregation, it is important to consider the choice of rheological properties (i.e. yield stress and plastic viscosity), casting technique, and maximum size aggregate for the individual casting. The rheological properties of SCC have a significant effect on the segregation resistance. A high yield stress increases both static and dynamic segregation resistance, whereas a high plastic viscosity will add to the dynamic segregation resistance [6, 7, 8]. Thus, SCC designed for certain applications will be less prone to segregation. For instance, for simple horizontal applications it is recommended to apply a relatively high yield stress, corresponding to a slump flow of about 550 mm, to ensure high stability and control of the moving concrete front and a low plastic viscosity to ensure easy handling and sufficient self-consolidation [9]. In Denmark, SCC is for the large part used for such horizontal applications and it has been possible to reach a good balance between cost and performance. This has resulted in a SCC market share of 30 % of ready-mixed concrete. The extra material costs are mainly due to slightly higher paste contents and higher amounts of superplasticizer in Danish SCC [10].

For more fluid SCC, the concrete becomes more sensitive to variations in the water content, e.g. variations in aggregate moisture content. Here, the use of VMA has shown to enhance the segregation resistance which partly may be due to its effect on the rheological properties [11]. For instance, Leemann et al. [12] have shown that different VMAs affect the rheological properties in somewhat the same manner; additions of VMA increases significantly the yield stress and to a minor extent the plastic viscosity. The question is whether VMA can also increase the robustness of SCC, e.g. will an SCC containing VMA be less sensitive to water additions compared to a SCC without VMA but with similar rheological properties. Traditionally, the use of VMA is an integral part of the mix composition and is added to the concrete during the mixing procedure at the individual concrete production facility. However, mixtures containing VMA then require more superplasticizer to obtain a given slump flow (yield stress), i.e. such mixtures will be more costly and must perform better in terms of providing more robust concrete to be attractive to the concrete producers. According to Corradi et al. [13] a good VMA would be one that would retain the stability of the SCC even with a variation of the water content of $\pm 10 \text{ kg/m}^3$. Billberg [14] tested seven different VMAs and their rheological response to variations in aggregate water content. Different robustness was observed for the tested VMAs and the best performing VMA showed a reduction in the so-called relative rheology area to 69 % compared to that of the reference mix without VMA. Stabilizing effect may be achieved by adding filler and admixture (limestone filler, fly ash, blast furnace slag).

In this paper, another use of VMA is proposed based on its ability to manipulate the rheological properties. An attempt was made to establish a methodology for performing flow property adjustment at the jobsite focusing on the use of VMA to adjust concrete that has too high slump flow (too low yield stress), i.e. is too fluid, unstable and segregating. Similarly, superplasticizer can be used to adjust concrete that has too low slump flow (too high yield stress), i.e. is too stiff. Such use of VMA is, contrary to the use of superplasticizer, not presently allowed by the European concrete standard EN 206-1, possibly because neither SCC nor VMA was used to any appreciable extent when the standard was drafted. If simple means of correcting the flow properties of SCC at the jobsite were available it could potentially reduce significantly the

number of poor SCC castings. However, in some national standard documents e.g. in Sweden, the use of VMA may be approved as long as it is clearly shown that it not will have any negative consequences on the concrete properties.

2. EXPERIMENTAL

2.1 Mix design

The concrete composition of the concrete investigated was similar to a typical Danish C30 SCC. However, the air entrainment was omitted, so that effectively the concrete probably was a C35. The mix design is provided in Table 1. The aggregates used were sea-dredged having rounded shape. The cement was a European CEM I, 52.5 and the fly ash was a low-calcium ash corresponding to EN 450-1. The superplasticizer used was a commercially available polycarboxylate-type product that was added to provide the desired yield stress of about 25 Pa (slump flow of 650 mm) of the SCC. Two commercially available VMAs (VMA-1 and VMA-2) were added to the concrete following the initial mixing and testing. The solid content was 6.6 %-wt. in VMA-1 and 1.8 %-wt. in VMA-2.

Table 1 – Mix design of the concrete investigated.

Material	kg/m³
Fine aggregate, 0/4 mm	847.0
Coarse aggregate, 4/8 mm	371.0
Coarse aggregate, 8/16 mm	628.4
CEM I, 52.5	274.5
Fly ash	81.9
Water	161.5
Superplasticizer	3.6

2.2 Mixing and testing procedures

The mixing of the concrete was performed at the laboratory of Danish Technological Institute using their full-scale mixing station, comprising a 250 liter Haarup pan type counter-current mixer with Skako industrial process control software. 200 liters of concrete was mixed for each test with the mixing sequence being 0/4, 4/8, 8/16, cement + fly ash, water, superplasticizer in order of addition. The mixer rotated during the full sequence and each material was added immediately following complete addition of the previous material. After addition of superplasticizer the mixing continued for 60 seconds. Subsequently, a sample of about 10 liters was taken and used for determination of rheological properties using the 4C-Rheometer. Following the initial determination of rheological parameters, 10 kg/m³ of water was added to the concrete in order to induce instability (segregation), and the concrete was mixed for 60 seconds. The extra 10 kg/m³ of water correspond approximately to an error of 0.5 in the estimation of the aggregate moisture. Subsequently, a sample of about 10 liters was taken and used for determination of rheological properties. Next, VMA was added to the concrete in an attempt to eliminate or at least reduce the instability of the concrete. The VMAs were added as 0.5 kg/m³ and 1.5 kg/m³ for VMA-1 and VMA-2 respectively, in order to obtain the desired stabilizing effect, i.e. a reduction in slump flow of approximately 100 mm. The concrete was mixed for 60 seconds. Subsequently, a sample of about 10 liters was taken and used for

determination of rheological properties. The addition of VMA was repeated once in the same aliquots and the concrete was mixed for 60 seconds and the rheological parameters determined. The air content of the concrete was measured initially and after addition of VMA. Additionally, the rheological properties of the reference mix without VMA were tested over time, i.e. at 0 min (just after mixing), 15 min, 30 min and 60 min. Subsequently, VMA was added and a test was performed at 75 min.

2.3 4C-Rheometer

The 4C-Rheometer system is shown in Figure 1. This is a new apparatus capable of assessing the yield stress and plastic viscosity in a quick, easy-to-use, and operator independent manner. The equipment performs an automated slump flow test based on an upright Abrams cone, extracting the rheological parameters instantly while also providing the empirical parameters slump flow and t_{500} [15]. The system is a PC-automated slump flow test where the spread versus time is determined using digital video image analysis. The base plate is a dry sand blasted glass plate and the lifting of the Abrams cone is performed at a constant speed of 7.0 cm/s. The video recording is done at a frame rate of 15 s⁻¹. For each frame the position of the concrete front is determined using a standard “find edge” image analysis algorithm.

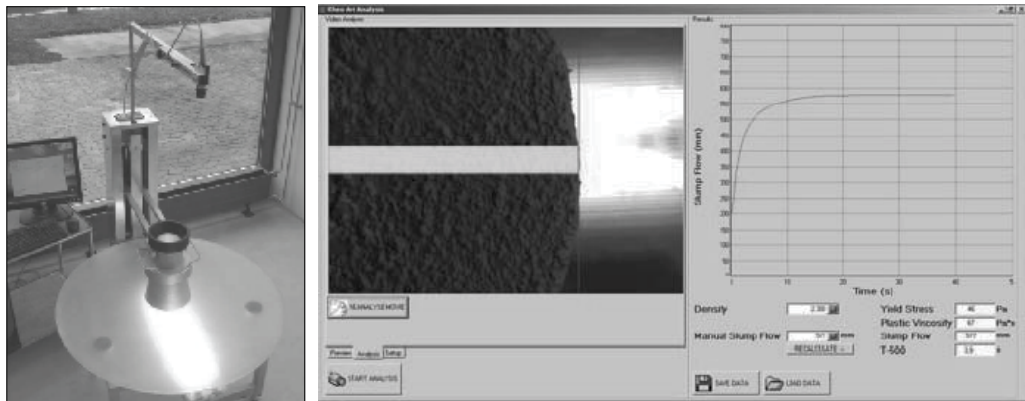


Figure 1 – The 4C-Rheometer system. To the right the software user interface.

The flow curve is subsequently compared to a database of simulated flow curves using boundary conditions as in the experimental setup, i.e. a no-slip surface and a cone lifting velocity of 7.0 cm/s. The yield stress is estimated directly from a relation between the slump flow, yield stress, and density. In case the flow is asymmetrical around the cone, the system can apply the manually measured slump flow.

Estimating the plastic viscosity requires an accurate and detailed monitoring of the flow curve. The initial part of the flow curve is especially important and the plastic viscosity is estimated within slump flows from 200 mm to 450 mm. Above 300 mm spread, the yield stress starts to become of importance, which is taken into account. The absolute values of yield stress and plastic viscosity have shown to correlate well with those used to simulate the actual flow of SCC in e.g. the L-box. Also, the yield stress and plastic viscosity measured by the 4C-Rheometer have been compared with those measured by the BML viscometer [15]. The same trends are observed for changes in mixture proportions although the absolute values yielded by the 4C-Rheometer are roughly twice as high as those yielded by the BML viscometer.

It is the opinion of the authors that the t_{500} value itself is a questionable estimate of the plastic viscosity if it is not used with care, as it is possible to obtain the same t_{500} for different plastic viscosities because it also depends on the yield stress. Empirical investigations correlating the t_{500} value with the plastic viscosity from rheological measurements have also not shown a clear relationship [16]. Therefore, in addition to the 4C-Rheometer, the knowledge of the relation between the slump flow curve (spread versus time) and the rheological properties has been used to identify three classes of plastic viscosity (low, medium and high), which can be obtained from the slump flow and t_{500} value, providing the contractor and concrete producer with a very simple tool to estimate the actual rheological properties of SCC [17].

3. RESULTS AND DISCUSSION

In order to avoid misinterpretation of test results it was necessary to demonstrate that the concrete mixture under investigation had constant flow properties within the expected time span of planned testing of about 45 minutes. This was done by mixing the reference concrete shown previously in Table 1 and measuring the rheological properties using the 4C-Rheometer at different ages. The results, shown in Table 2 as mixture ID “REF” and in Figure 2, reveal that the rheological properties are quite consistent for at least an age of 60 minutes. The yield stress is varying between 17 Pa and 26 Pa and the plastic viscosity varies from 18 Pa·s to 23 Pa·s, i.e. the concrete mixture was stable over time in terms of its rheological properties albeit at the verge of static segregation. Also, the air content was stable at 1 % during the first 60 minutes. The plastic viscosity for the reference mix is in the low range.

Table 2 – Mixing history, rheological parameters and air content obtained for the three concretes (REF, VMA-1 and VMA-2) tested.

Mixture ID	Age min	Addition kg/m ³	Yield stress Pa	Plastic viscosity Pa·s	Slump flow mm	T ₅₀₀ Sec	Air content %
REF	0	-	26	23	650	2.0	1
REF	15	-	20	18	680	1.8	-
REF	30	-	17	20	700	1.9	-
REF	60	-	22	21	670	2.1	1
REF	75	0.5 VMA-1	39	36	600	3.4	-
VMA-1	0	-	30	21	630	1.9	1
VMA-1	15	10 water	14	6	720	1.1	-
VMA-1	30	0.5 VMA-1	27	15	640	1.7	1
VMA-1	45	0.5 VMA-1	49	23	570	2.5	-
VMA-2	0	-	32	18	620	2.4	1
VMA-2	15	10 water	15	6	720	1.1	-
VMA-2	30	1.5 VMA-2	32	19	620	2.0	1
VMA-2	45	1.5 VMA-2	90	24	500	6.7	-

Similar 200 liter batches of concrete (VMA-1 and VMA-2) were mixed and immediately following determination of rheological properties and air content, 10 kg/m³ of water was added to the concrete that was subsequently remixed in the counter-current mixer. The extra water significantly reduced the stability of the concrete lowering both the yield stress and the plastic viscosity to the extent that the concrete was visually segregating i.e. no aggregates observed at concrete surface in the mixer. The measured rheological parameters of the two concretes tested were 14 Pa and 6 Pa·s, and 15 Pa and 6 Pa·s respectively for the VMA-1 and VMA-2 mixtures as shown in Table 2. Addition of VMA-1 corresponding to 0.5 kg/m³ or 1.5 kg/m³ of VMA-2 to

these highly fluid concretes followed by remixing resulted in increased yield stress and plastic viscosity. Indeed after addition of VMA, the concretes had virtually identical rheological parameters as before the addition of excess water. Repeating the addition of VMA having reached a stable concrete resulted in further increase of the yield stress and plastic viscosity, with the increase in yield stress being the more significant. The change in rheological parameters between each step is illustrated for VMA-1 and VMA-2 in Figure 3.

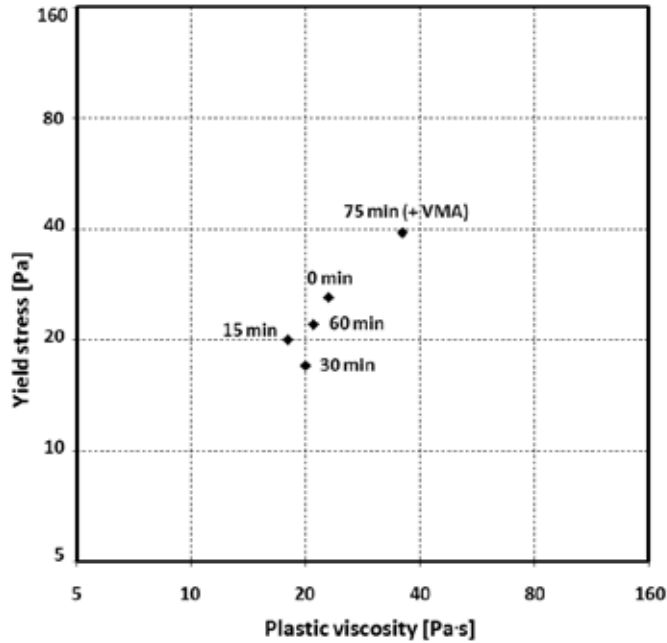


Figure 2 – Yield stress versus plastic viscosity of the “REF” concrete batch measured using the 4C-Rheometer right after mixing (0 min), after 15, 30 and 60 minutes, and following the addition of 0.5 kg/m^3 of VMA-1.

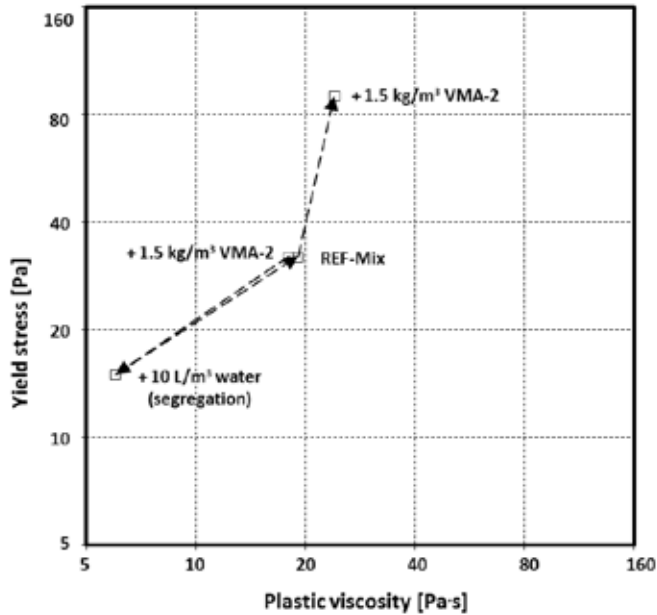
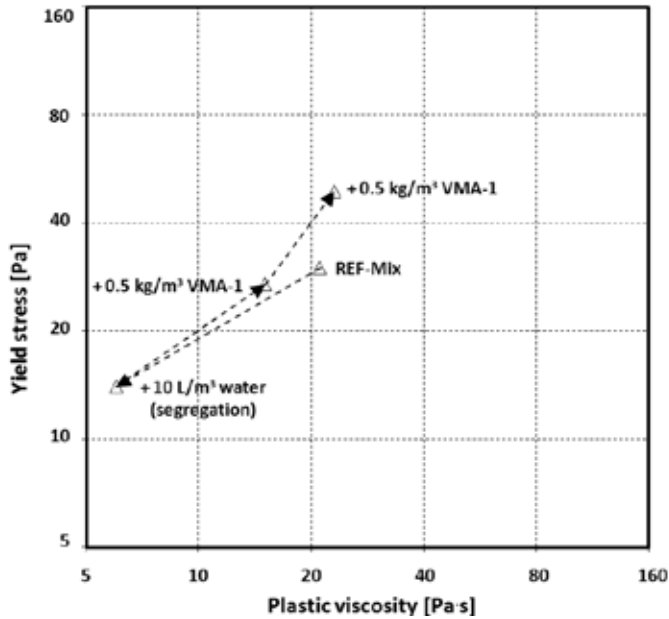


Figure 3 – Yield stress versus plastic viscosity of the “VMA-1” and “VMA-2” concrete batches measured using the 4C-Rheometer. At the top just after mixing (REF-Mix), after addition of 10 kg/m³ of water, after addition of 0.5 kg/m³ of VMA-1, and after addition of extra 0.5 kg/m³ of VMA-1. At the bottom just after mixing (REF-Mix), after addition of 10 kg/m³ of water, after addition of 1.5 kg/m³ of VMA-2, and after addition of extra 1.5 kg/m³ of VMA-2.

The laboratory results obtained strongly suggest that addition of VMA can be used to adjust/correct the rheology of SCC at the jobsite. By adding aliquots of either of the two commercially available VMAs investigated in this study to the concrete in the truck and spinning the drum for a few minutes, a segregating concrete can potentially be saved. Spending the extra 10 minutes on adjusting the rheology of the concrete is much to be preferred over rejection of the concrete or casting of the faulty concrete as both procedures will jeopardize the integrity of the hardened concrete. The suggested procedure of adjusting flow properties of SCC by using VMA at the jobsite:

1. Take a wheelbarrow size sample of concrete from the truck.
2. Measure slump flow of the concrete.
3. Add an already prepared aliquot of VMA to the concrete if the slump flow is higher than specified or if the concrete is segregating. The amount of VMA added should correspond to the amount needed to reduce the slump flow by 50-100 mm.
4. Spin the drum on the truck for 5 minutes.
5. Measure the slump flow of the concrete.
6. Repeat steps 1-5 only once. If this is not sufficient to fix the flow properties of the concrete it should be rejected.

Similarly, a procedure for adjusting the flow properties using addition of superplasticizer can be used if the slump flow is too low (too high yield stress).

The procedure was tested at a ready-mixed concrete mixing plant, where a batch of 3 m³ of a C25 SCC was mixed and subsequently poured into a concrete truck. A wheelbarrow size sample (approximately 100 liter) was taken from the truck and the slump flow was measured. Then 0.5 L/m³ superplasticizer was added to the concrete in the truck the drum was rotated at maximum velocity for 5 minutes and a wheelbarrow size sample was taken for measurement of slump flow. Finally, 0.5 L/m³ VMA-1 was added to the concrete and again the drum was rotated at maximum velocity for 5 minutes and a wheelbarrow size sample was taken for measurement of slump flow. The procedure was tested again on a new 1 m³ batch, where only 0.4 L/m³ VMA-1 was added. The results are shown in Table 3.

Table 3 – Slump flow before and after addition of superplasticizer/VMA-1 in concrete truck.

	Batch 1	Batch 2
	slump flow (mm)	slump flow (mm)
Initial measurement	510	630
After 0.5 L/m ³ superplasticizer	645	-
After 0.5 L/m ³ VMA-1	530	540

The results suggest that it is possible to adjust the flow properties of SCC in the concrete truck by adding superplasticizer or VMA.

To take advantage of the above procedure it needs to be documented by trial casting that the addition of VMA does not influence negatively the performance of the hardening and hardened concrete. Consequently, it must be documented that e.g. setting time, strength development and final strength are not significantly reduced. This was not tested in the present study. However, previous results indicate that addition of VMA does not influence the mentioned parameters to any appreciable extent [11].

4. CONCLUSION

It has been shown in the laboratory in fairly large scale testing, that if VMA is added to segregating self-consolidating concrete it can stabilize the concrete, i.e. increase primarily the yield stress but also somewhat the plastic viscosity of the concrete. Using VMA in this way to modify the rheological properties of SCC can potentially be used advantageously at the construction site to save delivered batches of concrete that should otherwise have been rejected because their flow properties are outside specifications, i.e. too fluid and perhaps even segregating. A simple procedure of how the adjustment of the rheological properties using VMA can be performed at the jobsite has been proposed and tested with positive result. If this procedure is embraced and successfully adopted by contractors and concrete producers it could be an important step towards decreasing the risk of having poor castings results when using SCC.

5. REFERENCES

- [1] Cussigh, F., ‘SCC in practice – opportunities and bottlenecks’, *Proceedings of 5th RILEM Symposium on Self-Compacting Concrete*, Ghent, Belgium, pp. 21-27 (1), 2007.
- [2] Desmyter, J.R., ‘Barriers to the application of cast-in-place Self-Compacting Concrete’, *Proceedings of 5th RILEM Symposium on Self-Compacting Concrete*, Ghent, Belgium, pp. 373-380 (1), 2007.
- [3] ERMCO, ‘European ready-mixed concrete industry statistics year 2006’, European Ready-Mixed Concrete Organization, www.ermco.org, September 2007.
- [4] Roussel, N., ‘A thixotropy model for fresh fluid concretes: Theory, validation and applications’, *Cement and Concrete Research*, Vol. 36 (10), pp. 1797–1806, 2006.
- [5] Skarendahl, A., ‘The Present - the Future’, *Proceedings of the 3rd International RILEM Symposium on Self-Compacting Concrete*, Reykjavik, Iceland, pp. 6–14, 2003.
- [6] Roussel, N., ‘A theoretical frame to study stability of fresh concrete’, *Materials and Structures*, Vol. 39 (285), pp. 75–84, 2006.
- [7] Thrane, L.N, Stang, H., Geiker, M., ‘Flow induced segregation in full scale castings with SCC’, *Proceedings of 5th RILEM Symposium on Self-Compacting Concrete*, Ghent, Belgium, pp. 449-455 (1), 2007.
- [8] Han, M., Kim, C., Kim, M., Lee, S., ‘Particle migration in tube flow of suspensions’, *Journal of Rheology*, Vol. 43 (5), pp. 1157–1174, 1999.
- [9] SCC-Consortium, ‘Guidelines on execution of SCC’, Danish Technological Institute, Denmark, 48 pp., 2008.
- [10] Nielsen, C. V., Thrane, L. N., Pade, C., ‘Danish experiences with self-compacting concrete’, *Concrete Plant International*, Vol 1, pp. 60-70, 2008.
- [11] Khayat, K.H., ‘Viscosity-enhancing admixtures for cement based materials – an overview’, *Cement and Concrete Composites*, pp. 171-88 (20), 1998.
- [12] Leemann, A., Winnefeld, F., ‘The effect of viscosity modifying agents on mortar and concrete’, *Cement and Concrete Composites*, pp. 341-349 (29), 2007.
- [13] Corradi, M., Khurana, R., Magarotto, R., ‘Low fines content Self-Compacting Concrete’, *Proceedings of 5th RILEM Symposium on Self-Compacting Concrete*, Ghent, Belgium, pp. 839-844 (2), 2007.
- [14] Billberg, P., ‘Robustness of fresh Self-Compacting Concrete’, *Proceedings Nordic Concrete Research*, Bålsta, Sweden, pp. 10-11, 2008.

- [15] Thrane, L.N, Pade, C., Svensson, T., 'Estimation of Bingham rheological parameters of SCC from slump flow measurement', *Proceedings of the 5th RILEM symposium on Self-Compacting Concrete*, Ghent, Belgium, pp. 353-358 (1), 2007.
- [16] Nielsson, I., Wallevik, O. H., 'Rheological evaluation of some empirical test methods-preliminary results', *Proceedings of the 3rd International symposium on Self-Compacting Concrete*, Reykjavik, Iceland, pp. 59-69, 2003.
- [17] Thrane, L.N, Nielsen, C.V., Pade, C., Glavind, M., Schou, J., 'Successful in-situ casting with SCC – from an economical and rheological point of view', *Proceeding of the 3rd ASTM conference on Self-Consolidating Concrete*, Chicago, 2008.

Practical Experiences on Cracking of Concrete Slabs on Ground



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ABSTRACT

Concrete ground floor slabs are commonly used floor type in Finland. According to Finnish Guide for Concrete Floors (by 45) concrete slab on grade can be made with centric reinforcement if slab thickness is varied between 80 – 120 mm.

A survey about industrial and warehouse floors showed that extensive surface cracking was found very often in the slabs with centric reinforcement. In many cases cracks were so wide that they reach the reinforcement in the neutral axis or in some cases cracks reach the bottom surface of slab. Cracking can seriously reduce esthetical value of floor, but also long-term durability of reinforcement can be decreased due to the possible chemical attack through cracks and because the surface coating is broken. Cause for cracking is due to the differential shrinkage when the top of the slab dries faster than the bottom of the slab.

Key words: concrete floor, slab on ground, cracking, shrinkage

1. INTRODUCTION

1.1 Background

Concrete ground floor slabs are commonly used floor type in Finland. According to Finnish Guide for Concrete Floors (by 45) [1] concrete slab on grade can be made with centric reinforcement if slab thickness is varied between 80 – 120 mm.

However, in the slabs with centric reinforcement extensive cracking have been observed in many cases. Typically, cracks reach the reinforcement level, and in some cases cracks are open through the slab thickness. Cracking is harmful considering the durability of structure. Chlorides or other chemicals can cause corrosion of reinforcement affecting through the cracks. On the other hand, cracks can disturb surface coatings.

Cause for cracking is due to the differential shrinkage when the top of the slab dries faster than the bottom of the slab. In addition, the differential shrinkage cause also upward edge curling, this can be problematic near walls and when considering flatness of slab surface.

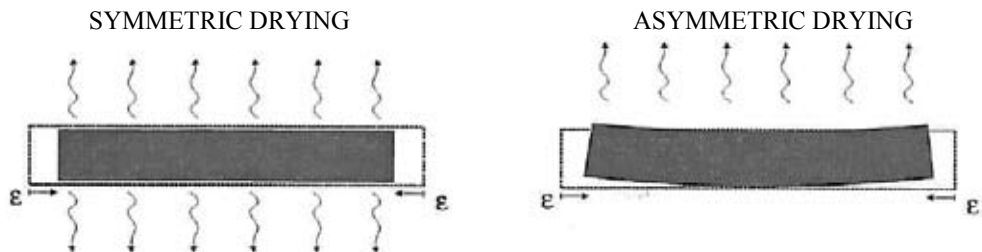


Figure 1. Deformations of concrete slab caused by drying and shrinkage.

1.2 Research data

The research data is gathered from condition investigations about the concrete ground floors made by Tampere University of Technology (TUT) researchers. In addition, two experimental research projects have been carried out concerning curling of floating concrete floors [2, 3].

2. STRUCTURAL BEHAVIOUR OF SLAB ON GROUND

The design of ground-floor slabs has traditionally been based on Westergaard's solution for slabs on ground [4]. The solutions are available for point loading situated at different critical locations (corner load, internal load and edge load). According to these solutions the slab's thickness can be determined using maximum allowable tensile stresses. Plastic methods are also available in which slab is designed as reinforced concrete section in ultimate limit state. Numerical methods (FE-analysis) can also be used in design, but normally only "hand calculation" based on theoretical solution of Westergaard are made.

In Finnish Guide for Concrete Floors (by 45) [1] design flow is such that in ultimate limit state the slab's thickness and reinforcement is determined and in service limit state concrete cracking is checked. Both of these analyses are made for point loading conditions. The stresses generated by environmental conditions (due to restraint to temperature and moisture change) are not clearly defined and design procedures for these indirect stresses are insufficient. Yet, indirect stresses can be similar order of magnitude than stresses introduced by applied loads.

In concrete ground-floor slab two types of indirect loading condition occurs due to restraint to temperature and shrinkage movement. Firstly, change in length causes evenly distributed tensile

stresses to the slab's cross-section, which magnitude depends on the amount of shrinkage and degree of the restraint and axial stiffness of the floor construction. Secondly, change in shape (warping/curling due to the thermal/moisture gradient) causes tensile stresses usually in upper surface of the slab because of differential shrinkage (moisture loss starts from upper surface).

Ideally, if contraction joints are working properly and are not placed too far apart and bonding to sub-base is prevented, the stresses from change in length produces very low tensile stresses to the slab. Curling due to differential shrinkage does induce tensile stresses to the upper surface. The magnitude of induced stresses depends on the spacing of the contraction joints and the magnitude of differential shrinkage. Applied loading to the curved slab can cause remarkable danger of cracking because cantilevered edges are not in contact with sub-base and the slab itself have to withstand all the loading.

Concrete slab will crack if tensile stresses due to applied loading or indirect loading (restraint stresses) exceeds the tensile strength of the concrete. The severity of cracking can be reduced by reinforcement. At a crack tensile force is carried by reinforcement. The effective way to reduce crack width is to use closely spaced a small diameter bars at minimum concrete cover.

A concrete slab with centric reinforcement is not working effectively for crack control. The centric reinforcement is so far away from cracked surface that it has practically no influence to cracking. In order to control cracking, reinforcement should be placed as close as possible to the top of slab, since the upper half of the slab has the greatest drying shrinkage. Reinforcing in the bottom half of slab is therefore not needed for indirect loading cases, but applied loading cause tensile stresses to the bottom of the slab, and thus bottom reinforcing is needed for bearing capacity. Therefore, in order to control cracking of a slab, reinforcing steel in top half of the slab is needed, and in order to increase the loading capacity of the slab, reinforcing steel in bottom of the slab is needed.

3. DESIGN GUIDELINES FOR CONCRETE SLABS ON GROUND

According to Finnish Guide for Concrete Floors (by 45) [1] slab on ground can be made with centric or eccentric reinforcement (on both surfaces). The thickness of the slab and the amount of reinforcement is dependent on loading conditions and sub-base modulus. Point loading cases are usually decisive in design.

Centric reinforcement can be used when magnitude of point loading is small ($P < 30 - 50$ kN) and thickness of slab is 120 mm or less. Guidelines state that reinforcement should be placed just above of the neutral axis during the slab construction.

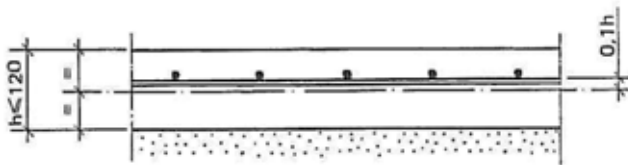


Figure 2. Centric reinforcement in the slab [1].

In heavily loaded slabs ($P > 50 \text{ kN}$) the thickness is greater than that of 120 mm, and then slab has to be designed with eccentric reinforcement (reinforcement placed close to the top and the bottom surface). Minimum concrete cover is 25 mm.

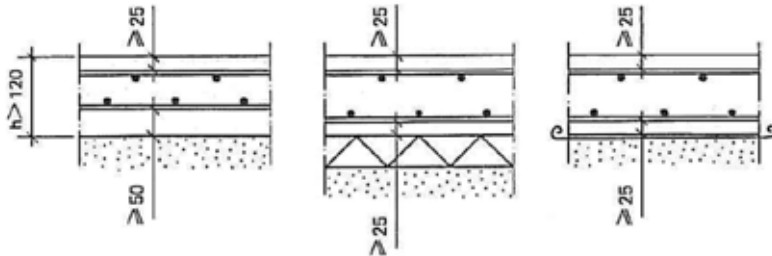


Figure 3. Eccentric reinforcement in the slab [1].

4. SHRINKAGE OF CONCRETE

The shrinkage of concrete is mostly caused by drying and hydration. Normally, the drying shrinkage means specifically physical desiccation by evaporation, excluding the chemical drying caused by the hydration. The influence of the hydration on the external volume of a concrete body is known as autogenous shrinkage, and also it is caused mainly by desiccation.

Usually only drying shrinkage is an issue of substance. In typical concrete mixtures, autogenous shrinkage is normally insignificant, but in high strength concrete where there is a low water-to-cement ratio, autogenous shrinkage can be a concern.

Concrete shrinkage can be divided into two parts: early age and long-term shrinkage. The mechanisms for both shrinkage stages are basically the same, but their influence is different because at early age concrete has not gained much strength and stiffness.

4.1 Early age shrinkage

The early age shrinkage is caused by chemical reactions and drying. Early age shrinkage is the part of the total shrinkage that occurs before concrete still has not gained much strength. This stage is critical, because here even the smallest stress can have large resulting shrinkage strains or cracking. At early age, concrete also has the greatest tendency to shrink, because there is a lot of free water and no structure to prevent it from bleeding to the surface where it can evaporate, and because the hydration process is the most intensive.

There is not exact definition which part of total shrinkage is early age shrinkage and which part is long term shrinkage. Often it is considered the early age shrinkage takes place immediately after casting until the age of 24 hours or until the demoulding. In that time, concrete starts to change from fluid to rigid stage (setting) and starts to gain strength (hardening).

At the very first hours after the mixing of water and cement, when concrete is still liquid, there will not be internal stresses generated by the shrinking. This means that the volume of concrete will decrease as much as water is evaporated from it and components will shrink by the hydration.

As soon as concrete has gained stiffness, the external volume reduction of concrete will not be equal to the volume of evaporated water and chemical shrinkage. Usually, a couple of hours after the mixing of the concrete, as a result of the hydration, there have formed skeletal structures that will partially restrain the deformations caused by drying and hydration. Now the chemical shrinkage takes effect mainly by the chemical desiccation. [5]

Desiccation, both external (evaporation) and internal (chemical), causes empty voids, where capillary forces are generated. They lead to internal stresses, which may cause cracking if the tensile strength is exceeded.

As concrete is hardening, it gets denser and this resists the convection of free water and water vapour. Also the concentration of unreacted cement particles is decreasing which slows down the total speed of hydration and self-desiccation. In addition to increasing stiffness that resists shrinkage, the drying that causes shrinkage is decreasing. Within the first day after the casting, the shrinkage can be even more than ten times as much as after that.

4.2 Long-term shrinkage

Long-term shrinkage continues from one day onward up to many years. Usually long-term shrinkage is considered as only drying shrinkage. It is good to notice that in that case drying consists of both physical drying by evaporation and chemical drying by hydration. In modern high-strength concretes with a low water-to-cement ratio, the importance of chemical self-desiccation can be greatly remarkable.

In fresh concrete pores are water filled. As concrete desiccates capillary stresses are generated at local water surfaces. Intensity of capillary stress is inversely proportional to the size of the pore. Capillary stress pulls cement particles closer each other, which causes shrinkage. Total amount of shrinking stress is dependent on the size, amount and humidity of the pores in concrete.

Aggregate particles restrain drying shrinkage in concrete. It is also shown that the larger the maximum aggregate size, the lower are the drying shrinkage strains [6]. In addition, nonuniform drying causes internal stresses which partially restrain local shrinkage strains. Some restraint arises also from reinforcing bars and connections to adjacent structures. All restraints cause stresses to the shrinkable concrete. If the induced tensile stresses are greater than the tensile capacity of the concrete, cracks will arise.

When shrinkage strains are restrained, partially or fully, creep causes the internal stresses to decrease [7]. For this reason the total complete shrinkage of nonuniformly desiccated concrete body is less than if it was desiccated uniformly.

Besides drying and autogenous shrinkage, also the carbonation causes shrinkage in the long run. Still, because carbonation develops normally so slowly and its contribution to total shrinkage is normally insignificant, it is usually ignored as a shrinkage phenomenon and concerned as a separate durability issue.

5. EXPERIMENTAL RESEARCH IN LABORATORY

In the experimental part, the drying shrinkage of several concrete mixes was studied with concrete prisms and full-scale slabs. The aim of the slab test was to find out the warping effect

caused by asymmetric drying of concrete slab. The thickness of test slabs was 70 mm with concentric reinforcement #8-200. The strength of concrete was C30 and the size of slab was 2 x 2 m² [2].

5.1 Slab tests

Four concrete slabs were casted on EPS or mineral wool bed (thickness of 30 mm) in the plywood moulds in the Laboratory Hall of TUT (Tampere University of Technology). The indoor climate in the laboratory was during the spring time, from mid. Mars to end of May, temperature $t = 21 \pm 2$ °C and relative humidity $RH < 35$ % (15 – 30 %). The indoor air was really dry and drying of the slabs very fast in the beginning. During summer and early autumn, temperature was temperature $t = 25 \pm 2$ °C and relative humidity RH from 30 % to 65 %. The total monitoring time was six months [2].

After one week aftercare of concrete (covered with plastic), drying of concrete happened freely. The displacement of drying slabs was measured from corners, middle of the edge lines and the middle of the slab in each case. In the corners and edges the displacement happened upward and in the middle point went down. The maximum displacement difference between corners on the middle point of slab was from 3.4 mm to 4.2 mm and it was measured after 104 to 126 days. Distance of middle point to edge point was 1325 mm. In visual inspection any crack was found on top surfaces of test slabs during monitoring.

5.2 Prism tests

The normal way to measure drying shrinkage is to cast 100 mm x 100 mm x 500 mm prisms. The prisms will be stored in a climate room and drying shrinkage will be monitored 90 days. According to literature review long-term shrinkage is typically from 0 to 1 % for age of 90 days. However, the measurements made in TUT shows that magnitude of drying shrinkage continues to increase after the 90 days measurement and the final drying shrinkage could be about 1,3 – 2 %. This means that the true final value of drying shrinkage can actually be 2 - 3 times bigger than that of 90 days measure.

In this experiment the size of prisms were 70 mm x 150 mm x 500 mm. The concrete prisms were sealed so that drying was possible for top surface only (150 mm x 500 mm). The maximum drying shrinkage of the top surface varied from 0.74 ‰ to 0.87 ‰ with these asymmetric drying samples. The shrinkage peak reached its peak value after the seven weeks' drying. The peak values were from 0.5 ‰ to 0.6 ‰ [2].

6. CONDITION INVESTIGATION DATA FOR SEVERAL CONCRETE FLOORS

Condition investigation has been made by TUT researchers for six different storage and industrial buildings in which cracking of concrete floors have been observed. The following remarks are based on these field surveys.

In all cases concrete slabs on ground were designed with centric reinforcement and the amount of reinforcement percentage varied from 0.21 to 0.63 %. The thickness of slabs was 120 - 130 mm. Typical concrete grade was C30 (cubic strength class of 30 MPa). Contraction joint spacing was more than 10 m.

6.1 Visual observation

In all investigated slabs cracking was visually observed. Typically cracks were quite long and oriented random directions see figure 4. Crack widths varied from 0.1 mm to 1.0 mm, see figure 6, and crack spacing was typically 300 – 1000 mm. Generally narrow cracks have smaller spacing and wide cracks have larger spacing.

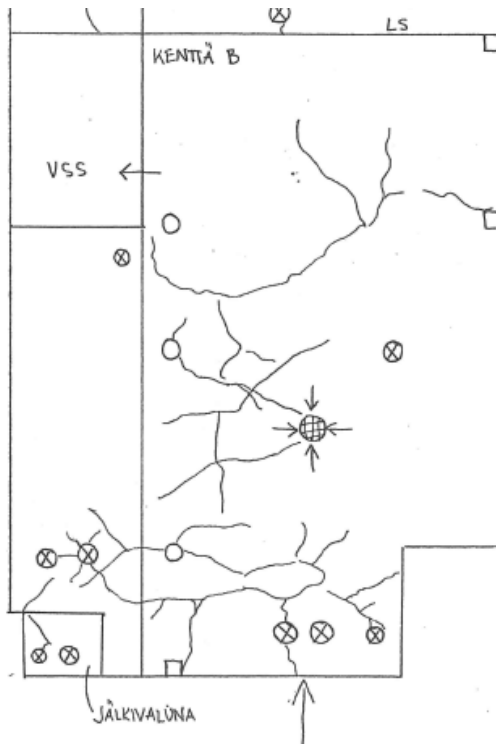


Figure 4. Example of cracking in slab on ground. Thickness of slab was 120 mm reinforcement (#8-150) should be centric, but it was measured to be on the deepness of 90 to 110 mm from the top surface.

Two types of contraction joints were used: concrete shear keys and doweled joints. In the vicinity of contraction joints only perpendicular cracks were observed and their spacing was about 2-3 meters.

Most of the cracks were located near columns of the building frame. In these locations cracks had radial orientation and approximately 1- 5 cracks were founded around the columns. Concrete floor was separated from columns and wall structures using isolation joints. According to investigations these isolation joints worked properly in all cases.



Figure 5. In many cases wide visible cracks has been filled up with epoxy. Most of the cases fissures were still able to detect after repairs.

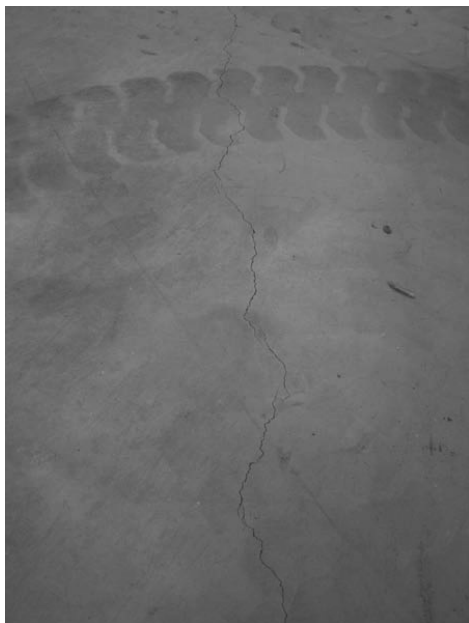


Figure 6. Crack widths varied from 0.1 mm to 1.0 mm.

6.2 Laboratory investigations

Drilled cylinder samples were taken from all investigated floors. Some of the samples were taken cracked parts of the floor. In those samples cracks were so wide that they reach the reinforcing bar in the neutral axis or in some cases cracks were widely open from the upper surface to the bottom surface of slab (see Fig. 4). The crack widths of samples were quite big, because of a relatively large spacing of the cracks. The reinforcements of the slab were usually located 15-30 mm below the neutral axis. This partly explains the great crack widths.



Figure 7. A drilled sample of a cracked slab.

7. DISCUSSION

Drying of concrete slab on ground takes place mainly from its upper surface. Drying downward direction is negligible because of the higher moisture content of the sub-base. Moisture gradient will be thus introduced and the slab is subjected to differential shrinkage (due to the drying shrinkage). This produces upward curling of the slab and tensile stresses in the upper surface. Depending on the magnitude of drying shrinkage and degree of the restraining the tensile stresses can be greater than tensile strength of concrete causing cracking to the slab. Cracking of slab can be controlled using adequate reinforcement close to top surface.

According to field survey, extensive cracking at upper surface of slab was found in cases where centric reinforcement of slab was used. This type of reinforcement is not appropriate for crack controlling. The reinforcement should be placed as close as possible to the top of the slab.

According to Finnish Guidelines for Concrete Structures (by50) [8] ordinary concrete ground floor slab is no requirements for cracking in Exposure Class X0 and XC1. Finnish Guidelines for Concrete Surfaces (by40) [9] recommends that the maximum crack width should be less than 0,1mm and crack length should be less than 500 mm for surface class A. Cracking is not allowable for surface class AA. In Finland it is very common to use centric reinforcement with ground floor slabs. With centric reinforcement it is not possible to meet mentioned requirements.

Concrete slabs on ground having requirements for crack widths, water permeability or surface coatings should be design and construct using both top and bottom reinforcing. Crack control is possible with top reinforcement and loading capacity is ensured with bottom reinforcement.

REFERENCES

- 1 Anon. 2002. Finnish guide for concrete floors by 45 / bly 7. Helsinki, Finnish Concrete Assosiation. 168 p. (in Finnish)
- 2 Hietala J. 2001. Warping of floating floors. Tampere, Tampere University of Technology, Structural Engineering. Publication 108. 87 p. (in Finnish)
- 3 Hietala J. 2003. Warping of floating floors, Part II. Tampere, Tampere University of Technology, Structural Engineering. Publication 118. 70 p. (in Finnish)
- 4 Westergaard H. M. 1927. "Analysis of Stresses in Concrete Roads Caused by Variations of Temperature", *Public Roads*, V. 8, No 3, May 1927, pp. 54-60.
- 5 Holt E. 2001. Early age autogenous shrinkage of concrete. Espoo 2001. Technical Research Centre of Finland, VTT Publications 446. 184 p. + app. 9 p.
- 6 Videla C. & Aguilar C. 2006. An updated look at drying shrinkage of Portland and blended Portland cement concretes. *Magazine of Concrete Research* 58(2006)7, pp. 459–476
- 7 Kovler K. 1995. Interpedence of Creep and Shrinkage for Concrete under Tension. *Journal of Materials in Civil Engineering* 7(1995)2, pp. 96–101
- 8 Anon. 2004. Finnish guidelines for concrete structures by 50. Helsinki, Finnish Concrete Assosiation. 263 p. (in Finnish)
- 9 Anon. 2003. Betonirakenteiden pinnat / luokitusohjeet by 40. Helsinki, Finnish Concrete Assosiation. 168 p. (in Finnish)

Using a standard mix design to study properties of a flooring compound



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ABSTRACT

Self-levelling flooring compounds are complex products that are optimised mainly in order to obtain a good flow, a smooth and wear resistant surface, a controlled open time followed by a rapid setting and hardening and low shrinkage. In this article a standard mix design is presented that is similar to a commercial mix design, but not optimised to the flow. With this mix design it is possible to study hydration rate and properties of the hardened product. The mix design was used to study the influence on moisture properties and strength of three polymers and one thickener. The mechanical properties were clearly influenced both by the additives and the air entrainment caused by the additives, while the drying behaviour was only influenced to a minor extent.

Key words: self-levelling; screed; polymer; mix design.

1. INTRODUCTION

Cement-based self-levelling flooring compounds (SLCs) are dry mortars that normally contain about 15-20 components; binders, aggregates and additives, of which about half are additives (7). Typical binders are aluminat cement, calcium sulphate and Portland cement, while typical aggregates are siliceous sand and limestone filler. Typical additives are:

- Polymers that increases flexural strength, tensile strength, abrasion resistance and improves the flow. This polymer is added in rather large quantities in the form of a redispersible powder.
- Thickeners that prevent bleeding and separation.
- Defoamers that are used to decrease the air content as many additives cause air entrainment.
- Accelerators and retarders that control the rate of reaction and time to setting and hardening.

- Flowing agents that improves the flowability by preventing flocculation, so that the particles can move more freely in the fresh state.

SLCs are complex products and it is generally not possible to change one of the components without also adjusting some of the other components. Even if each component is added to modify a certain property of the SLC (either in the fresh state, the hardened state or both) it will also influence other properties.

The following four properties are probably the most important for SLCs:

- A controlled flow without separation in the fresh state.
- A controlled open time followed by a rapid setting and hardening.
- Low shrinkage.
- A smooth and wear resistant surface.

Of these, the most difficult one to achieve is the controlled flow, that is, good flow without separation. Therefore flowability is the main parameter tested on SLCs, for example according to the European standard EN 12706 (6) where a steel tube (30 mm diameter and 50 mm height) standing on a glass plate is filled with fresh SLC and lifted, allowing the SLC to flow out on the glass plate. The diameter of the flowed mixture is measured, and should for each product be within rather tight limits (for example 135-145 mm). The loss of flowability is one important factor determining the shelf-life of SLC dry mortars and the shelf-life is typically six months.

When doing materials research on properties of SLCs there are several difficulties. In common with products such as paints and adhesives, it is hard to find details of from which components an SLC was made. Manufacturers will only provide a general overview and no details regarding for example the additives. It is also probable that the mix design from which an SLC is made will change with time. The producer's main interest is to obtain and optimise the desired properties and they will continuously adjust the mix design to achieve that. Other issues are that SLC dry mortars change properties during storage and that some of the raw materials, e.g. the cement, derive from natural sources that also change over time. The last three factors will make it difficult to repeat experiments with commercial SLCs. Further, in an optimised mix design the risk of separation is rather high when for example changing the quantity of an individual additive.

Our research interest is how the properties of hydrating and hardened SLCs are influenced by its different components. This involves such properties as strength, sorption isotherms, diffusion coefficients, shrinkage etc. (but not flow). We have therefore developed a generic SLC mix design based on common components, but not optimised it with respect to the flow. This has resulted in a robust mix design in which we can change the concentrations of for example additives without separation. With this mix design we get a product that has the properties of an SLC except that it does not give the extremely high and controlled flow of commercial SLCs. The standard mix design was formulated so that concentrations of components can be changed, components can be replaced or new components can be added without risk of separation that may occur in a fully optimised mix design.

We have found one published mix design of an SLC (12), but this did not include additives. The purpose of the current paper is thus to present the standard mix design and a study of the influence of additives on moisture and other physical properties. Two of the additives, the polymer and the thickener, which we believed had large influence on the moisture properties,

were studied. Due to the relatively large quantities used, the polymer generally represents a rather large part of the total raw material cost of an SLC. In the present tests, we used polymers in dispersion, polymer latex (PL), instead of redispersible polymers that essentially are spray-dried polymer latex (11). Three different types of PLs and one cellulose ether thickener (CE) were studied. The mechanical properties were influenced both by the additives and the air entrainment caused by the additives, while the drying behaviour was only influenced to a minor extent.

2. METHODS AND MATERIALS

2.1 Formulation of standard mix design

On the market today, there are several different types of SLCs, for example, those using mainly Portland cement, those using mainly calcium sulphates, and those using a mixture of several binders. We have used a combination of calcium aluminate cement, Portland cement and one calcium sulphate, α -hemihydrate.

When using blended cements it is important to be able to adjust the rate of hydration. It is common to use a combination of a retarder and an accelerator that mainly act during different phases of the hydration process. The retarder controls the onset of the main hydration and the accelerator increases the rate of the main hydration reaction. The influence on the hydration rate of accelerator and retarder was studied using a TAM Air isothermal calorimeter (TAM Air, Thermometric AB, Järfälla, Sweden) (13). Lithium carbonate was used as accelerator and tartaric acid as retarder. Both were added as mass-% of binder. Figure 1 shows typical results from a feasibility study. It is seen that it is possible to adjust both the time until the main reactions starts and the intensity of the main reaction by using different concentrations of accelerator and retarder. In the present mix design we used 0.1% accelerator and 0.3% retarder. As shown in Figure 2, the product has a similar hydration pattern as a commercial product based on the same type of binders.

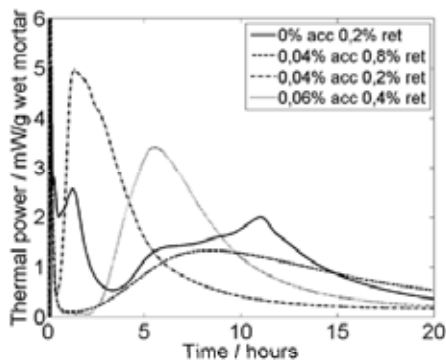


Figure 1 - Example of adjustment of accelerator and retarder.

The water binder ratio was chosen to 0.95, which is in the range of commercial normal drying products and will thereby give similar pore structure as commercial products. The product is self-compacting, but not self-levelling. As there was no wish for self-levelling properties it was decided that no flowing agent should be used (this can however be added).

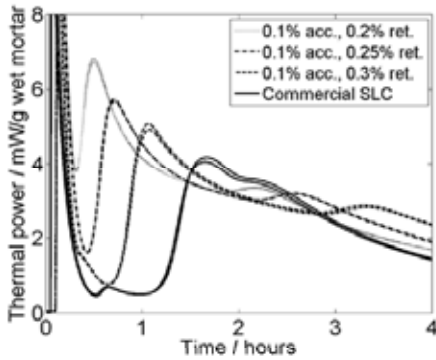


Figure 2 - Results from experiments to adjust the setting time of the final formulation using different amounts of retarder. The commercial self-levelling flooring compound (SLC) contains the same type of binders as the standard mix design.

As noted above, defoamers are needed in SLCs as many additives act as foamers, increasing the air content to unacceptable levels. Commercial SLCs that we have tested have had air contents below 2%. In the present standard mix design a commercial defoamer was used to reduce the air content to around 3% at a concentration of 0.4 mass-% of binder. Octanol was also tested as a standard alternative to a commercial defoamer, but was found to have poor defoaming properties, an unpleasant odour, and unfavourable viscosity.

2.2 Materials

The materials used in the standard mix design are described in Table 1. The binders used were kept in a freezer at $-25\text{ }^{\circ}\text{C}$ from delivery until one week prior to casting as we have found that this decreases the changes in the material properties (2). Table 2 shows the composition of the standard mix design.

Table 1 - Components in the standard mix design including all three polymer latex used in this study. For the polymer latex, MFT is the minimum film formation temperature and T_g is the glass transition temperature.

Calcium aluminate cement (CAC) - binder	CAC40, Istra Cement, Croatia
Ordinary Portland cement (OPC) - binder	Cem I / 52,5 R, Cements AB, Sweden
Alfa-hemihydrate (α -HH), $\text{CaSO}_4 \cdot 0.5\text{H}_2\text{O}$ - binder	α -HH 50, Södharzer Gipswerke GmbH, Germany
Quartz sand (SiO_2)	0-1 mm, Fyleverken IMB AB, Sweden
Limestone filler (CaCO_3)	0-0.2 mm, Nordkalk AB, Sweden
Thickener (CE)	Methylcellulose, Methocel A4M, The Dow Chemical Company.
Defoamer	Non-ionic surfactants on silica support, Rhoximate DF 770 DD, Rhodia PPMC, Switzerland.
Retarder	Tartaric acid ($\text{C}_4\text{H}_6\text{O}_6$)

Accelerator	Lithium carbonate (LiCO_3)
Polymer latex A (PL A)	Acrylate, stabilizing system: anion surfactant, solid cont. 47.3%, pH 7.9, viscosity 5.9 Pa·s, MFT 5 °C, T_g 10 °C
Polymer latex B (PL B)	Poly-(vinyl acetate-co-ethylene), stabilizing system: non-ion surfactant, cellulose derivate, solid cont. 54.5%, pH 3.9, viscosity 1.5 Pa·s, MFT 0 °C, T_g -8 °C
Polymer latex C (PL C)	Poly-(vinyl acetate-co-ethylene), stabilizing system: anion/non-ion surfactant, polyvinyl acetate (PVOH), solid cont. 53%, pH 4.6, viscosity 1.28 Pa·s, MFT 1 °C, T_g 8 °C

Table 2 - Composition of standard mix design.

Binder	Mass / g	Aggregate	Mass / g	Additive	mass-% of binder
CAC	520	CaCO_3	1050	Accelerator	0.1%
OPC	80	Sand (SiO_2)	1800	Retarder	0.3%
Alfa-HH	200			Polymer	8%
				Thickener	0.25%
Water	760			Defoamer	0.4%

2.3 Tested properties

The mix design was used to study how different types and different concentrations of the polymer latexes (PLs) and the thickener influenced selected properties. The mix design was used without the addition of any polymer and with the additions of 5, 8 and 11% (by mass of binders) of PLs A, B and C. Finally were also three different concentrations of the thickener used with a constant content of PL C.

One batch was cast for each formulation. Water was first added to the idle mixing bowl followed by the polymer latex. After that, the remaining additives, sand, limestone and binder were added. Mixing was then done in a Hobart mortar mixer with 45 seconds on low speed, followed by a short stop to remove adhering mortar from the wall and bottom of the bowl, and finally 2 minutes mixing on medium speed. No separation was observed in any of the mixes.

The following properties were measured; rate of surface evaporation, moisture sorption isotherms, moisture diffusion coefficients, density, modulus of elasticity, flexural strength and compressive strength.

Surface evaporation

The rate of surface evaporation was measured during 28 days by registration of the mass loss of specimens cast in circular moulds of 17 mm height and 142 mm diameter. The measurements were performed in a climate room, 20 °C and 55% RH. Double specimens were used. The first mass was registered six minutes after starting the mixing. The air speed above the specimens was 0.1 m/s.

Moisture sorption and diffusion coefficients

Moisture sorption and moisture diffusion coefficients were studied by casting the mortars in small stainless steel tubes (5 mm long and 5.5 mm inner diameter). The tubes were after 28 days

of membrane curing inserted into a sorption balance (DVS 1000, Surface Measurement Systems, UK) and exposed to a stepwise decrease in RH. The sorption isotherm was evaluated from extrapolated equilibrium values in each measurement step and the diffusion coefficient from the sorption kinetics. This method is further described by Anderberg and Wadsö (3). Single test specimens were used.

Density

Prior to testing the modulus of elasticity, the density was determined by measuring the dimensions and mass of the three prisms used for each material (see below).

Modulus of elasticity

For the modulus of elasticity, three prism 40 mm x 40 mm x 160 mm were cast for each material and cured for 28 days in the steel moulds, with one surface exposed to air (20 °C and 55% RH). The measurements were done with an impulse excitation technique using a GrindoSonic MK5 that measures the resonance frequency of an object exposed to a mechanical impulse. The test specimens were standing on a foam mat during the measurements. The relation between the modulus of elasticity and the resonance frequency for a material is given by Vinkeloe (14):

$$E_d = \frac{f^2 m l^3 T}{C^2 I} \quad (1)$$

where E_d (Pa) is the dynamic elastic modulus, f (s^{-1}) the resonance frequency, m (kg) is the mass of the specimen, l (m) is the length and T (about 1.4 in the present case) is a correction factor depending on the dimensions of the specimen and the Poisson's ratio ν (in the present study assumed to be 0.2), C is a constant (3.56 for the fundamental oscillation was used in the present case) and I (m^4) is the area moment of inertia. The measured dynamic E-modulus is generally about 20% higher than the static E-modulus (4).

Compressive and flexural strength

As the testing of the dynamic modulus is non-destructive, the same prisms were also used for flexural and compressive strength measurements. These were tested and evaluated in accordance with EN 196-1 (5), where the flexural strength is determined by three point bending and the two pieces from each bending test are tested in compression. It is important to note that due to that SLC are not construction materials the compressive strength is of less practical importance, while the flexural strength is of one of its more important properties.

3. RESULTS AND DISCUSSION

Surface evaporation

The results of the surface evaporation measurements are presented in Figure 3. For each sample type the mean of the two measurements is shown. While the surface evaporation rate seems to increase with increasing amount of PL A the opposite result is seen for PL B. For PL C no difference could be seen between the different concentrations, but a difference was seen as compared to when no PL was used. The results from measurements made with different concentrations of CE show similar results up to about 5 days and thereafter a slight increase in surface evaporation rate with increasing amount of CE.

Table 4 - Diffusion coefficients of self-levelling flooring compounds with different concentrations of polymer latex (PL). Values shown are diffusion coefficients with water vapour content as potential (10-6 m²/s) in different relative humidity (RH) intervals (%).

RH	No PL	PL A			PL B		PL C		
		5%	8%	11%	5%	8%	5%	8%	11%
95-90	1.5	1.3	1.1	1.3	1.3	1.1	1.3	1.3	1.5
90-80	1.4	0.96	0.88	0.94	1.0	0.83	0.90	0.84	0.75
80-70	1.2	0.82	0.59	0.52	0.71	0.56	0.63	0.48	0.43
70-50	0.74	0.52	0.36	0.31	0.48	0.41	0.48	0.36	0.31
50-30	0.23	0.21	0.13	0.13	0.19	0.23	0.25	0.20	0.23
30-10	0.12	0.12	0.083	0.076	0.085	0.11	0.10	0.10	0.10

Table 5 - Desorption isotherms and diffusion coefficients of self-levelling flooring compounds with different concentrations of a cellulose based thickener (CE). Moisture contents are shown as % of mass at 10% relative humidity (RH) and diffusion coefficients (10-6 m²/s) were calculated using water vapour as potential.

RH	Moisture content			RH	Diffusion coefficient	
	0.1% CE	0.25% CE	0.5% CE		0.1% CE	0.25% CE
95	5.3	5.1	5.5	95-90	1.4	1.3
90	4.6	4.4	4.7	90-80	0.85	0.84
80	3.6	3.4	3.6	80-70	0.51	0.48
70	2.6	2.3	2.6	70-50	0.35	0.36
50	0.88	0.79	0.82	50-30	0.24	0.20
30	0.38	0.34	0.33	30-10	0.097	0.10
10	0	0	0			

Density

The measurements of density, Figures 4-6 top left, show a clear decrease between the formulation without PL and the formulations with 5% PL. For PL B the density then increases somewhat with increasing concentration, while the densities for PL A and PL C are rather constant when further increasing the concentration above 5%. Generally the density will decrease when polymer latex is added as these polymers have a lower density than the sand-binder matrix and as they contain surfactants that tend to create air bubbles (11).

As shown in Figure 7 the test specimens with CE show a quite linear relationship between concentration and density, where each tenth of a percent added CE results in almost 2% reduction in density.

Flexural strength, compressive strength and modulus of elasticity

The flexural strength decreased by the addition of 5% PL for all specimens. For higher concentrations, the spread in the results exceeds the differences seen between the different concentrations. According to Ohama (1+) the flexural strength is generally improved in latex modified mortars and an optimum in polymer/cement ratio is often seen. One explanation of this is that a certain amount of polymer is needed for continuous polymer film formation (1). In the present measurements the addition of the polymer latex also led to an increased air content. This results in discontinuities that will reduce the strength (11). This may explain the somewhat lower values for flexural strength for the latex modified specimens as compared to the non-modified specimens.

The results of the compressive strength measurements correlate rather well with the density up to 8% PL, but at the highest concentrations of PL A and PL C there is a loss of compressive strength while the density is fairly constant. Generally, polymer modification does not improve the compressive strength (10).

The modulus of elasticity decreased by the addition of 5% PL for all specimens. A further increase in PL concentration only led to smaller changes in the modulus of elasticity for PL A, while an increase was seen for PL B and a decrease was seen for PL C. Polymer modified mortars have lower modulus of elasticity compared to mortars without polymers (11).

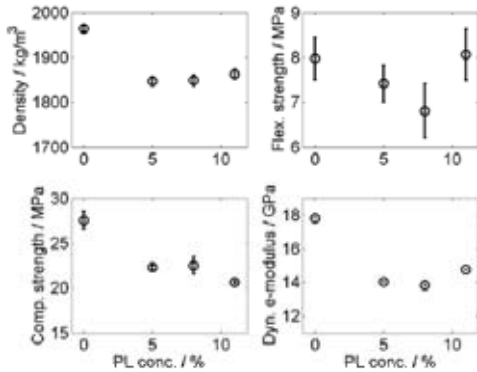


Figure 4 - Density, flexural strength, compressive strength and modulus of elasticity for specimens without polymer latex (PL) and specimens modified with 5, 8 and 11 mass-% of binder of PL A. Error bars mark one standard deviation.

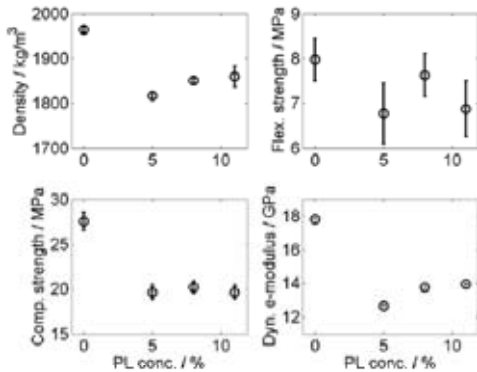


Figure 5 - Density, flexural strength, compressive strength and modulus of elasticity for specimens without polymer latex (PL) and specimens modified with 5, 8 and 11 mass-% of binder of PL B. Error bars mark one standard deviation.

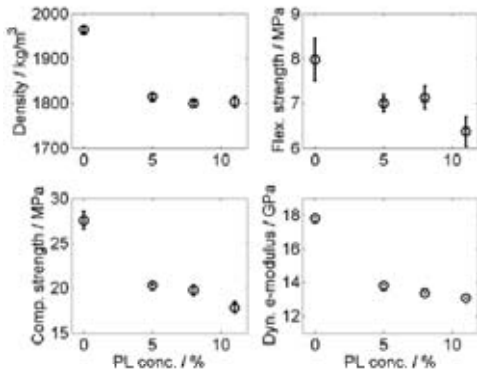


Figure 6 - Density, flexural strength, compressive strength and modulus of elasticity for specimens without polymer latex (PL) and specimens modified with 5, 8 and 11 mass-% of binder of PL C. Error bars mark one standard deviation.

The density decreased significantly with an increase in concentration of cellulose ether (CE) due to air entrainment caused by the CE as discussed in for example (8). This explains the decrease in both flexural and compressive strength with an increase in CE concentration. No explanation has been found regarding the increase in modulus of elasticity with increasing concentration of CE.

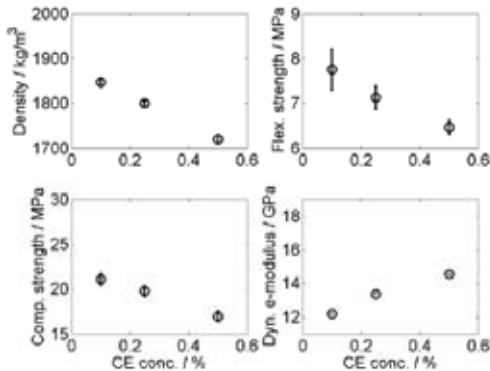


Figure 7 - Density, flexural strength, compressive strength and modulus of elasticity for specimens with 8 mass-% of binder of polymer latex C and 0.1, 0.25 and 0.5 mass-% of binder of cellulose ether (CE). Error bars mark one standard deviation.

4. GENERAL DISCUSSION

Air content was not measured in these studies, but the decrease in density seen mainly results from an increase in air content. Density is a difficult factor to handle in this type of studies as it can be influenced by all the added components; also the components not added for the purpose of increasing air content. It is thus important to measure density as a check on if this parameter has changed, and to judge changes in all other properties in relation to the density changes.

In all cases in the present study the largest change in density comes when the polymer is added to the mix design. According to Neville (9) the average loss of compressive strength in concrete is 5.5% for each percentage point of air present, but the effect on flexural strength is lower. For PL A, for example, the increase in air content is about 6% and the reduction in compressive strength about 20%. This gives an average loss in compressive strength as related to the increase in air content that is within the same range, but slightly lower, than the value given above. The figures are similar for PL B, PL C and CE modified specimens.

The curing conditions are vital for the strength development in polymer-modified mortars as moist conditions are favourable for the cement hydration, but drying is needed for the coalescence of the polymer particles. Generally, initially moist conditions for rapid cement hydration followed by dry conditions that promotes polymer film formation are desired (10). All specimens in the present investigation were cured in the same way and it is possible that the degree of hydration of specimens with different concentrations of PLs were different. As the specimens were only allowed to dry by surface evaporation in one direction it is also possible that the film formation was not complete throughout the specimens as the bottom of the specimens may not have been sufficiently dry for this to happen. This would also reduce the influence of the polymers on the flexural strength.

The SLC mix design developed is a “laboratory mix design” that can be used as a base in studies of hydration properties and properties of hardened SLCs. In this paper it is shown how one can study the influence of additive concentrations on for example transport properties and mechanical properties. The mix design naturally also makes it possible to study the influence of different curing conditions. The influence on rate of reaction can easily be studied with calorimetric measurements as shown in Figures 1-2.

All components of the mix design except the defoamer have well defined constituents (although the properties of for example the cements may be slightly variable over time). This makes it possible for future usage of the mix design where only minor adjustments have to be done in order to obtain similar properties as in the present mix design. The mortar was stable and showed no tendencies for separation even though large variations in concentrations of both polymer latex and thickener were used.

For the study of moisture properties careful experimental set-ups are required due to the relatively small differences between different formulations. One way of decreasing the uncertainty when studying moisture properties is to increase the specimen thickness as the evaporation is highly influenced by the thickness. Other physical properties like strength show relatively larger differences and are therefore more easily evaluated. One common way in the studies of polymer-modified mortars is to increase the amount of defoamer with increasing amount of polymer. This would keep the air content rather stable and thereby making the evaluation of for example flexural and compressive strength easier.

5. CONCLUSION

The laboratory mix design for a flooring compound that was formulated in this study enables studies of the influence of different components on its hydration and the properties of the product. The results indicate that even when only one factor is changed in a mix design, several properties may change. Density should always be measured in this type of studies as air content can be influenced by many of the components used in this type of products.

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REFERENCES

- 1 Afridi, M. U. K., Ohama, Y., et al., "Development of polymer films by the coalescence of polymer particles in powdered and aqueous polymer-modified mortars", *Cement and Concrete Research* no. 33 2003 pp. 1715-1721.
- 2 Anderberg, A. and Wadsö, L., "Measurements of the influence of storage time and storage temperature on properties of raw inorganic binders and dry mortars". 12th International Congress on the Chemistry of Cement, Montreal.2007
- 3 Anderberg, A. and Wadsö, L., "Method for simultaneous determination of sorption isotherms and diffusivity of cement based materials", *Cement and Concrete Research* no. 38 2008 pp. 89-94.
- 4 Bastgen, K. J. and Hermann, V., "Experience made in determining the static modulus of elasticity of concrete", *Materials and Structures* no. 10(6) 1977 pp. 357-364.
- 5 CEN, European Committee for Standardization. Methods of testing strength - Part 1: Determination of strength. Brussels, 1994.
- 6 CEN, European Committee for standardization. Adhesives - Test methods for hydraulic setting floor smoothing and/or levelling compounds - Determination of flow characteristics. Brussels, 1999.
- 7 Harbron, R., "A general description of flow-applied floor screeds-An important application for complex formulations based on CAC". International Conference on Calcium Aluminate Cements 2001, Edinburgh, UK, IOM Communications Ltd, London.2001
- 8 Jenni, A., Holzer, L., et al., "Influence of polymers on microstructure and adhesive strength of cementitious tile adhesive mortars", *Cement and Concrete Research* no. 35 2005 pp. 35-50.
- 9 Neville, A. M., Properties of concrete. Harlow, Longman Group Ltd, 1995.
- 10 Ohama, Y., "Principle of latex modification and some typical properties of latex-modified mortars and concretes", *ACI Materials Journal* no. 84 1987 pp. 511-518.
- 11 Ohama, Y., "Polymer-based admixtures", *Cement and Concrete Composites* no. 20 1998 pp. 189-212.
- 12 Scrivener, K. L., Rettel, A., et al., "Effect of CO₂ and humidity on the mechanical properties of a formulated product containing calcium aluminate cement". Ibausil, Weimar, Germany.1997
- 13 Wadsö, L., "Application of an eight-channel isothermal conduction calorimeter for cement hydration studies", *Cement International* no. 3(5) 2005 pp. 94-101.
- 14 Vinkeloe, R., "Prüfverfahren zur Ermittlung des dynamischen Elastizitätsmoduls von Betonprismen", *Tonindustrie Zeitung* no. 86 1962 pp. 272-276.

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