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SUMMARY

If, as a result of a short mixing time, excess air entraining agent is added during the production of air-entrained concrete in order to achieve the required air content then the fresh concrete will contain air-entraining agent that has not been activated. If there is a subsequent input of mixing energy the air content of the concrete can rise. The extent of this rise (the re-activation potential) is affected substantially by the active substance on which the air-entraining agent (AEA) is based. A sufficiently long mixing time always avoids any rise in air content. Accurate understanding of the way the air void formation depends on mixing time is therefore very important for dependable production of air-entrained concrete that meets the requirements. The functioning of an air-entraining agent can be characterized in laboratory trials during extended initial testing. However, the air void formation is also affected by the mixer type, quantity of mixture, filling level and mixing intensity. The extent to which laboratory results can be applied to practical construction conditions has not yet been clarified. The air void formation in fresh and hardened concrete in relation to the mixing time was therefore determined in the laboratory and in a ready-mixed concrete plant in a research project. Comparison of the test series shows that the re-activation potential under practical conditions can be determined in laboratory trials. ◂

ZUSAMMENFASSUNG

Wird bei der Herstellung von Luftporenbeton infolge einer kurzen Mischzeit der LP-Bildner zur Erreichung eines angestrebten Luftgehalts überdosiert, enthält der Frischbeton nicht aktivierten LP-Bildner. Bei einem nachträglichen Eintrag von Mischenergie kann sich der Luftgehalt des Betons erhöhen. Das Ausmaß der Erhöhung (Nachaktivierungspotenzial) wird wesentlich von der Wirkstoffbasis des LP-Bildners beeinflusst. Eine ausreichend lange Mischzeit beugt in jedem Fall einem Anstieg des Luftgehalts vor. Die genaue Kenntnis der mischzeitabhängigen Luftporenbildung ist daher von großer Bedeutung für die zielsichere Herstellung eines anforderungsgerechten LP-Betons. In Laborversuchen kann in einer erweiterten Erstprüfung die Wirkungsweise eines LP-Bildners gekennzeichnet werden. Die Luftporenbildung wird aber auch durch den Mischertyp, die Mischungsgröße, die Füllmenge und die Mischintensität beeinflusst. Ungeklärt war bisher die Übertragbarkeit von Laborergebnissen auf baupraktische Bedingungen. In einem Forschungsvorhaben wurde daher die mischzeitabhängige Luftporenbildung am Frisch- und Festbeton in zwei Versuchsreihen im Labor und in einem Transportbetonwerk ermittelt. Der Vergleich der Versuchsreihen zeigt, dass in Laborversuchen das Nachaktivierungspotenzial in der Praxis ermittelt werden kann. ◂

Air void formation in the laboratory and in practice

Luftporenbildung in Labor und Praxis

1 Introduction

The basic requirement for dependable production of an air-entrained concrete that meets the requirements is an understanding of the action mechanisms involved in the formation of air voids. Previous investigations have been based on small-scale laboratory trials. A research project examined whether the influence of mixing time, the basis of the active substance in the air-entraining agent and the quantity of agent added on the re-activation potential found in laboratory trials also holds true under practical conditions during production in a ready-mixed concrete plant or construction site mixing plant. This should prove whether the results of the initial testing can be applied to practical conditions. An understanding of the relationships will make it possible to reduce the risk of unwanted air void formation and of an air void system in the hardened concrete that does not meet the requirements.

2 Current understanding

A sharply increased air content has been found in the hardened concrete in some sections of concrete pavement when using air-entraining agents based on synthetic active substances. Laboratory investigations have shown that a substantial increase in air content can occur if, as result of too short a mixing time, excess air-entraining agent is added in order to maintain the required air content. The fresh concrete will then contain air-entraining agent that has not been sufficiently activated. More air bubbles will be stabilized if there is a subsequent input of mixing energy into the fresh concrete, e.g. by the distributing screw of the slipform paver during placement, and the air content can rise. Similar effects are known with ready-mixed concrete, in which the air content can rise between the mixing plant and the construction site due to the rotating drum.

The extent of the rise, the re-activation potential, is affected substantially by the active substance on which the air-entraining agent used is based. With air-entraining agents based on natural active substances (wood resins) most of the air-entraining agent added is precipitated in the pore solution even if it has been added in excess. In spite of the disproportionately high addition of air-entraining agent the increase in the air content of the concrete is therefore comparatively slight. These air-entraining agents are always almost completely activated and have a comparatively low re-activation potential. For air-entraining agents based on synthetic active substances with a shortened mixing time and excess addition level a fairly large proportion of the added air-entraining agent remains in the pore solution because of its better solubility. If there is a subsequent input of mixing energy, air bubbles will be continuously introduced into the fresh concrete and stabilized until all the air-entraining agent has been fully activated. A subsequent increase in the air content can therefore occur under construction conditions when synthetic air-entraining agents are used [1].

The production of an appropriate aerated concrete requires extensive initial testing in which the various factors affecting the air void formation are taken into account. Appropriate regulations for the composition and production of air-entrained concrete are laid down in the body of rules [2–4]. Extended fresh concrete tests are recommended so that even during the initial testing it is possible to assess the re-activation potential of a concrete [5, 6]. The addition level for the air-entraining agent determined in the initial testing can be doubled in an additional test (❱ Fig. 1) and the air contents of the mixtures with the two addition levels of air-entraining agent can be determined after a short mixing time of, for example, 30 seconds and after an extended mixing time of about four to six minutes. If there is a substantial rise in the air content with the doubled addition level and extended mixing time there is the risk of a subsequent increase in air content when the construction work is carried out. Regardless of the particular conditions this can always be avoided if the air-entraining agent has already been fully activated during production by using a sufficiently long mixing time.

An understanding of air void formation relative to the mixing time is therefore very important for assessing the re-activation potential. The recommendations are based on the trials with laboratory mixers (capacity approximately 0.1 m^3). Air content and air void distribution are dependent not only on the concrete composition and the fresh concrete temperature but also on the manner in which the concrete is produced, such as mixer type, size of mix and mixing intensity [7–10].

3 Test procedure

3.1 Aim and extent of the trials

The investigations were intended to provide a basic understanding of the action mechanism of the air-entraining agents during use under practical conditions in a mixing plant. The first step was to select three air-entraining agents with different re-activation potentials. The air void formation in fresh and hardened concrete relative to the mixing time was then

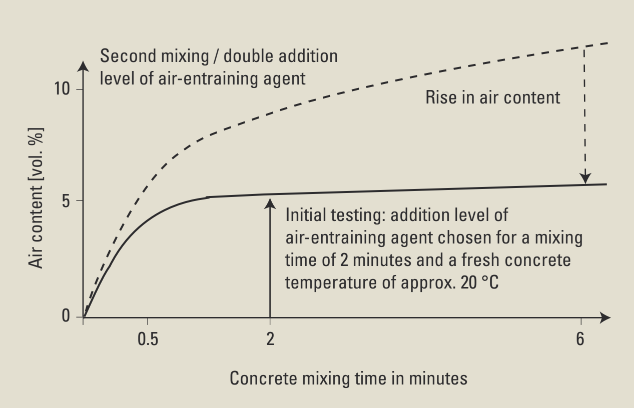

Figure 1: Testing the re-activation potential of a concrete composition during initial testing in the laboratory [1]

determined in two test series in the laboratory and in a ready-mixed concrete mixing plant using comparable starting materials and concrete compositions. This was intended to prove that the interactions and relationships between mixing time, active substance basis and addition level of the air-entraining agent established during the initial testing in the laboratory can also be applied to practical conditions.

3.2 Laboratory trials

3.2.1 Initial testing

3.2.1.1 Starting materials

Three air-entraining agents based on different active substance were chosen after considering the available investigative results [1]: active substance with low re-activation potential: modified wood resin, active substance with average re-activation potential: alkyl sulfate, and active substance with high re-activation potential: alkyl polyglycol ether sulfate. Diluted air-entraining agents were used in order to simulate the conditions that occur in practice. A CEM I 42,5 N cement that is used as standard in the corresponding ready-mixed concrete plant was used as the cement. The cement was delivered to the Research Institute of the Cement Industry at the end of 2011. Cement samples were taken from the silo at this time and during the practical trials (June 2012). The cement samples fulfilled the requirements of DIN EN 197 Part 1 and also of TL Beton-StB 07. The aggregates used in the ready-mixed concrete plant (0/2 mm Rhine sand, 2/8 and 8/18 mm Rhine gravel from the Düsseldorf area) were used for the laboratory and practical trials. The local mains water was used for producing the concretes.

3.2.1.2 Mix composition

The cement content was 350 kg/m^3 and the w/c ratio was 0.44. The aggregate mix consisted of 0/16 mm gravelly Rhine sand with a grading curve in the middle of the A/B 16 grading curve range specified in DIN 1045-2. The aggregate content was 1797 kg/m^3. It was intended that the fresh concrete should have a stiff consistency (compacting factor class C1, $\nu \geq 1.26$) at about 30 minutes after production.

3.2.1.3 Production

The amount of the respective air-entraining agents added was set so that at a fresh concrete temperature of about 20 °C the air content of the concrete tested with the 8 l pressure vessel ten minutes after production was 5.0 ± 0.5 vol. %. 150 l of fresh concrete was produced for each concrete. The cement and aggregate were premixed dry for 15 seconds in a 250 l mechanical mixer. The air-entraining agent was added to the mixing water immediately before the concrete was mixed. The mixing time after the addition of all the constituents was two minutes.

a) Fresh concrete investigations

The air content and bulk density were determined with the 8 l pressure vessel and the consistency was determined with the compaction box 10 and 30 minutes after the production (end of mixing). The air void vessel and the compaction box were compacted on a vibrating table.

b) Hardened concrete investigations

Test pieces were compacted in steel moulds on the vibrating table ten minutes after the end of mixing for the tests on the hardened concrete. Seven cubes with edge lengths of 150 mm were produced: three cubes for determining the 28-day compressive strength and the air void parameters in the hardened concrete (1 cube) as well as three cubes with inserted Teflon sheets for testing the resistance to freeze-thaw with de-icing salt by the CDF method.

3.2.1.4 Storage and testing

a) Fresh concrete

The temperature and bulk density were determined as well as the air content of the fresh concrete using the pressure equalization method in the 8 l air void vessel. The compacting factor was also measured. The tests were carried out in accordance with the DIN EN 12350 series of standards.

b) Hardened concrete

After production the test pieces were stored for 24 ± 1 hours in a climatic chamber at an air temperature of 20.0 ± 2.0 °C and a relative air humidity of 65 ± 5 % in their moulds covered with moist cloths. The test pieces were then removed from the moulds and stored and tested as follows:

Compressive strength

After they had been removed from the moulds three cubes were stored under water in accordance with DIN EN 12390-2:2001-06 until they were seven days old and then stored in a climatic chamber at an air temperature of 20.0 ± 2.0 °C and a relative air humidity of 65 ± 5 % in accordance with DIN EN 12390-3 until the compressive strength was tested at an age of 28 days.

Air void parameters

After it had been removed from the mould one cube was stored under water until it was seven days old and then stored in the climatic chamber until two slices were taken from the cube for determining the air void parameters using the procedure described in DIN EN 480-11.

Resistance to freeze-thaw with de-icing salt by the CDF method

Three cubes with Teflon sheet inserts were removed from their moulds after one day. Five CDF slabs (dimensions approximately 150 mm x 110 mm x 75 mm) were cut from the cubes and stored under water. After seven days the CDF slabs were stored in the 20/65 climatic chamber until the 28th day. Between the 21st and 26th day after the production of the test pieces the side faces of the CDF slabs were sealed with butyl rubber using aluminium adhesive tape. The test pieces were then stored in the climatic chamber again. After the 28th day the test pieces were placed for seven days in preliminary storage in a footbath of 3 % NaCl solution as specified in DIN CEN/TS 12390-9. The freeze-thaw stressing then started with two cycles per day (the test surface was the surface originally covered by Teflon sheet). The relative dynamic elastic modulus and the scaling of the test surface were determined after, as a rule, 7, 14 and 28 freeze-thaw cycles. The dynamic elastic modulus was calculated from the ultrasonic transit time in the concrete and provided an indication of the extent of the internal damage.

3.2.2 Air void formation relative to mixing time

The air void formation in fresh concrete relative to the mixing time was determined with the three air-entraining agents using the "single" addition level determined in the preliminary test and also double and triple addition levels. At the single addition level the air-entraining agent was not included in the calculation of the mixing water. For the double and triple addition levels the quantity of air-entraining agent added was subtracted once and twice respectively from the mixing water to ensure the same water content for all three

Table 1: Results of the fresh concrete investigations (laboratory)

Active substance basis of air-entraining agent	Solids content of air-entraining agent in mass %	Quantity added in mass % w.r.t. cement		Air content in vol. %		Compacting factor	
		Air-entraining agent	Active substance	10 min	30 min	10 min	30 min
Modified wood resin	4.12	0.30	0.012360	5.3	4.5	1.24	1.27
Alkyl sulfate	1.69	0.30	0.005100	5.5	4.8	1.21	1.23
Alkyl polyglycol ether sulfate	0.32	0.47	0.001504	4.7	3.6	1.20	1.24

addition levels. The low solids content of the air-entraining agents (0.3 to 4 mass %, ❱ Table 1) was ignored. The air-entraining agents were added to the mixing water immediately before the concrete was mixed. After addition of all constituents the concrete was mixed for 30 seconds and the mixer was then stopped briefly. Some concrete for testing the air content with the pressure vessel was removed and the air content was then determined immediately as described in Section 3.2.1.4. Immediately after the concrete had been removed from the mixer the remaining concrete was mixed further and the air content test was repeated after 45 seconds and after 1, 2, 4, 6, 8, 10 and 15 minutes. One cube (edge length 150 mm) was produced for each of the variants made with the single and double addition levels after mixing times of 30 seconds and one, two and seven minutes in order to determine the effect of mixing time and addition level on the air void parameters. The storage and testing were as described in Section 3.2.1.4.

3.3 Practical trials

3.3.1 General

The practical trials were carried out at Dyckerhoff AG's ready-mixed concrete plant in Neuss. Two mixing plants that operated independently of one another were available. The smaller mixing plant was used for the trials so that the normal daily business was not affected. The mixing plant was provided with a 2 m^3 pan mixer and silos for cement and aggregates (0/2 mm, 2/8 mm and 8/16 mm). The trials were carried out over three days in June 2012. A different air-entraining agent was tested on each day: first the air-entraining agent based on natural active substances and then the synthetic air-entraining agents based on the alkyl sulfate and alkyl polyglycol ether sulfate active substances. In contrast to the laboratory trials the first measurements were of the air void formation relative to mixing time because these curves were used for estimating the quantities of air-entraining agent to be added for the initial testing to achieve an air content of about 5 vol. % after mixing times of 30, 45 and 60 seconds. A rise in air temperature from on average about 20 °C through 23 °C and up to 25 °C was recorded during the three days. This produced a corresponding increase in the fresh concrete temperature.

3.3.2 Air void formation relative to mixing time

The test procedure was examined and optimized in preliminary trials. A constant air content was obtained after a mixing time of 90 seconds. Longer mixing times did not produce any substantial change in the target air content of 5 vol. %. The quantity of air-entraining agent was therefore chosen so that an air content of 5.0 ± 0.5 vol. % was achieved after a mixing time of 90 seconds. This (single) as well as double and triple addition levels were used to determine the mixing time curves. An indication of the mixing process, such as was obtained in the laboratory, could not be obtained in the plant because the start-up would have caused damage to the motor due to overloading. The mixer therefore had to be run for the full mixing time of ten minutes without interruption during the practical trials.

The maximum possible capacity of the mixer was also reduced from 2 m^3 to 1.25 m^3 to avoid damage to the motor. At given times about 50 litres of fresh concrete was dropped into a truck mixer through a flap on the underside of the mixer (❱ Figs. 2a to 2c) to permit continuous record-

Figure 2: a) General view of mixing plant, truck mixer and site laboratory; b) unloading fresh concrete into the truck mixer after a specified mixing time; c) unloading the fresh concrete from the truck mixer into mortar pans

Table 2: Results of the hardened concrete investigations (laboratory)

Active substance basis of air-entraining agent	28-day compressive strength in N/mm^2	Bulk density in kg/dm^3	Scaling loss after 28 freeze-thaw cycles in g/m²	Air void parameters in hardened concrete		
				Air content in vol. %	Micro air void content in vol. %	Spacing factor in mm
Modified wood resin	60.9	2.27	133	6.20	2.23	0.17
Alkyl sulfate	56.9	2.27	157	5.86	2.77	0.16
Alkyl polyglycol ether sulfate	59.9	2.28	110	5.77	2.73	0.17

ing of the air void formation. The truck mixer was emptied by reversing the rotation of the drum and the fresh concrete was discharged via a chute into a total of seven mortar pans. Each mortar pan was allocated to a mixing time of 30, 60 or 90 seconds or 2, 4, 7 or 10 minutes. The mixing time of 45 seconds was abandoned in the practical trial as it would no longer have been possible to make a clear separation of the fresh concrete samples released after mixing times of 30, 45 and 60 seconds.

The concrete composition corresponded to the laboratory trials. The aggregates and cement were taken from the silos, weighed and fed into the mixer. The mixing water was weighed in a storage container. The quantity corresponded to the total water content (154 kg/m^3, w/c = 0.44) minus the inherent moisture content of the aggregate mix (which was determined daily before the start of the trial). The weighed air-entraining agent was added directly into the container with the mixing water, corresponding to the procedure in the laboratory trials. The mixing water was then added to the cement and aggregates in the mixer. The mixing time started when all the water had been added. For the single addition level the air-entraining agent was not included in the calculation of the water content. For the double and triple addition levels the quantity of air-entraining agent added was subtracted once or twice respectively from the mixing water to ensure the same w/c ratios for all three addition levels. 1.25 m^3 fresh concrete were produced in each batch.

3.3.3 Initial testing

The addition levels for the air-entraining agents were determined on the basis of the mixing time curves in order to achieve a fresh concrete air content of 5.0 ± 0.5 vol. % after mixing times of 30 seconds (shorter mixing time than the minimum mixing time of 45 seconds specified in TL Beton-StB [4]), 45 seconds (minimum mixing time) and 60 seconds (longer mixing time). When these values had been achieved the following test pieces were produced: three cubes (edge length 150 mm) for testing the 28-day compressive strength, one cube (edge length 150 mm) for determining the air

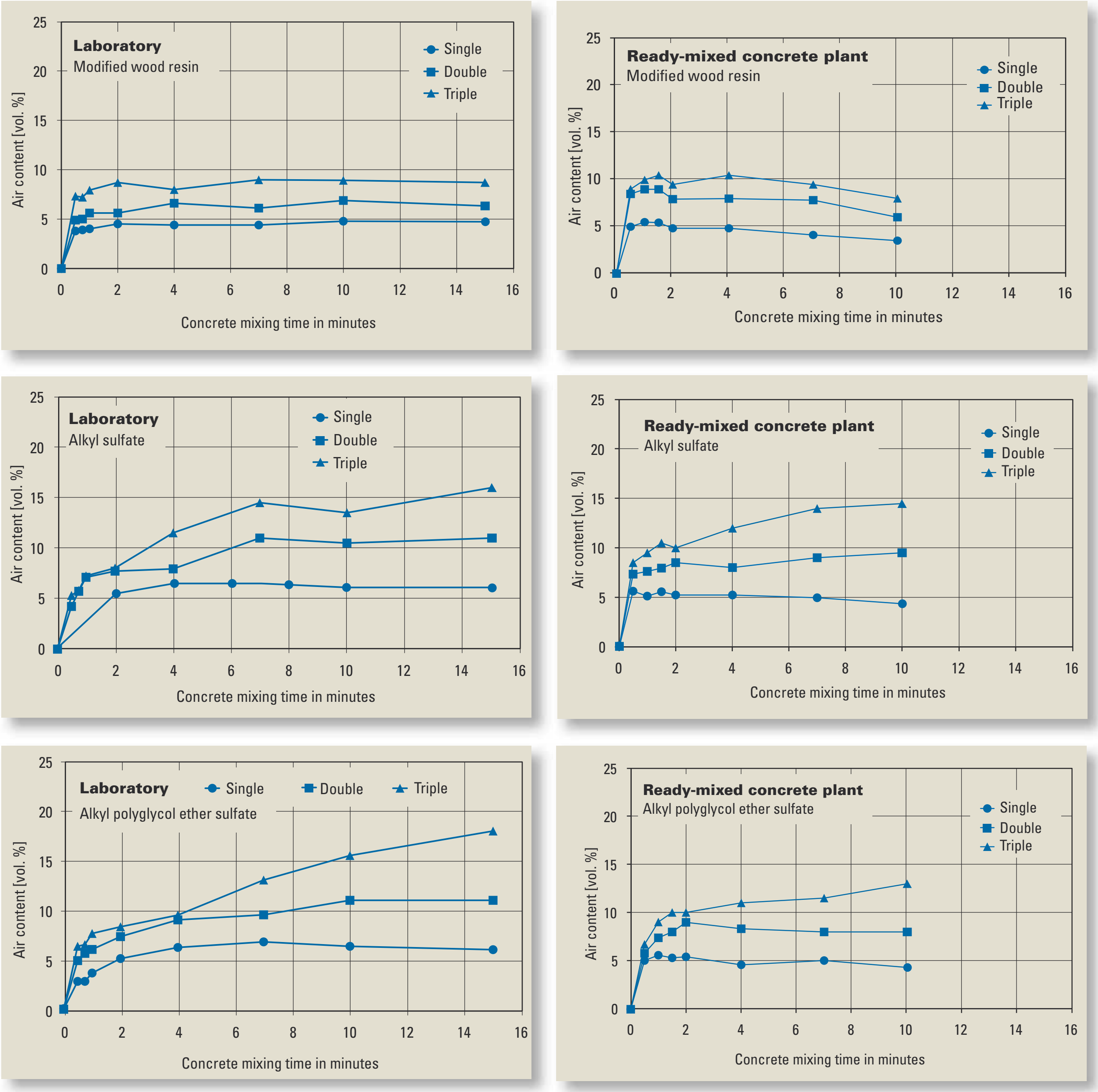

Figure 3: Air content of the fresh concrete in relation to the mixing time, the active substance and the amount of AEA added (left: laboratory, right: ready-mixed concrete plant)

Table 3: Fresh concrete air content in the laboratory and in the ready-mixed concrete plant in relation to the type of active substance and the quantity of AEA added and the mixing time

Active substance	Mixing time	Air content in vol. %		Air content in vol. %		Air content in vol. %	
		Laboratory	Plant	Laboratory	Plant	Laboratory	Plant
		Addition level: single		Addition level: double		Addition level: triple	
Modified wood resin	30 s	3.8	5.6	4.9	8.5	7.3	9.0
	45 s	3.9	–	5.0	–	7.2	–
	1 min	5.2	5.1	5.6	9.0	7.9	10.0
	1.5 min	–	5.5	–	9.0	–	10.5
	2 min	5.3	5.2	5.6	7.9	8.7	9.5
	4 min	6.4	5.2	6.6	8.0	8.0	10.5
	7 min	6.5	4.9	6.1	7.8	9.0	9.5
	10 min	6.2	4.3	6.9	6.0	8.9	8.0
	15 min	6.2	–	6.3	–	8.7	–
Alkyl sulfate	30 s	3.8	5.6	4.2	7.3	5.3	8.5
	45 s	3.9	–	5.7	–	5.8	–
	1 min	5.2	5.1	7.1	7.6	7.2	9.5
	1.5 min	–	5.5	–	7.9	–	10.5
	2 min	5.3	5.2	7.7	8.5	8.0	10.0
	4 min	6.4	5.2	7.9	8.0	11.5	12.0
	7 min	6.5	4.9	11.0	9.0	14.5	14.0
	10 min	6.2	4.3	10.5	9.5	13.5	14.5
	15 min	6.2	–	11.0	–	16.0	–
Alkyl polyglycol ether sulfate	30 s	2.8	5.0	4.9	5.8	6.3	6.7
	45 s	2.8	–	5.6	–	6.5	–
	1 min	3.6	5.6	6.0	7.4	7.6	9.0
	1.5 min	–	5.3	–	8.0	–	10.0
	2 min	5.1	5.4	7.3	9.0	8.3	10.0
	4 min	6.2	4.6	9.0	8.3	9.5	11.0
	7 min	6.8	5.0	9.5	8.0	13.0	11.5
	10 min	6.3	4.3	11.0	8.0	15.5	13.0
	15 min	6.0	–	11.0	–	18.0	–

Table 4: Air void parameters in the hardened concrete in relation to the type of active substance and the quantity of AEA added and the mixing time (laboratory)

Air-entraining agent active substance	Parameter		Addition level	Mixing time			
				30 s	1 min	2 min	7 min
Modified wood resin	Air void content A	Vol.-%	Single	4.9	5.0	5.7	5.1
			Double	6.2	6.5	6.4	6.7
	Micro air void content A_{300}	Vol.-%	Single	2.0	2.1	2.7	2.8
			Double	2.7	3.5	4.5	4.7
	Spacing factor	mm	Single	0.19	0.15	0.13	0.12
			Double	0.17	0.13	0.09	0.07
Alkyl sulfate	Air void content A	Vol.-%	Single	4.8	6.2	5.9	7.5
			Double	5.5	6.7	8.4	10.3
	Micro air void content A_{300}	Vol.-%	Single	2.2	3.5	3.8	5.7
			Double	2.4	4.2	5.6	7.4
	Spacing factor	mm	Single	0.16	0.13	0.11	0.08
			Double	0.18	0.12	0.09	0.06
Alkyl polyglycolether sulfate	Air void content A	Vol.-%	Single	3.2	3.5	5.4	6.3
			Double	5.5	6.2	7.1	9.9
	Micro air void content A_{300}	Vol.-%	Single	1.6	2.3	4.0	4.9
			Double	3.4	4.3	5.5	7.5
	Spacing factor	mm	Single	0.21	0.16	0.11	0.08
			Double	0.13	0.12	0.08	0.06

void parameters and four slabs for testing the resistance to freeze-thaw with de-icing salt by the CDF method. The mixing time was also extended in these investigations. Cubes of 150 mm edge length for determining the air void parameters after extended mixing times were also produced after the predetermined mixing times had been doubled from 30 to 60 seconds, from 45 to 90 seconds and from 60 to 120 seconds. The consistency (compacting factor) was also determined about 30 minutes after the end of the mixing time.

The fresh concrete temperature was measured after mixing times of 30 seconds and 10 minutes and the water content was determined by drying a fresh concrete sample in a microwave unit as described in [5]. The test pieces for the hardened concrete tests as well as the air void vessel and the compaction box for the fresh concrete investigations were compacted on the vibrating table at the ready-mixed concrete plant. After compaction the test pieces for the hardened concrete investigations were covered with film and a moist jute cloth and stored in the plant laboratory. In each case the test pieces were transported on the morning of the following day to the Research Institute of the Cement Industry where they were removed from the moulds at an age of about 24 hours and placed in their respective storage systems. The storage and the fresh and hardened concrete tests were carried out as described in Section 3.2.1.4.

4 Test results

4.1 Laboratory trials

4.1.1 Initial testing

The air-entraining agent containing the alkyl polyglycol ether sulfate active substance required the highest addition level of 0.47 mass % in order to achieve the required air content of about 5 vol. %. 0.3 mass % was needed for each of the other air-entraining agents (Table 1). The sequence was reversed when the quantity of active substance was considered. The highest addition level of active substance was needed for the natural air-entraining agent (modified wood resin active substance). An intermediate amount of alkyl sulfate was needed while the smallest quantity was required for the alkyl polyglycol ether sulfate. The compacting factors 30 minutes after the end of the mixing time were 1.23 (wood resin), 1.24 (alkyl sulfate) and 1.27 (alkyl polyglycol ether sulfate) so for two concretes the value fell slightly below the stiff consistency C1 (ν ≥ 1.26) required and for one concrete it was achieved. After two minutes' mixing time the fresh concrete temperature was about 20 °C. The 28-day compressive strengths and the air void parameters met the requirements of TL Beton-StB 07. With scaling losses of about 150 g/m^2 the concretes exhibited a high resistance to freeze-thaw with de-icing salt. No dependence on the particular air-entraining agent could be detected (▸ Table 2).

Table 5: Parameters from the practical trials

Air-entraining agent active substance	Mixing time during production	Quantity of AEA added	Compaction factor 30 min	Fresh concrete temperature[1]	Water content (dried) in practical trial	Water content (target) from laboratory trials[2]
	Seconds	Mass % w.r.t. cement	–	°C	l/m³	l/m³
Modified wood resin	90	0.37 (single)	1.27	20.1	–	163
	90	0.74 (double)	1.27	22.1	158	163
	90	1.24 (triple)	1.24	22.2	158	163
	30	0.41 (5.6)	1.36	22.8	168	163
	45	0.37 (5.2)	1.40	23.7	165	163
	60	0.34 (5.1)	1.37	23.1	167	163
Alkyl sulfate	90	0.27 (single)	1.38	22.1	165	162
	90	0.54 (double)	1.25	22.1	167	162
	90	0.81 (triple)	1.18	21.7	151	162
	30	0.30 (6.2)	1.36	22.7	165	162
	45	0.29 (5.6)	1.33	22.1	161	162
	60	0.27 (5.1)	1.38	22.1	–	162
Alkyl polyglycol ether sulfate	90	0.42 (single)	1.38	22.7	170	163
	90	0.84 (double)	1.29	24.3	161	163
	90	1.26 (triple)	1.19	23.6	157	163
	30	0.42 (5.0)	1.38	22.7	170	163
	45	0.41 (4.6)	1.36	25.7	156	163
	60	0.40 (5.7)	1.41	25.5	168	163

[1] Fresh concrete temperature after 30 s, 45 s, 60 s or 90 s mixing time (about 3 °C to 4 °C higher after 10 min mixing time)

[2] Total of inherent moisture/core moisture of aggregate: approx. 0.40 mass %: approx. 8 l/m^3, mixing water 154 l/m^3, air-entraining agent approx. 1.5 kg/m^3 = approx. 163 kg/m^3

4.1.2 Air void formation relative to mixing time

a) Fresh concrete

At the single addition level the air content of about 5 vol. % was achieved after two minutes' mixing time, after which there was no substantial change (❱ Fig. 3, left). After two minutes' mixing time the fresh concrete temperature was about 20 °C and after 15 minutes' mixing time it rose to about 22 °C. There were no differences between the three air-entraining agents. Differences between the air-entraining agents were detected with the triple addition level and extended mixing time. With the air-entraining agent based on natural active substances there was a disproportionately low increase in air content to only about 9 vol. %. With the air-entraining agent based on the alkyl sulfate active substance the air content rose to 16 vol. % after 15 minutes' mixing time and with the air-entraining agent based on the alkyl polyglycol ether sulfate active substance it rose to 18 % (❱ Table 3).

b) Hardened concrete

The air void parameters are listed in ❱ Table 4. The air-void parameter requirements (spacing factor ≤ 0.20 mm, micro air void content ≥ 1.8 vol. %) were fulfilled after a mixing time of one minute. With a short mixing time of 30 seconds the parameters were not fulfilled in an individual instance (spacing factor 0.21 mm and micro air void content 1.6 vol. % with the air-entraining agent based on the alkyl polyglycol ether sulfate active substance at the single addition level). However, it must be borne in mind that as a consequence of the short mixing time the total air content was not 5 vol. % but only 3.2 vol. %. The parameters were fulfilled in all cases with the double addition level and short mixing time. The proportion of micro air voids in the total air content rose with increasing mixing time, i.e. longer mixing times produced finer air void systems.

4.2 Practical trials

4.2.1 General

The amount of air-entraining agent to be added to achieve the required air content of 5.0 ± 0.5 vol. % at a mixing time of 90 seconds was specified at the start of the trial day. The air void formation relative to mixing time was then determined with single, double and triple addition levels in the morning from about 9:00 to 13:00 hours. The three initial

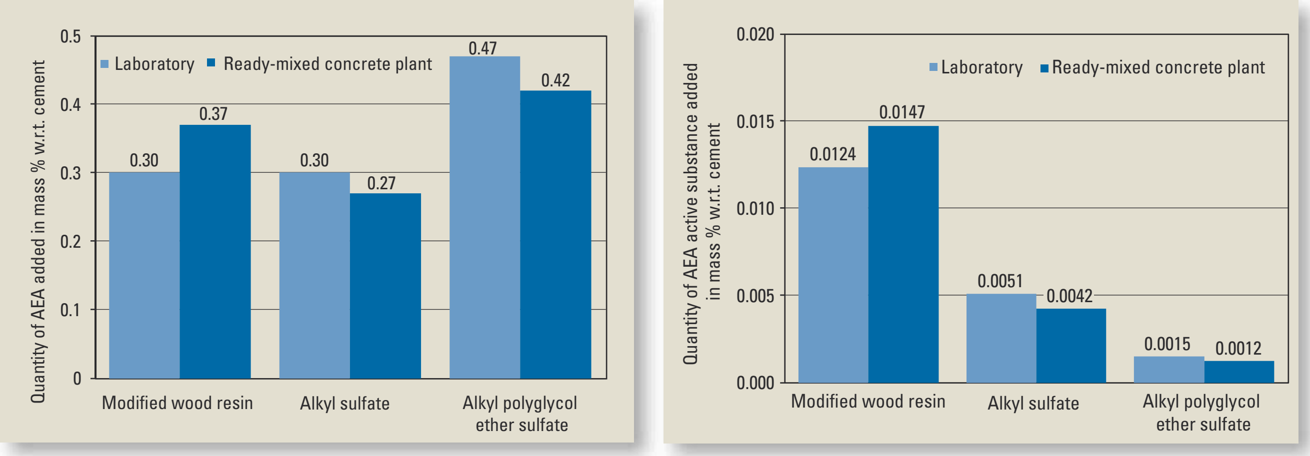

Figure 4: Quantities of air-entraining agent (left) and of air-entraining agent active substance (right) added in the laboratory and in the ready-mixed concrete plant to achieve an air content of approximately 5 vol. %

Table 6: Hardened concrete parameters under practical conditions

Air-entraining agent active substance	Mixing time during production	Quantity of AEA	Hardened concrete bulk density	28-day compressive strength	Scaling loss after 28 freeze-thaw cycles
	Seconds	Mass % w.r.t. cement	kg/dm³	N/mm²	g/m²
Modified wood resin	30	0.41 (5.6)1)	2.25	51.5	46
	45	0.37 (5.2)	2.28	57.5	62
	60	0.34 (5.1)	2.28	58.8	58
Alkyl sulfate	30	0.30 (6.2)	2.25	50.5	50
	45	0.29 (5.6)	2.24	50.6	62
	60	0.27 (5.1)	2.28	58.7	52
Alkyl polyglycol ether sulfate	30	0.42 (5.0)	2.28	52.3	176
	45	0.41 (4.6)	2.29	54.5	43
	60	0.40 (5.7)	2.27	53.3	45

1) Figures in brackets: fresh concrete air content after the respective mixing time during production

Table 7: Air void parameters in relation to the mixing time (practical conditions)

Agent active substance	Spacing factor for mixing time of in mm		Micro air void content for mixing time of in vol. %		Air content for mixing time of in vol. %	
Modified wood resin	30 s	60 s	30 s	60 s	30 s	60 s
	0.11	0.13	2.4	2.4	4.5	6.0
	45 s	90 s	45 s	90 s	45 s	90 s
	0.09	0.17	2.9	1.8	4.5	4.8
	60 s	120 s	60 s	120 s	60 s	120 s
	0.11	0.11	2.4	1.8	4.6	3.5
Alkyl sulfate	30 s	60 s	30 s	60 s	30 s	60 s
	0.10	0.12	3.7	2.8	5.0	4.9
	45 s	90 s	45 s	90 s	45 s	90 s
	0.11	0.12	3.1	2.4	4.8	4.1
	60 s	120 s	60 s	120 s	60 s	120 s
	0.12	0.13	2.4	2.0	4.3	4.6
Alkyl polyglycol ether sulfate	30 s	60 s	30 s	60 s	30 s	60 s
	0.16	0.14	2.3	2.3	5.1	4.0
	45 s	90 s	45 s	90 s	45 s	90 s
	0.15	0.16	2.3	2.5	5.0	5.4
	60 s	120 s	60 s	120 s	60 s	120 s
	0.14	0.12	2.6	2.8	4.6	4.4

tests with mixing times of 30, 45 and 60 seconds then followed in the afternoon until about 17:00 hours. On all three days there was a rise in the fresh concrete temperature with the concretes that were produced later (❱ Table 5). The addition levels of air-entraining agents and active substances needed to achieve the fresh concrete air content of 5.0 ± 0.5 vol. % are shown in ❱ Fig. 4. Somewhat more of the air-entraining agent based on natural substances and somewhat less of the admixtures with the synthetic air-entraining agents were required in the laboratory than in the plant. At nearly comparable mixing times (plant: 90 seconds, laboratory: 120 seconds) and air-entraining agent addition in the mixing water comparable addition levels were required in the laboratory and in the plant. 30 minutes after the end of the mixing time the compacting factor at the single addition level lay, depending on the air-entraining agent, between 1.27 (20.1 °C) and 1.40 (23.7 °C) with the modified wood resin, between 1.33 (22.1 °C) and 1.38 (22.8 °C) with the alkyl sulfate and between 1.36 (25.7 °C) and 1.41 (25.5 °C) with the alkyl polyglycol ether sulfate. As a result of the higher fresh concrete temperature the concrete stiffened more rapidly with the result that, as a rule, the compacting factor rose. Because of the higher air content at the double and triple addition levels there was an improvement in workability with an associated reduction in the compacting factor. The water content determined in the mixing plant by drying in the microwave unit agreed well with the laboratory trials (Table 5). This means that the concretes from the two test series had comparable water contents. The better workability of the laboratory concretes is therefore due to the higher fresh concrete temperatures of the concretes prepared under practical conditions.

4.2.2 Air void formation relative to mixing time (plant)

At the single addition level the air content of about 5 vol. % was achieved after a mixing time of only 30 seconds, after which it hardly changed (see Fig. 3 and Table 3). Longer mixing times caused a slight drop in air content with the synthetic air-entraining agents and, in particular, with the natural air-entraining agent. There were no appreciable differences between the air-entraining agents. Differences due to the air-entraining agents could be detected at the excessive (double and triple) addition levels and extended mixing time. The rise in air content with the air-entraining agent based on natural active substances at the triple addition level was disproportionately low at about 10 vol. % after four minutes' mixing time, after which it dropped to about 8 vol. %. With the air-entraining agent based on the alkyl sulfate active substance with the triple addition level and ten minutes' mixing time the air content rose to 14.5 vol. % and with the air-entraining agent based on the alkyl polyglycol ether sulfate active substance it rose to 13 vol. %. This was reversed in the laboratory trials: alkyl sulfate 13.5 vol. % and alkyl polyglycol ether sulfate 15.5 vol. %. This was presumably due to the higher fresh concrete temperature in the practical trials that produced a stiffer consistency in the concretes made with the air-entraining agent based on the alkyl polyglycol ether sulfate active substance.

4.2.3 Initial testing

When the mixing time was extended from 30 to 45 and 60 seconds it was possible to make a slight reduction in the quantity of all three air-entraining agents (see Table 5). All the concretes exhibited high resistance to freeze-thaw with de-icing salt with maximum scaling losses of 175 g/m^2. No reduction in the dynamic elastic modulus was observed. The 28-day compressive strengths of the laboratory and plant concretes were comparable (Tables 2 and 6). In contrast to the laboratory concretes the air void parameters (❱ Table 7) of all the plant concretes met the requirements of TL Beton, even after the short mixing time of 30 seconds. No differences due to the air-entraining agents were found in the hardened concrete parameters investigated. This also applied to the influence of the mixing time during production (30, 45 or 60 seconds). The air void formation in the laboratory and in the practical trials did exhibit some differences. At the short mixing time of 30 seconds the air contents obtained in the plant were higher than the values from the laboratory trials (Table 3). At the sin-

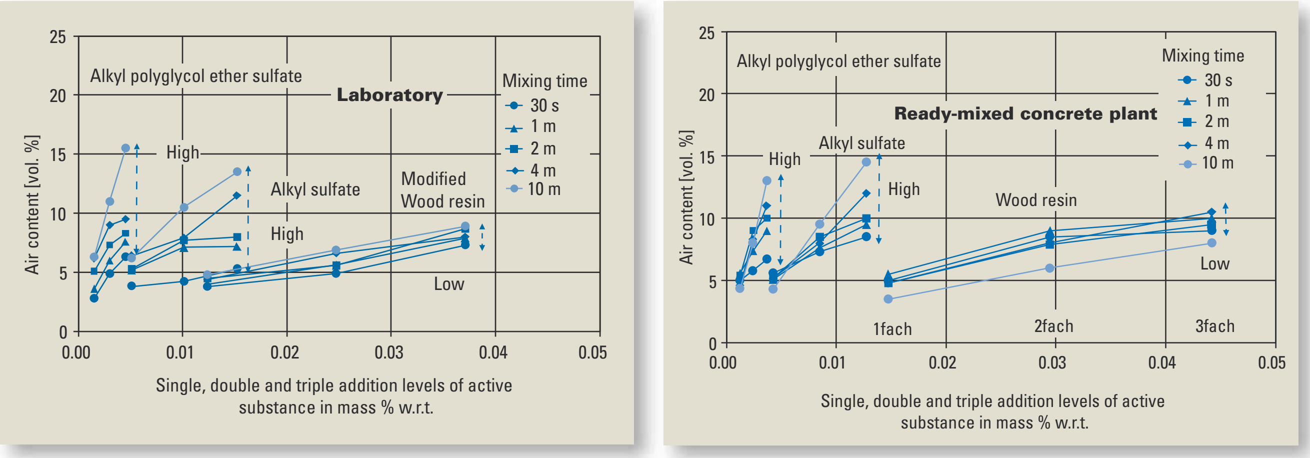

Figure 5: Air content in relation to the quantity of air-entraining agent active substance added and the mixing time in the laboratory (left) and in the ready-mixed concrete plant (right), and classification of the re-activation potential (low or high)

gle addition level the air contents in the laboratory and in the practical trials after a mixing time of one minute were comparable. At the double and triple addition levels longer mixing times were required in the laboratory to achieve comparable air contents. These differences are presumably due to the better mixing effect in the practical trials.

4.3 Comparison of the test results from the laboratory and the plant

4.3.1 Preliminary comment

To ensure transferability from laboratory to practical conditions the marginal conditions in the two test series were, as far as possible, kept comparable. Starting materials and concrete compositions as well as the way the air-entraining agents were added were kept the same. Pan mixers were used in the laboratory and in the practical trial. In the laboratory the fresh concrete temperature was kept consistently at 20 °C while somewhat higher fresh concrete temperatures were recorded in some cases in the plant. In particular, the concretes produced in the mornings had lower fresh concrete temperatures than the concretes produced in the afternoons.

4.3.2 Air void formation in fresh concrete relative to mixing time

The air void formation in the laboratory and in the ready-mixed concrete plant exhibited differences relative to the mixing times. At a mixing time of 30 seconds the air contents obtained in the practical trials were higher than the values from the laboratory trials (see Table 3, Fig. 3). At the single addition level the air contents after a mixing time of one minute were comparable in the laboratory and the plant. At the double and triple addition levels longer mixing times were needed in the laboratory to achieve comparable air contents. This applied to all the active substances used in the air-entraining agents. The reason is presumably the better mixing intensity of the plant mixer. This causes the air-entraining agent molecules to become attached more rapidly to the air bubbles so that the air void system is formed in a shorter mixing time.

4.3.3 Re-activation potential

The air content was plotted against the addition level of active substance in the air-entraining agent and the mixing time (❱ Fig. 5) in order to compare the air void formation in the laboratory and under practical conditions. The air-entraining agent has no detectable influence at the single addition level. At the double and triple addition levels there is a behaviour pattern that depends on the active substance. The air content at the triple addition level rose to a maximum of 10 vol. % with the natural air-entraining agent based on wood resin while with the synthetic air-entraining agents it rose to over 15 vol. %. Air-entraining agents based on wood resin have a low re-activation potential because even at high addition levels most of the active substance is precipitated in the pore solution. Synthetic air-entraining agents are highly soluble so they exhibit a higher re-activation potential. Substantially smaller quantities of active substance are needed to achieve the required air content. The diagrams show that the re-activation potential determined in the initial testing remains the same under practical conditions.

4.3.4 Hardened concrete parameters

The laboratory and plant concretes had comparable compressive strengths and resistance to freeze-thaw with de-icing salt. Somewhat better air void parameters were achieved under practical conditions than in the laboratory, especially with the short mixing time. This is presumably due to the better mixing effect in the plant mixer than in the laboratory mixer. This supports the results on air void formation in fresh concrete.

4.3.5 Applicability of laboratory conditions to practical conditions

The relationships determined in the laboratory also occur under practical conditions. The mode of operation of the air-entraining agent and the expected re-activation potential can be estimated with laboratory trials. The extended initial testing described in [5, 6] with determination of air void formation relative to mixing time with normal and excessive addition levels of air-entraining agent after short and extended mixing times (Fig. 1) is suitable for characterizing the re-activation potential of a concrete during the initial testing. A more effective air void formation was established in the plant as a result of the greater mixing intensity when compared with the laboratory.

Final remarks

The research project examined whether the influence of the mixing time, the basis of the active substance in the air-entraining agent and the quantity of agent added on the re-activation potential found in laboratory trials also holds true under practical conditions during the production of air-entrained concrete in a ready-mixed concrete plant or construction site mixing plant. Three air entraining agents with different re-activation potentials were chosen for this purpose. The air void formation in the fresh and hardened concrete relative to the mixing time was then determined in the laboratory and under practical conditions using comparable starting materials and concrete compositions. The compressive strength and resistance to freeze-thaw with de-icing salt of the laboratory and practical concretes were comparable. Comparable addition levels of air-entraining agent were needed in the two test series to achieve the required air content of approximately 5 vol. %. With the exception of the 30 second mixing time the air void formation relative to the mixing time was comparable in the laboratory and in practice. Under practical conditions the required air content of 5 vol. % was achieved after a mixing time of 30 seconds while longer mixing times were needed in the laboratory. The reason is presumably the better mixing intensity of the practical mixer so that the molecules of the air-entraining agent become attached more rapidly to the air bubbles and the air void system is established in a shorter mixing time. This is also apparent in the air void parameters. The spacing factors were lower and the micro air void contents were higher under practical conditions than in the laboratory, especially at short mixing times. The results of the laboratory trials can be applied to practical conditions. The procedure described in the instructions for determining the air void formation in relation to mixing time with "normal" and excessive addition levels of air-entraining agent after short and extended mixing times during the initial testing is suitable for characterizing the functioning of an air-entraining agent and the anticipated re-activation potential of a concrete.

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