Calcareous fly ash in Hydraulic Road Binders - Long term observation on existing roads versus laboratory test -

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1 Introduction

The European Standards for hydraulically bound base courses EN 14227 part 3 and 4 dealing fly ash bound mixtures and fly ash for hydraulically bound mixtures respectively refer to construction methods using pozzolanic and/or hydraulic based binders, as e. g. siliceous and calcareous fly ashes.

The standards were produced covering the experience in different European countries where they have been successfully applied for base courses in the classified road network. According to the applicable regulations in Germany, however, base courses with hydraulically bound binders have to be built with cement or base course binder only. Thus the use of fly ash bound mixtures is restricted to exceptional cases only, above all to test constructions. In specific projects also siliceous and calcareous fly ash have been used in or as hydraulic road binder.

To evaluate whether the requirements in the European standards are sufficient to cover also the experience gained with the German regulations a research project on “Suitability of mixtures for hydraulically bound base courses according to European Standards for applications in Germany” /1/ was conducted.

This paper deals with the experience with hydraulically bound mixtures in road construction and will focus the long term observations of road binders with calcareous fly ash in existing roads in Germany and investigations on fresh binders produced in the laboratory scale.

2 Background and aims of the research project

The aim of the research project was to gather the experience in Europe with Hydraulic Road Binders (HRB) and gained with the European standards EN 14227, parts 2 to 4 with slag bound and fly ash bound base course mixtures, to test their efficiency on existing road pavements, and to determine under which conditions they are an efficient alternative for Germany to the currently applied procedure of exclusively using cement or base course binder. In addition to these field investigations, several fly ashes and ground granulated blast furnace slags have been investigated to find out whether and under which conditions they can be used for the construction of base courses which fulfil the requirements of ZTVT /2/ and TL-Beton /3/ to hydraulically bound base courses having a defined early strength.

The research activities include a literature study regarding experiences gained in the use of slag bound or fly ash bound base courses according to EN 14227, parts 2 and 3, in 12 countries.

The use of fly ashes, blast furnace slags and granulated blast furnace slags for the production of hydraulically bound mixtures in road construction is mainly considered under the aspects of ecology and economy:

- use of local materials to reduce costs
- use of pozzolan- and/or hydraulic and latent hydraulic material based binders with low CO_2 emission
- reduction of the layer thicknesses of the asphalt paving with the option for a gradual increase in dependence on the traffic load

This applies, above all, to Belgium, France, Great Britain, Poland and Spain. In these countries, construction methods using suitable fly ashes or granulated, ground or not ground granulated blast furnace slag as sole binder or in combination with cement or lime are efficient alternatives to “traditional” cement bound base courses.

All over Europe, 42 % of the slags are used in road construction. Especially in Great Britain, France, Poland and Slovakia, these construction methods are widely applied. In the main, there are three categories for the flexural rigidity of the base course with hydraulic binders (HRB):

1. HRB of high rigidity (pressure strength > 10 MPa, E ≈ 15,000 to 30,000 MPa, usually provision of grooves to avoid wide cracks) - Belgium, Germany, France
2. HRB of medium rigidity (pressure strength ≈ 2.5 to 4 MPa, E ≈ 7,000 MPa to 10,000 MPa, narrow cracks) – Italy
3. HRB of low rigidity (pressure strength < 2 MPa, E ≈ 1,000 to 2,000 MPa, microcracks) - Switzerland

Here, one differentiates between slow (self-) hardening mixtures and mixtures having a defined early strength in the meaning of a hydraulically bound base course or compaction according to the German ZTVT-StB /2/ (28d pressure strength 7 N/mm² to 12 N/mm² under asphalt and > 15 N/mm² under concrete).

3. Investigations

The long-term behaviour of base courses is decisive for the assessment of their evaluation as an alternative to the base courses usually applied in Germany. This long-term behaviour can be best determined on already completed road structures.

In Germany, nine different test roads were built with slag bound and fly ash bound base courses from the years 1985 to 1998, which have been exposed to traffic for several years already. Within the research project each of the road structures and relevant material parameters, determined from samples taken for dimensioning, were studied in field investigations.

3.1 Investigations for slow hardening base courses

The bearing capacity of slowly hardening base courses was measured by Benkelman beam and Falling Weight Deflectometer in the years 2005 and 2006. Simultaneously with the field investigations, laboratory investigations of the base materials used for these construction projects were made.

To assess and classify such alternative hydraulically bound base courses in the system of Rules for the Standardisation of the pavement – RStO - the specific deformation module was also determined by means of the Falling Weight Deflectometer - FWD - on the basis of the measurements of the bearing capacity.

The approximation function {1} for the two-layer system, developed by WEINGART, was used for the iterative evaluation of the deflection moulds measured in the test routes with fly ash bound and slag bound base courses, providing sufficient coincidence with the BISAR calculation:

$$\frac{w_r}{w_{r=0}} = \frac{1}{\sqrt[6]{1+\left(\kappa * {r}/{a}\right)^2 + \left(2*\lambda * {r}/{a}\right)^6}} \quad \{1\}$$

with

$$\lambda = 1 - \frac{2}{\pi} * \left(1 - \frac{1}{n^3}\right) * \arctan\left(\frac{h*n}{2*a}\right) = \frac{E_0}{E_ä} \quad \{2\}$$

and $$n = \sqrt[2,75]{{E_1}/{E_0}}$$

as well as the approximation solution for the relative settlement of layer 1 in the load centre

$$\frac{\Delta w(r=0)}{w(r=0,E_1)} \approx 1 - \sqrt[3]{e^{-\frac{h}{a}}} \quad \{3\}$$

and for the specific modulus of elasticity of the asphalt

$$E_{Asphalt} \approx 28.000 / e^{0,07*T_{Asphalttemperatur}} \quad \{4\}$$

with

r = distance from the load centre
a = radius of the loading plate
h = thickness of layer 1
E1 = specific modulus of elasticity of the top layer 1
E0 = modulus of elasticity of the semi-infinite elastic solid
Eä = equivalent modulus of elasticity on the surface of the two-layer system
wr = deflection at the distance r from the load centre
Asphalttemperatur = temperature of asphalt

In addition, $E_{Asphalt}$ {4} was checked by measurements above and below the asphalt layer in the borehole.

3.2 Investigation of mixtures with selected early strength (hydraulically bound base course according to ZTVT)

On the basis of the chemical-mineralogical data of the fly ashes and granulated blast furnace slags, three ground granulated blast furnace slags, four fly ashes (calcareous fly ash from Schkopau and Jänschwalde, hard coal fly ashes from Scholven and Bexbach) as well as two base course binders HRB 32,5E and one cement CEM I 32,5 R were also chosen according to the European Standards, whose chemical compositions served to cover the range of the potential binders. Pre-condition for the use of the ashes and slags was to fulfil both the requirements of the European Standards EN 14227-2 and EN 14227-3 and the ones of ZTVT (TL-Beton).

These binders were used to produce mixtures for hydraulically bound base courses in the laboratory (conforming to European Standards and ZTVT-StB) and investigated for their green strength, pressure and splitting tensile strength, dynamic modulus of elasticity, fatigue strength, frost resistance, volume stability and durability. The results of these investigations will only be described in the conclusions.

4. Projects with calcareous fly ash in hydraulic road binders

From 1985 to 1998 nine different test roads were built with slag bound and fly ash bound base courses in Germany. The projects with calcareous fly ash together with the rounded layer modul (see 3.1) categorised as explained before are given in table 1.

Project	base course mixture	Layer modul$_{rounded}$ [MPa]
Boxberg	crushed stone base course (Boxberg, y.o.c 1993)	400
Boxberg	95% BFA Jänschwalde + 5% cement without aggregates (Boxberg, y.o.c 1993)	1800
Lochau	cracked pavement of 30% CaO-rich BFA Schkopau + 70% recycled concrete (Lochau, y.o.c. 1997)	5000
Lochau	30% CaO-rich BFA Schkopau + 70% recycled bricks (Lochau, y.o.c. 1997)	9000
Asendorf	30% CaO-rich BFA Schkopau + 70% recycled concrete (Asendorf, y.o.c. 1998)	28000
Boxberg	51.2% RC + 28.8% gravely sand + 17.8% BFA Jänschwalde + 2,2% PZ (Boxberg, y.o.c. 1993)	28600

Table 1 List of the base courses produced with calcareous fly ash together with rounded layer module ($E_{base\ course\ with\ binder}$ modules of the bound mixtures produced with calcareous fly ash determined by the re-calculation of all FWD measuring results in comparison with the $E_{base\ course\ without\ binder}$ modules of base course mixtures without binder)

4.1 Project Boxberg

The main road to the power station Boxberg was built with the fly ash from the Jänschwalde power station in 1993 /6, 7/. The total length of the road built with fly ash is approximately 70 m. The road was constructed according to RStO class III in 3 parallel lines with 3 m width each. The HRB was covered with asphalt. Since its construction in 1993 the road is under regular control.

figure 1a
Placing of HRB with calcareous fly ash at Boxberg power station

figure 1b
Compaction of HRB with calcareous fly ash at Boxberg power station

The fly ash from the power plant is certified for use in concrete and was used with and without aggregates (mix 1 and 2). Due to lower lime content of the ash it can be considered a siliceous type and by this cement was used in addition. The chemical composition of the Jänschwalde fly ash is given in table 2.

Since its construction in 1993 the road is under regular heavy load of at least RStO class III. A visual inspection showed no significant changes compared to the production phase. The compressive strength of the two types of binders (see table 2) with and without recycling material equalized with time and showed 13 N/mm² after 1 year. After 3 years a compressive strength of 30 N/mm² was achieved. A further increase of the compressive strength was not observed /6/. After 14 years of service the road did not show any damage.

4.2 Project Asendorf

In November 1998 a fly ash bound road binder with fly ash from the Schkopau power plant was used for the demonstration project Asendorf of MUEG - Mitteldeutsche Umwelt- und Entsorgung GmbH. The project is the interlink from the main road L264 to a compost plant of MUEG which is regular used by big trucks (see figure 2a).

A mix of 30 % (607 kg/m³) fly ash and 70 % (1.412 kg/m³) concrete-recycling-material was mixed in a concrete mixer with ring gap. The water content was 0.35 (212 l/m³). As the distance between mixer and site was about 50 km a retarder was added. In total, 110 tonnes of non treated fly ash and 260 tonnes of concrete-recycling material was placed by hand and compacted by vibrator. The road was properly cured by wetting. The compressive strength of the samples produced with the site mix was 7.8

N/mm². The mix was placed on a frost resistance layer produced with limestone gravel and covered with an asphalt layer with a thickness between 2.5 and 4 cm.

project	Boxberg	Asendorf
Parameter	KW Jänschwalde 18.06.1993	KW Schkopau
	[% by mass]	
SiO_2	50.7	21.9
Al_2O_3	8.5	10.1
Fe_2O_3	9.3	4.1
CaO	7.8	46.5
CaO_{free}	1.0	15.5
MgO	4.3	4.2
K_2O	0.9	0.33
Na_2O	0.1	0.65
SO_3	2.3	11.0
Cl	< 0,01	n.d.
LOI	0.6	n.d.

	Mix 1	Mix 2	Mix
	Kg/m³		
aggregates	-	606	-
RC concrete	-	1076	1412
fly ash	1492	374	607
CEM I 32.5 F	78	47	-
water	313	240	212

n.d. not determined

Table 2: Chemical composition of fly ash from lignite combustion used in hydraulic road binders and mix design for road projects in Germany

After seven years, a set of 12 core samples were taken from the road. The compressive was 34.2 N/mm² with a standard deviation of 2.9 N/mm². By this, the hydraulic bound road base with this high-lime fly ash a similar compressive strength was achieved as with the road base of the Boxberg project. The drilled samples demonstrate the homogenous structure of the road base (see figure 2b)

figure 2a
Interlink to the compost plant of MUEG

figure 2b
Core samples taken form the fly ash bound road based at Asendorf

figure 2c
Road hole due to non sufficient connection of the layers

figure 2d
Reflexion cracks

During the visual inspection road holes were registered which are caused by the thin asphalt layer and a non sufficient connection between the layers. It can be seen in figures 2c that the fly ash bound road base is in proper condition.

Due to the thin cover layer and the high compressive strength of the hydraulic bound base road reflexion cracks were observed in 4 m up to 51 m distance on a total length of 150 m (see figure 2d). Furthermore, an open longitudinal seam was observed in the middle of the road.

The chemical composition of the fly ash from the Schkopau power plant used in the road project in November 1998 is given in table 2. Due to the high content of free lime of 15.5 % by mass and sulphate of 11.0 % by mass the ash tends to high expansion based on ettringite formation what was observed in soundness test in laboratory investigations (see figure 2e left side) .

The soundness problem based on ettringite formation in the laboratory tests was not observed in the real project. The observed reflexion cracks indicate a shrinkage but due to the chemical composition an expansion was expected.

figure 2e
left: Sample after storage in humid conditions without mold
right: Core sample taken from the test field of the test hall of the Anhalt University road

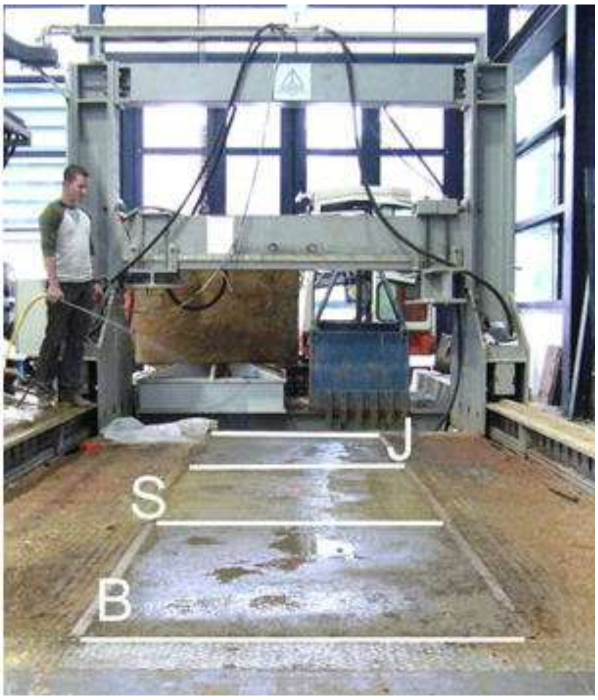

figure 2f
Test fields with fly ash bound road binders (15 cm high, 1.85 cm x 1,25 cm) at the laboratory hall of the Anhalt University

To investigate the soundness of HRB with this fly ash a small test field was produced in a laboratory hall of the Anhalt University. With the small test field no expansive cracks were observed although the fly ash from Schkopau have been used without pre-treatment, i.e. slaking. The compressive strength of the core sample taken from the test field after 28 d showed a compressive strength of 7.6 N/mm². This is similar to the compressive strength of the samples for the Asendorf road project from 1998. By this, the proper storage of the fresh sample in the mould is the pre-condition for crack free hardening /7/.

To verify this new samples were produced with 80 % by mass aggregates 0/8 und 20 % by mass Schkopau fly ash and tested for compressive strength after different storage. The results of these tests showed that a crack free hardening is guaranteed when the samples are stored longer in the mould. It can be concluded that samples for product testing with high lime fly ash should be stored in the mould as long as they are to be tested, 7 days is a minimum.

4.3 Project Lochau

Between July and October 1997, MUEG - Mitteldeutsche Umwelt- und Entsorgung GmbH –, produced a fly ash bound base course in their Lochau production site with the fly ash from the Schkopau power plant in fresh and treated state. Treated fly ash is produced with fresh ash which is slagged in a mixer with a certain amount of waster to hydrate the reactive lime. By 2007, the road was not covered with asphalt and by this was fully exposed to weather.

The road project consists of several parts where fresh ash and treated ash were used together with natural ground, recycled bricks, recycled concrete and sand. The material was placed mix in place with moulding and vibrating machine as well as with ready mixed material placed with a normal road finishing machine. The ash content of the mixed was between 20 to 30 % of the total with 10 to 15 % of water.

	Road part		
[kg/m³]	III-1	III-2	IV-1
recycled bricks	1393		
recycled concrete		1393	1408
fresh ash	418		423
treated ash		418	
retarder	0,627	0,627	
air entraining agent			0,423
water	167	167	169

n.d. not determined

Table 3: Mix design for HRB used for road parts III-1, III-2 and IV-1 of the Lochau road project

Samples taken from part III, produced mix in place with vibrating machine, showed a compressive strength of 7.8 N/mm² and those from part IV, produced with ready mixed HRB and placed with a road finisher, 5.8 N/mm². Compared to cement bound road binders the fly ash based road binders show longer setting times. For this, mixtures with fresh ash show compressive strengths of 5 to 6 N/mm² after 7 days and 16 to 17 N/mm² after 28 days. Treated ash show comparatively lower compressive strengths of 2 to 3 N/mm² after 7 days and 12 to 13 N/mm² after 28 days.

After nine years under service the road showed surface weathering in the road parts I, II and IV. In this parts the road could be supposed to be a top layer part. In road part III no damages or surface weathering was observed. In road part IV with the smallest thickness of the road base cracks have been observed due to heavy traffic.

The compressive strength of core samples of road part III taken after 9 years showed values double as high as after 28 days. Although the base course was not covered with asphalt and was exposed to weathering no change in the structure was observed. The fly ash bound base road looked similar to one made of concrete with a compressive strength of 25 N/mm².

The E-modulus was tested with the Falling Weight Deflectometer (FWD) and was re-calculated to 15.000 up to 30.000 MPa. These values are in the same range as those for cement bound bases. By this, the fly ash bound mixes placed in the Lochau road project can be seen as equal to normal road binder, also taking into consideration the missing cover layer with asphalt. Pre-condition is, that the height of the fly ash bound layer is sufficient for the work load. In the road part IV-1 this is not the case and cracks were observed. The E-modulus of the cracked layer is than reduced and is sometimes of the same height as for unbound bases. Another pre-condition is a homogenous structure of the layer and – when placing two layers - a proper connection between the layers.

5 Summary and conclusions

Within a research project in Germany different tests roads built with slag bound and fly ash bound base courses from 1985 to 1998 have been investigated regarding the bearing capacity by Benkelman beam and Falling Weight Deflectometer. Core samples were tested regarding compressive strength and durability. Aim of the research work was to evaluate whether the requirements in the European standards 14227 part 2 to 4 are sufficient to cover also the experience gained with the German regulations.

It was verified that suitable slag bound and fly ash bound mixtures are sufficiently resistant against frost and have a high long-term durability under the prevailing climatic conditions in Germany, too. Even in the case of an investigated object with different fly ash bound mixtures without asphalt superstructure, just some surface weathering occurred. The bearing capacity of the whole fly ash bound layer was practically not affected by such weathering and remained undamaged on all test sections. Furthermore it can be stated that the load-bearing parameters of road pavements with widely varying rigidity and layer thicknesses, required for dimensioning, can be favourably determined by the Falling Weight Deflectometer.

Fly ash bound mixtures, like the slag bound mixtures, have usually not reached their final strength after 28 days. Furthermore, the results show that for the execution of suitability tests of mixtures of calcareous fly ash with a high percentage of lime, the test specimens have to remain in the formwork for a period of ≥ 7 days according to EN 14227-1, Appendix C, after treatment procedure D, to ensure the hardening without cracks.

To avoid too high rigidities and the associated too high risk of reflection cracks, it is generally useful to prescribe the strength class $C_{3/4}$ according to DIN EN 14227, part 2 and part 3 for the preparation of the regarding mix in the suitability test.

The main results of the additional laboratory tests for the production of base course mixtures with a defined early strength and a defined load-bearing behaviour according to the current base courses bound with cement or base course binder as per ZTVT-StB /2/ (hydraulically bound base courses) can be summarised as follows:

a. By using the investigated calcareous or siliceous fly ashes or by using ground granulated blast furnace slag with different activators (cement, NaOH), it was possible to produce mixtures for hydraulically bound base courses which fulfilled either the requirements to the pressure strength of hydraulically bound base courses under asphalt covers, under concrete covers or under both of them.

b. Hard coal fly ashes need approx. 2 M.-% cement as activator to achieve the required pressure strength. Ground granulated blast furnace slag obtained this strength by means of cement, lime-rich calcareous fly ash or NaOH as activators; lime-rich calcareous fly ashes were able to also achieve this strength without additives.

c. Hydraulically bound base courses with sufficient pressure strength and sufficiently long hydration time were also sufficiently resistant against frost and repeated strong penetration of moisture and drying.

d. Structural failures caused by the attack of sulphate and the formation of ettringite (sulphate expansion) were not found.

6. Outloock

The results of the investigations revealed that the introduction of the European Standards for slowly hardening slag bound and fly ash bound mixtures in Germany can be generally recommended.

It was verified that suitable slag bound and fly ash bound mixtures are sufficiently resistant against frost and have a high long-term durability under the prevailing climatic conditions in Germany, too.

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