

Durable two lift pavements with different cements

R. Breitenbücher¹ and C. Schulte-Schrepping²

Abstract

For the construction of two lift concrete pavements according to the German guideline “ZTV Beton-StB 07” it is mandatory to use the same cement for the upper and lower lift of the pavement. By allowing the use of different binders in the two lifts, ecological and economic advantages could be achieved. This article proposes the approach to use cements with a high clinker content in the thin upper lift, which is directly exposed to high mechanical and freeze-thaw stresses. On the other hand, the thick lower lift should be produced using low clinker cements. Hence, the susceptibility to alkali-silica reactions (ASR) as well as the environmental impact (CO₂ emissions) of the pavements are reduced.

Research Background

The German regulations for concrete pavements require the use of a cement of the same type and strength class for both the upper and lower lift of two lift concrete pavements. Depending on the mechanical and weather-related stresses acting on the material, it would make sense to choose different cements for the upper and lower lift. This approach would yield both ecological and economic advantages. This leads by applying the upper lift onto the still fresh lower lift to a shear-stable connected system of two concretes with potentially different mechanical properties (E-modulus, coefficient of thermal expansion) and different hydration processes.

First, it is necessary to ensure that no major adverse effects concerning the construction, the use and the durability of concrete pavements would result from the mentioned modifications.

For this purpose, the composite and deformation behavior of the two different concretes must be examined under realistic boundary conditions. In addition to a long-term study in which cyclic loadings were applied, the produced concrete was also exposed to the crucial loading condition, when it was run over by a wheel loader at a young age. Such a loading condition would result, for example, from the production of exposed aggregate concrete surfaces within the first 8 to 12 hours after the concrete was cast.

Compared to a conventional exposed aggregate concrete, the compressive strength development can be reduced by using low clinker cements in combination with a further substitution of the cement by fly ash or blast furnace slag in the lower lift. Consequently, in the event of an impact, the lower lift concrete shall be of sufficient strength to prevent damages in the concrete structure and, even more importantly, in the bonding joint.

¹ Full Professor, Prof. Dr.-Ing., Institute for Building Materials, Ruhr-University Bochum, Universitätsstr. 150, 44801 Bochum, Germany, PH (+49) 234-3222649; FAX (0049) 234-3214113, email: rolf.breitenbuecher@rub.de

² Research Assistant, M.Sc., Institute for Building Materials, Ruhr-University Bochum, Universitätsstr. 150, 44801 Bochum, Germany, PH (+49) 234-3226062; FAX (0049) 234-3214113, email: christoph.schulte-schrepping@rub.de

In addition, this research project explores the potential of binders containing ground granulated blast furnace slag and/or fly ash, which could be used to reduce ASR in

the lower lift. The findings pave the way for the use of aggregates in the lower lift, which must currently not be used in the production of concrete pavements.

Based on the achieved results, the aim is to modify the specifications given in the German regulations “TL Beton-StB 07” and “ZTV Beton-StB 07”.

On top of this, investigations are conducted, which should allow the consideration of fly ash for the calculation of the water-binder-ratio of pavement concrete according to the German guideline “TL Beton-StB 07”.

Long-term test: cyclic load

Cyclic load and bonding strength. Within the scope of the experimental studies, large composite concrete beams (180 x 35 x 27 cm³) were cyclically loaded. Different combinations of concrete were investigated and the bond strengths analyzed after exposure. For the upper lift, which had a thickness of 7 cm, a common composition for exposed aggregate concrete was used. For some combinations, a portion of the binder was substituted for fly ash or furnace slag. In the lower lift, which had a thickness of about 20 cm, low-clinker binders were used, for example a CEM III with 15 percent fly ash (Table 1). As a realistic reference, the concrete combination S1.1 with the exclusive use of ordinary Portland cement and crushed basalt as aggregates was used.

Table 1. Examined concrete combinations

combination	ID	Component	Binder	fly ash	Aggregate
S1.1 (ref.)	S1.1.1	upper lift	CEM I 42.5 N	0	crushed basalt
	S1.1.2	lower lift	CEM I 42.5 N	0	crushed basalt
S1.2	S1.2.1	upper lift	CEM I 42.5 N	0	crushed basalt
	S1.2.2	lower lift	CEM I 42.5 N	0	gravel
S1.3	S1.3.1	upper lift	CEM II/A-S 42.5R	0	crushed basalt
	S1.3.2	lower lift	CEM II/B-S 32.5R	30	crushed basalt
S2.1	S2.1.1	upper lift	CEM I 42.5 N	30	crushed basalt
	S2.1.2	lower lift	CEM III/A 42.5 N	15	crushed basalt
S2.2	S2.2.1	upper lift	CEM II/A-S 42.5R	30	crushed basalt
	S2.2.2	lower lift	CEM III/A Labor	0	crushed basalt
S2.3	S2.3.1	upper lift	CEM I 42.5 N	30	crushed basalt
	S2.3.2	lower lift	CEM III/A (50 % slag)	0	gravel
S2.4	S2.4.1	upper lift	CEM II/A-S 42.5R	30	crushed basalt
	S2.4.2	lower lift	CEM III/A (50 % slag)	0	gravel

At the age of 28 days (after production) the test beams were loaded cyclically in a 4-point-flexural-test with up to 5 million (in one case up to 10 million) load cycles (Figure 1).



Figure 1. Setup for the simultaneous testing of six concrete beams in a 4-point-flexural-test

The chosen high and low stresses represent different stress conditions of superposing loads acting on a concrete pavement. The slowly recurring thermal restraint stresses are to be superposed with high-frequent cyclic traffic stresses. Thus, a high stress and a corresponding low stress ($\sigma_{\max}$ and $\sigma_{\min}$) can be derived from these loading conditions.

As a result of the cooling of the concrete from the top (negative temperature gradient of 0.4 K/cm), a restraint stress of about 2.0 MPa occurred at the concrete's top surface. A 40-ton truck running over the center of the concrete slab generates an additional flexural stress of approximately 1.0 MPa and thus acts relieving on the concrete's top surface. Following, in this load combination the stress ratio amounts to $\sigma_{\max}/\sigma_{\min} = 0.5$ ($f_{ct,fl} = 4,8$ MPa) (Wittmann, 2009). The load range ($\sigma_{\max} - \sigma_{\min}$) was defined by 1.0 MPa.

To define the respective degradation and the decrease of the relative dynamic E-modulus in the loaded area, comparative ultrasonic velocity measurements in the resting state of the composite beams were performed. The results are shown in Figure 2 as a function of the number of cycles. With an increasing number of cycles a decrease of the rel. dyn. E-modulus for all concrete combinations was observed.

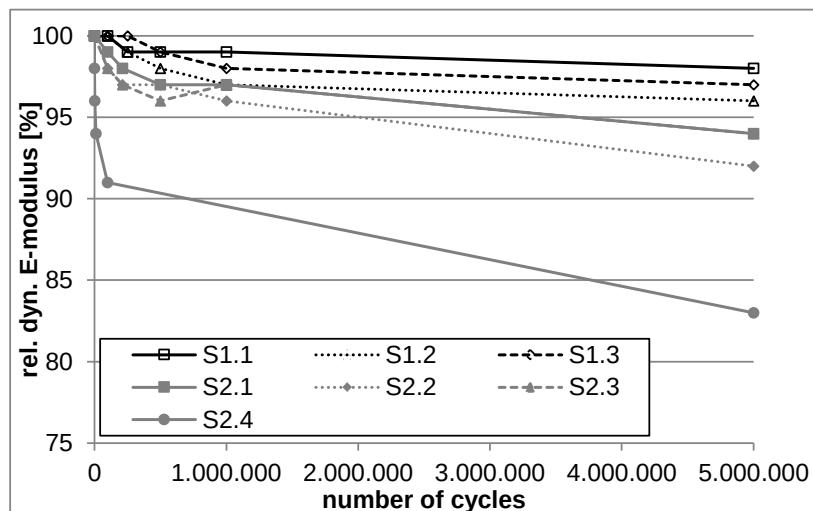


Figure 2. Development of the rel. dyn. E-modulus as a function of the number of cycles

As a method to quantify the bond strength after exposure centric tensile tests on cores ($d = 100 \text{ mm}$, $h = 200 \text{ mm}$) were conducted between the upper and lower lift in accordance with the European standard “DIN EN 14488-4”.

Additionally, the maximum shear strength in the bond area in accordance with the German guideline “TP Asphalt-StB - part 80” was investigated. The adhesive shear strength was determined using cylindrical cores ($d = 150 \text{ mm}$, $h = 270 \text{ mm}$). In this test setup, a shear stress was applied to the bond area between the lower and the upper lift concrete. Only the lower lift concrete was placed in the test device, while the load was applied perpendicular to the axis of the drilling core, i.e. as close as possible to the bonding joint. The determined bond strengths were compared with those from the reference and the unloaded area, respectively.

Experimental results - Bonding strength after cyclic loading. The results of the bond strength for the first series of concrete combinations S1.1 - S1.3 shown in Figure 3 (left) verify that there is no difference between the reference area and the loaded area, and between the reference concrete combination S1.1 and the others. Furthermore, all values lie above the typical average of 1.5 MPa, thus demonstrating a sufficient bond strength even after a load of 5 million cycles.

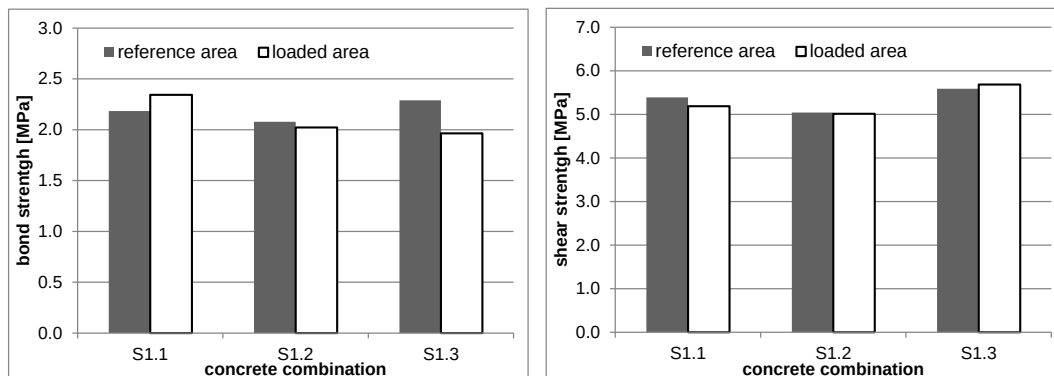


Figure 3. Results of the centric tensile (left) and shear test (right) of series 1

Compared to the reference combination, the measured shear strengths (Figure 3, right) also showed no negative influence of the different concretes on the bond strength in combination with a cyclic loading. The results of series 1 were confirmed by the investigations of series 2 (S2.1 - S2.4).

Taking into account the different numbers of load cycles applied to individual test beams (failure of S1.2.1 at 728 thousand cycles in comparison with the beam S1.3.1 with a cycle number of 10 million) shown in Figure 4, it becomes evident that the number of cycles has no influence on the bond strength in the case of an upper lift thickness of 7 cm.

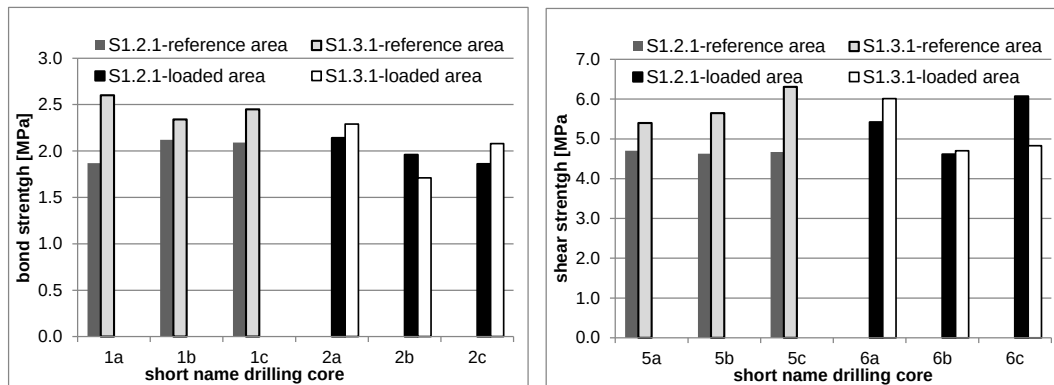


Figure 4. Centric tensile strength (left) and shear strength (right) of S1.2.1 and S1.3.1 at different numbers of cycles

Early mechanical load

Background and test setup. Within this research project, the comparison of the development of the compressive strength of the upper and lower lift suggested the significance of the early strength and potential exposure scenarios of concrete pavements at a young age.

Depending on the composition of the upper lift, the temperature of the fresh concrete and the prevailing climatic conditions, the surface can sometimes not be prevented from the load of a wheel loader even a few hours after its manufacturing, which is used to create the exposed aggregate concrete surface and a sufficient roughness. A sufficient surface roughness can be achieved at a storage temperature of 20 °C until approx. 12 hours after the concrete's production, or up to a compressive strength of about 9 MPa.

In this regard, the lower lift concrete must have a sufficient compressive strength when driving on in order to avoid damages in the concrete structure and the interconnecting joint. In Figure 5, the compressive strengths of a conventional upper lift concrete (CEM I) and for a lower lift concrete (CEM III/A) at 20 °C during the production process of the exposed aggregate concrete surface (8 to 12 hours) are shown.

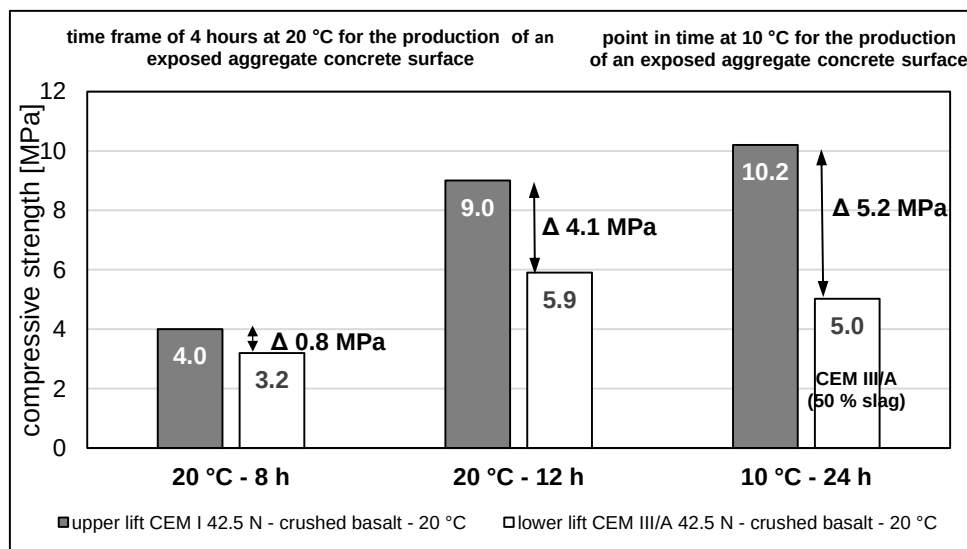


Figure 5. Differences in the development of the compressive strength of the upper and lower lift

Figure 5 shows also the compressive strength of a lower and upper lift, stored at 10 °C after 24 hours. It can be seen, that at 10 °C the time frame to produce the exposed aggregate concrete surface is almost exceeded and that there is a considerable difference in the compressive strength between the two concretes.

In order to ensure ideal conditions for the production of the exposed aggregate concrete surface, the pavement should be treated by a wheel loader before – a procedure, which results in an even greater difference in the compressive strengths of the two concretes.

To simulate such loads, a combination of a different upper and lower concrete lift at a young age (Table 2) was exposed to an early mechanical load, and in one case afterwards also to cyclic loads. The choice of the concretes for the upper and lower lift was based on the highest difference in the compressive strength at 20 °C within the first 12 hours, as shown in Figure 5.

Table 2: Concrete combination for the investigation of the early mechanical load

combination	ID	Component	Binder	fly ash	aggregate
B1 - B3	-	upper lift	CEM I 42.5 N	0	crushed basalt
	-	lower lift	CEM III/A 42.5 N	0	crushed basalt

After the upper lift concrete reached a sufficient compressive strength (> 4 MPa), which would allow the production of the exposed aggregate concrete surface, the composite test beams were overrun ten times by a profiled truck tire, which was attached to an additional dead weight of one ton (Figure 6).



Figure 6. Early mechanical load: rolling tire on the surface of specimen B1 (first cycle)

To this end, three additional composite beams were cast and tested. Test specimen B1 was stored at 20 °C and exposed to the mechanical load 8 hours after its preparation. At that time, the compressive strength of the upper concrete lift was approx. 4 MPa. Test specimen B2 was produced and stored at 10 °C. After the upper concrete lift reached the necessary compressive strength for brushing, i.e. after 24 hours, the load was applied. Test specimen B3 was also prepared and stored at 10 °C. After 24 hours, it was exposed to a mechanical load as composite specimen B2.

Subsequently, test specimen B3 was installed in the multi-test device (Figure 1) and was loaded in one million cycles.

Experimental Results. The results of the bond strength test shown in Figure 7, that were achieved by comparing the reference area and the loaded area of the test beams B1 and B2, lead to the conclusion, that an early mechanical load has no negative influence on the bond strength between the upper and lower lift. Both, the results of the shear strength of all tested samples and the measured bond strengths lie within the range of the reference samples and, more generally, in the expected typical range. Compared to the reference storage at 20 °C the results show that a production and storage temperature of 10 °C leads to a slight decrease in bond strength.

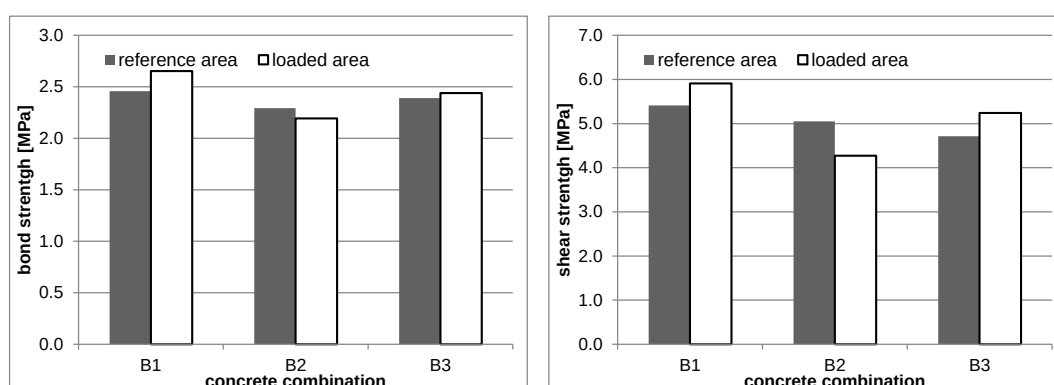


Figure 7. Results of the bond strength test (left) and shear test (right) of the test beams B1, B2 and B3

Furthermore, it becomes obvious that the combination of an early mechanical load and a subsequent cyclic load (B3) has no negative influences on the bond strength. The average bond strengths of the composite body B2 without an additional cyclic load and of the composite test specimen B3 with additional cyclic loads lie on the same level.

Durability studies

Alkali silica reaction. Within this research project, it was further investigated whether the addition of granulated blast furnace slag and fly ash to the binder of the upper and lower concrete lift would have an effect on the ASR. These studies on the ASR reduction potential were performed by using storage with alternating climates by the FIB Institute Weimar. This allows a time-lapse simulation of changing climatic conditions with the involvement of attacking media.

The chosen ASR-performance test is usually comprised of 12 cycles with a duration of 3 weeks each. One climate cycle implies the following storage phases:

- 4 days drying at a relative air humidity of < 10%
- 14 days of cloud storage at 45 °C and 100% relative humidity
- 3 days storage with 6 freeze-thaw cycles of + 20 to -20 °C

After each cycle, strain measurements are performed and, on the basis of a quantity survey, potential changes in the moisture content are assessed. In order to avoid an influence of temperature on the strain measurements, the test beams are tempered to 20 °C prior to each measurement.

The results for the lower lift, shown in Figure 8, clearly illustrate that the exchange of 30 percent cement (CEM I) with fly ash, already leads to a considerable reduction of the ASR-potential. Compared to CEM I the concrete using CEM III shows much lower strains under exposure and hence also a lower ASR-potential.

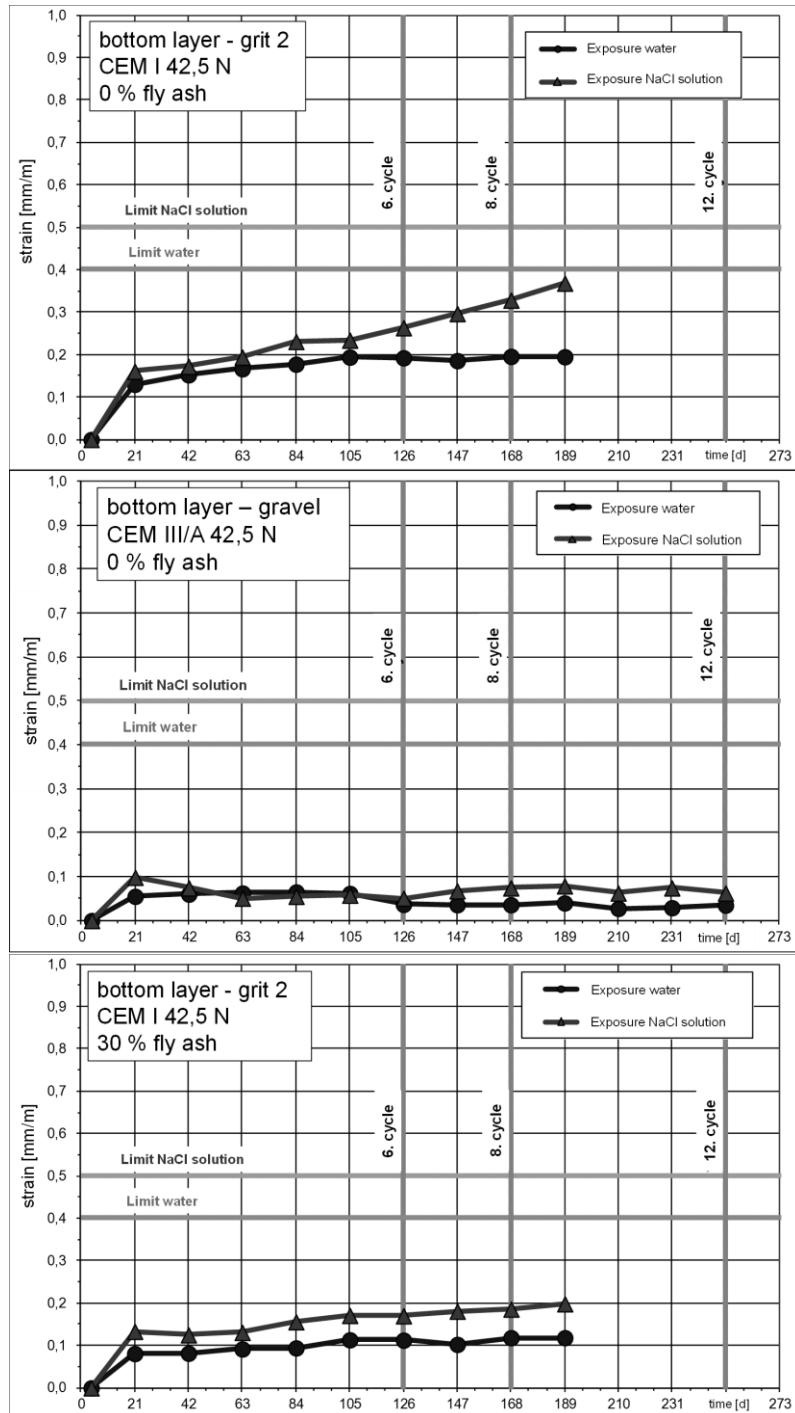


Figure 8. Alternating climate storage results: top: CEM I 0 % fly ash, middle: CEM III/A 0 % fly ash, bottom: CEM I 30 % fly ash

Freeze-thaw resistance. The freeze-thaw resistance of the concrete that contained different amounts of fly ash and different cements for the upper lift was determined using the CDF-method. In a second step, it was compared to the freeze-thaw resistance of fly ash-free concretes. The tests were performed in accordance with the reference method of “DIN CEN / TS 12390-9” on a PTFE-switched test surface, but also on the surface of the exposed aggregate concrete which was exposed to the freeze-thaw attack.

In order to ensure a representative load simulation, a realistic curing treatment of the exposed aggregate concrete was used. Compared to the reference storage (up to 7 days under water) this treatment is less favorable. For the evaluation, a limit of 1.500 g/m² of weathering was set. The results for the upper lift are shown in Figure 9 as a function that factors in the addition of fly ash.

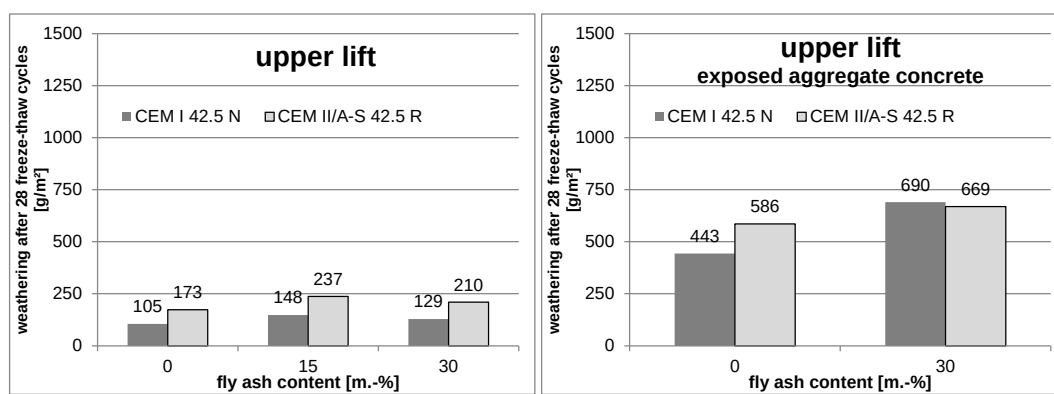


Figure 9. Freeze-thaw resistance of the upper lift. Left: reference storage, right: practical after-treatment

The weathering of the PTFE-switched surfaces after 28 freeze-thaw cycles amounts to about 100 to 250 g/m² – a value that lies well below the test criterion of 1500 g/m².

As a conclusion, the concretes feature an excellent freeze-thaw resistance. The partial replacement of cement with fly ash had only a marginal negative effect on the freeze-thaw resistance of the upper lift.

The weathering of the exposed aggregate concrete surface after 28 freeze-thaw cycles was considerably higher, however. The reason for this is probably the less favorable curing treatment as compared to the reference storage. Nevertheless, the amounts of weathering for all mixes still move within the low range.

Final discussion and conclusion

The achieved results of the investigation on the bond strengths allow the following statements:

On the basis of the reference combination that featured the exclusive use of Portland cement in the upper and lower lift, the partial substitution of the cement of the upper lift with fly ash, as well as the complete replacement of the Portland cement in the lower lift with a low-clinker binder and the variation of aggregates, showed no negative impact. Furthermore, the scale of the cyclic load does not influence the bond strength.

Besides that, an early mechanical load at a young age of the concrete does neither leads to immediate nor long-term damages in the loaded area or the interconnecting joint between the concrete lifts. Even if stored at 10 °C, the bond strength is not affected by the mechanical load.

The present state of durability investigations, which include ASR-performance and freeze-thaw resistance tests, show that a partial substitution of Portland cement clinker with fly ash or blast furnace slag is possible for both concrete lifts without any major restrictions.

Acknowledgement

The authors are grateful to the Federal Ministry of Transport and Digital Infrastructure and the Federal Highway Research Institute (Germany) for their financial support of this research project. The authors wish to acknowledge the cooperation with the Finger-Institute for Building Materials – Weimar whose experience in the field of ASR considerably helped to implement this project in the described manner.

References

Wittmann, F. H., Zhang, P., Zhao, T. (2009). *Eine zerstörungsfreie Messmethode zum Studium des Eindringens von Flüssigkeiten in Beton*. 17. Internationale Baustofftagung (ibausil), Weimar, Tagungsbericht, Band 1, S. 969-974.