Cold Recycling
Rehabilitation of a heavily trafficked road
The intention of this report is to give a working example of a road construction project which includes in-place and in-plant cold recycling methods, with the use of various binding agents. At the outset, it was decided, to recycle the existing distressed pavement with cementitious binders. The pavement would then be strengthened with a bituminous bound base course and a surfacing layer.

The report is based on the principle that each project should be investigated and that the recycled pavement structure will be determined from these investigations. The report follows a logical sequence of

- pavement investigation,
- laboratory testing,
- detailed pavement design,
- construction technique and
- control testing.
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1 Brief description

1.1 Background

A quarry access road was showing severe distress. The heavy trucks were having problems in negotiating the serious pot holes that had, to some extent, been temporarily repaired by filling with concrete and various building materials. The loading on this road, in terms of nett material as per weighbills, sums up to 800,000 tons per annum. This is equivalent to approx. 40,000 medium to heavily loaded trucks per annum with axle loads up to 11 tons. Due to this large volume of traffic and the continuous production of the quarry, the time available for the construction program was very limited.

1.2 Initial site inspection

Before starting any detailed investigations, a visual inspection of the road to be rehabilitated was carried out. Furthermore all information available on the road was collected and taken into account before the decision for any kind of rehabilitation was made.

Fig. 1: Condition of the distressed road.

At the initial visual inspection of the access road, it was evident that the asphalt surfacing was severely cracked for the first half of the section and that some rutting had started in other areas of the access road. The condition was not uniform with the second half being in a fill situation with bad drainage causing many of the failures (see fig. 3). It was thought that the subgrade was the cause of the problem in the severely damaged areas and that the lightly cracked areas were due to asphalt fatigue. Based on the limited information, the assumed existing structure and the initial rehabilitation design was proposed as shown in fig. 2 below.
Fig. 2: Assumed existing structure and initial proposed rehabilitated pavement structure.

Fig. 3: Cross section in the second half of the access road showing the crushed stone fill and drainage problems.

1.3 Detailed pavement investigation

Extensive investigations consisting of a detailed site inspection, testpits, DCP tests of the subgrade and plate bearing tests of the base were carried out. From these results a detailed laboratory investigation scheme consisting of grading analysis, Proctor tests (i.e. moisture/density relationship tests) and optimum binding agent determination tests was scheduled. Based on this series of investigations, laboratory tests and a mechanistic pavement design, it was evident, that both the initial assumed existing structure and the rehabilitation proposal were incorrect and were changed as shown in fig. 4.

The difference when comparing the initial proposal (see fig. 2) to the final proposal for the rehabilitated pavement structure (see fig. 4) illustrates the importance of carrying out a detailed investigation of the existing pavement.
1.4 Pavement structure

The pavement structure selected for rehabilitation is shown in fig. 4. It is different from the initial proposal due to the damaged layer being the 10 cm unbound crushed stone base layer below the asphalt layers.

Water had penetrated this crushed stone base through cracks in the asphalt layers and from the poor drainage conditions. This could be seen from the loss of fines in the base and the freeze/thaw damage evident on the surface. Although these failures were not uniform along the length of the road, it was decided to recycle the existing asphalt and the underlying crushed stone base along the full length of the road to increase the final load carrying capacity of the pavement and to achieve a uniform foundation. Due to the higher strength gained by this layer, the unbound crushed stone layer could be eliminated. This decreased the pavement thickness and thereby reduced the required shoulder fill material. A substantial reduction in the costs was thus achieved.

From the laboratory tests there was a clear indication that the existing layers of asphalt and crushed stone should be stabilised with cement instead of lime, due to the lack of plasticity evident as initially anticipated. In addition, the subgrade was found to be relatively dry and its load bearing capacity higher than initially assumed. The in-place recycling process was carried out with the Wirtgen WR 2500 recycler and a Wirtgen WM 400 mobile cement slurry mixer.

A further 15 cm thick layer constructed from bituminous treated material mixed in a Wirtgen KMA 150 cold mixing plant was then placed as a new base course. The material in the mix consisted of a blend of previously milled and crushed asphalt and 0/2 crusher dust, both stockpiled at the quarry. This base layer was divided into two sections, one treated with foamed bitumen and the other treated with bitumen emulsion. The foamed bitumen bound layer being from km 0+000 to km 0+714 and the other from km 0+714 to km 1+000. This was done to assess the relative behaviour between the two methods of bitumen treatment of cold recycled materials under similar conditions.

A 4 cm 0/11 S asphalt wearing course was laid over the cold recycled base layer.
The cold mixed base layer as well as the asphalt wearing course were placed by a Vögele paver Super 1800 with high compaction screed. The rehabilitation construction phase had to be carefully planned to avoid disrupting the haulage of material out of the quarry. It was decided to recycle the sub-base layer on one Saturday, leave the access road open for traffic for nearly a week and then to construct the cold-mixed base and asphalt wearing course over the following weekend.

2 Detailed report

2.1 Pavement assessment

2.1.1 Existing road details

Length: 1,000 m; Width: 5.1 m; Total area: 5,100 m²
Some pictures show the distress evident along the length of the road:

Fig. 7: Plan showing areas of different types of distress along the road.

Fig. 8: Fully loaded trucks with quarry product.
Fig. 9: Typical crocodile cracking.

Fig. 10: Standing water and frost damaging the road even more.

Fig. 11: Extensive base collapse.

Fig. 12: Lack of drainage causing failures.
2.1.2 Testpits

Three testpits were excavated, at km 0+080, km 0+210 and km 0+590. The existing 9 cm asphalt layers, consisting of 3–4 cm asphalt wearing course and 5–6 cm asphalt base course as well as 10 cm 0–32 crushed stone base were milled out, using a Wirtgen cold milling machine 500 DC. This was done in order to have a material for the laboratory testing similar to the grading produced by the Wirtgen WR 2500 recycling machine.
There was evidence of moisture in the crushed stone layer. The sub-base layer, which was excavated by hand, consisted of 50–75 crushed stone. This layer varied from 17 cm (testpits 1 and 2) to 50 cm (testpit 3). The subgrade consisted of clay and was found to be consistently dry in all three testpits.

2.1.3 Dynamic Cone Penetrometer (DCP) testing

Dynamic Cone Penetrometer tests were carried out, commencing from the bottom of the testpits to determine the structural capacity of the subgrade layer to a total depth of 116 cm. With the aid of the DCP software, a minimum CBR (California Bearing Ratio) value of 25% and a minimum E-modulus EV1 of 100 MN/m² (MPa) was recorded in all three testpits. This gives an indication that consistency existed along the entire length of the access road.

The DCP instrument, see fig. 17, measures the penetration per blow into a pavement through each of the different pavement layers. This penetration is a function of the in-situ shear strength of the material. The profile gives an indication of the in-situ properties of the materials in all the pavement layers up to a depth of penetration. Research has shown that a good correlation exists between DCP measurements and the well known California Bearing Ratio (CBR) of granular materials.
2.1.4 Static plate bearing tests

In order to test the load bearing capacity of the existing pavement structure from the top of the granular layers, four static plate bearing tests were done at km 0+040, km 0+222, km 0+550 and km 0+693. For this reason the asphalt layers had to be removed by means of a core drilling machine as shown in fig. 18 and 19.

Fig. 17: Dynamic Cone Penetrometer (DCP)

Fig. 18: 30 cm diameter coring had to be performed to remove the asphalt layers in order to carry out the plate bearing test on the pavement structure at km 0+222.
Fig. 19: The asphalt core is being removed from the corebit.

Fig. 20: The static plate bearing test being performed in borehole at km 0+222.

Fig. 21: View on the static plate bearing test equipment, showing the pneumatically operated loading cylinder and the deflection beam.
Result:
$E_v$ values of more than 100 MN/m$^2$ were recorded at all four test positions.

2.2 Laboratory tests
The aim of the laboratory testing is to give detailed information on the in-situ materials. This enables the optimum structure and mixtures for each layer of a rehabilitated road to be designed properly, resulting in a road fulfilling all the requirements.

2.2.1 Mix design testing: In-place recycled sub-base layer with cement
As described above, the granular material tested in the laboratory was milled out at the testpit locations. The test results concerning this material are summarised as follows:

![Milled material from the testpits done in the road.](image)

**Sieve analysis/grading**
Material from all three testpits was analysed. The sieve analysis showed a well graded material with a good distribution from fines to large aggregate as shown in fig. 23.
Plastic Index (PI)
The Atterberg-Test was carried out and the results show that the sub-base material is non-plastic.

Moisture/density relationship
The standard Proctor test (DIN 18127/AASHTO designation T 99) was performed to determine the Maximum Dry Density (MDD) and the Optimum Moisture Content (OMC) (see fig. 24).

Optimum lime/cement content determination
To decide whether lime or cement should be used and to determine the optimum lime/cement content, the Unconfined Compressive Strength (UCS) test was undertaken (see fig. 25).
The Unconfined Compressive Strength of the lime at 3% was not as high as that achieved with cement. It was therefore decided to use cement. In selecting the optimum percentage of cement the following aspects were taken into consideration: The increase in cement addition from 2% to 4% does not significantly increase the 7 day strength. For these and for economic reasons, it was decided to add 2% instead of 4% cement with an Unconfined Compressive Strength, at 7 days, of 3.62 N/mm².

2.2.2 Mix design testing: In-plant cold recycled base layer

As mentioned before, it was decided to divide the road into two sections, one treated with foamed bitumen and the other treated with bitumen emulsion. The foamed bitumen bound layer was constructed between km 0+000 and km 0+714 and the bitumen emulsion bound layer was constructed between km 0+714 and km 1+000.

2.2.2.1 Recycling with foamed bitumen

Samples of the imported milled/crushed asphalt and the crusher dust were taken directly from the stockpile in the quarry to guarantee consistency between the laboratory tests and the material used during the construction phase. The following laboratory tests were carried out:

Sieve analysis/grading

The sieve analysis of the asphalt and the crusher dust is shown separately in fig. 26. In both the sieve analysis graphs below (fig. 26 and fig. 27) the CSIR and the ZTVT envelopes have been plotted to show where the specified blend should be placed.

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Fig. 25: Optimum cement content of the in-place milled material.
Fig. 26 shows that both materials separately do not fulfil the requirements. By calculation, the optimum blend of 80% milled crushed asphalt and 20% crusher dust was achieved as shown in fig. 27.

![Graph showing the moisture/density relationship](image)

**Moisture/density relationship**

The standard Proctor test (DIN 18127/AASHTO designation T 99) was performed with the chosen blend to determine the Maximum Dry Density (MDD) and the Optimum Moisture Content (OMC).

Result: Average MDD = 2,088 kg/m³; Average OMC = 5.7%
Determination of the optimum foamed bitumen content

**Foamed bitumen**

Before this series of testing could commence, the foaming characteristics had to be investigated. Foamed bitumen is produced when small amounts of water are added to hot bitumen, thereby increasing the surface area and significantly reducing the viscosity of the bitumen. In this form it is well suited for mixing with cold damp aggregate. Foamed bitumen can be used as a stabilising agent with a variety of materials ranging from good quality crushed stone to marginal gravels with relatively high plasticity. Similar to stabilising with bitumen emulsion, cement or lime is normally added in small amounts to foamed bitumen treated material. In addition to improving the retained strength, such addition assists to disperse the bitumen by increasing the minus 0.075 mm fraction of the material. The retained strength is the relationship between the soaked and the dry strength of the material.
Foaming characteristics

Foamed bitumen is characterised in terms of expansion ratio and half-life. Expansion ratio is defined as the ratio between the maximum volume achieved in the foamed state and the volume of unfoamed bitumen. Half-life is the time taken, in seconds, for the foam to settle to half of the maximum volume attained. The foaming characteristics of a specific bitumen are influenced mainly by the temperature of the bitumen, the amount of water added to the bitumen and the pressure under which the bitumen is injected into the expansion chamber.

The bitumen used for this project, grade penetration 80/100 (B80), was foamed using the Wirtgen foam bitumen laboratory plant WLB 10 (see fig. 31). The optimum foam-water content was found to be 21/2 % as can be seen in fig. 32.

Fig. 30: Foamed bitumen sprayed into standard testing bucket to determine foaming characteristics.

Fig. 31: The Wirtgen laboratory-scale foamed bitumen plant WLB 10.
Adding foamed bitumen to the blended material

In order to optimize the bitumen content, various foamed bitumen contents were added to the blended material of milled material and crusher dust (80:20 blend) at its Optimum Moisture Content. This was done with the Wirtgen foamed bitumen laboratory plant WLB 10 and a standard laboratory Hobart mixer. As described above, in order to improve the retained strength, 1.5% cement was added to the blend before the foamed bitumen was injected. With this foamed bitumen treated material, testing briquettes were manufactured in two different methods. Method 1 uses the compaction effort according to “Foamed Asphalt Mixes – Mix design procedure” proposed by CSIR Transportek in South Africa (based on the Marshall test with 75 blows per side). Method 2 uses the compaction effort according to the “Richtlinie Komplexrecycling im Straßenbau”, proposed in Germany for cold recycling with bitumen emulsion.

Fig. 32: Half-life and expansion ratio vs. foam-water content.

Fig. 33: The Marshall compaction equipment used to manufacture the briquettes to method 1.

Fig. 34: The press used to manufacture the briquettes to method 2.
Optimum foamed bitumen content using method 1

The test briquettes were cured in an oven at a constant temperature of 40°C for 72 hours. After this time had elapsed, half of the briquettes for each bitumen content were soaked under water in a vacuum desiccator, applying a vacuum of 50 mm of mercury for 60 minutes at a temperature of 25°C. After drying the specimens, these and the other half of the briquettes are tested for the ultimate tensile load. From this load the Indirect Tensile Strength, ITS, can be calculated. The retained ITS is the relationship between the soaked and dry ITS results. According to the CSIR proposal the retained ITS should be above 50% and the dry and wet ITS should exceed 200 kPa and 100 kPa respectively. The results from this test were as follows:

The optimum bitumen content was found to be 2.5% by mass. All the retained ITS results were above 80%.

Fig. 35: ITS vs. bitumen content (72 h).
Fig. 36: Retained ITS vs. bitumen content (72 h).
Fig. 37: A standard Marshall press with a splitting device to determine the ITS.
Fig. 38: Specimen after the ITS test.
Optimum foamed bitumen content using method 2
The same foamed bitumen treated material as above was compacted and tested according to the “Richtlinie Komplexrecycling im Straßenbau” (i.e. “Guideline for complex recycling in the upper road layers”).

Variances in the results obtained using the two testing procedures are caused by the different methods of sample preparation and testing. For the purposes of the optimum foamed bitumen content the results obtained by the CSIR method were utilised.

2.2.2.2 Recycling with bitumen emulsion
To obtain a direct comparison between the foamed bitumen and the bitumen emulsion treated base layer, it was decided to use the same blend of 80% milled material and 20% crushe r dust.

Optimum bitumen emulsion content (method 1)
This series of laboratory tests were done according to GEMS – “The design and use of granular emulsion mixes” (SABITA, manual 14). In addition, 1.5% cement was added to the blended material.
All the retained ITS were above 60%.

**Optimum bitumen emulsion content (method 2)**
The same bitumen emulsion treated material as above was compacted and tested according to the “Richtlinie Komplexrecycling im Straßenoberbau”.

To maintain consistency between the foamed bitumen and bitumen emulsion treated material, the bitumen content of 2.5% (equal to 4% bitumen emulsion) was chosen. This was consistent with the method 2 series of testing.

### 2.2.3 Mix design testing: Asphalt wearing course

As this was a standard continuously graded asphalt mix, 0/11 S (asphalt concrete) according to ZTV – Asphalt, from the local batch plant, no further mix design testing was carried out. This asphalt wearing course had a Marshall stability of 10 kN to 12 kN with a bitumen content of 5.6% to 6.2% respectively.

### 2.3 Rehabilitation method

From the above pavement assessment and laboratory tests information, the pavement life could be estimated using a mechanistic design approach based on multi-layered linear-elastic theory. The selected structure (A) is shown in fig. 44 below.
Assuming a Class IV pavement the catalogue design according to RstO 86/89 specification is depicted in fig. 44 (B).

The difference between the road structures (A) and (B) is that structure (A) is built with recycled material whereas structure (B) is made of virgin materials. Both structures have a similar structural capacity of 400,000 equivalent standard 11 t axle loads.

2.4 Construction report

2.4.1 In-place recycled sub-base layer with cement

The existing 9 cm asphalt wearing course and the 10 cm 0–32 crushed stone base were milled and recycled with cement simultaneously. This was achieved with the Wirtgen WR 2500 recycler and the Wirtgen WM 400 mobile cement slurry mixer. The cement slurry, a mixture of cement (1.5%) and water (3%), was fed into the recycler’s spray bar, thus adding exact amounts to achieve the optimum mixture to the recycler’s forward speed. The compaction was achieved with a 9.7 ton multi amplitude single smooth drum roller and a 7 ton tandem roller. The total area of 5,300 m$^2$ was completed in one day.

![In-place milling, mixing and addition of binding agents (cement slurry), achieved with the Wirtgen WR 2500 recycler and Wirtgen WM 400 slurry mixer.](image-url)
As mentioned in the introduction of this report, the construction program was such that this recycled layer was able to cure for 40 hours before it was trafficked for 3 days. The surface was kept moist by applying water. The result after this trafficked period was very positive with only some loose stones on the surface. There were no signs of any deformation or cracking due to early loading. The surface was brushed with a mechanical broom before the cold mixed base course was constructed.

2.4.2 In-plant cold recycled base layer with foamed bitumen

The milled crushed asphalt material and the 0–2 mm crusher dust, both stockpiled in the quarry, were placed separately into the two-bin storage hopper of the Wirtgen cold mixing plant KMA 150. The blend of 80:20 crushed asphalt:crusher dust was then mixed with the addition of 2.5% foamed bitumen (B80), 1.5% cement and 2–3% water.

The material was transported with 4 tiptrucks to a Vögele Super 1800 asphalt paver, equipped with a high compaction screed, incorporating tampers, vibrators and pressure bars. The precompaction achieved by the paver significantly reduced
the effort required by the rollers. Final compaction was carried out using a 9.7 ton multi amplitude smooth drum roller and a 7 ton tandem roller. 1200 tons of treated base material were mixed and placed in the 714 m long, 5.1 m wide section.

2.4.3 In-plant cold recycled base layer with bitumen emulsion
The following day, similar blended material was mixed (ratio of 80:20 respectively) with 4% bitumen emulsion (U70K), 2% cement and 1% water using the Wirtgen cold mixing plant KMA 150. 500 tons of cold mixed material were transported to the paver by tip trucks and placed by the Vögele paver Super 1800, to a width of 5.1 m. Final compaction was done by the same rollers as the day before.

2.4.4 Asphalt wearing course
The next day, a tackcoat was sprayed onto the freshly paved cold mixed base layer. The 0/11S asphalt wearing course was paved using the Vögele Super 1800 as used for the base course. Compaction was achieved using two 7 ton tandem rollers.
The entire 5,100 m² which amounted to 600 tons was paved and compacted within 6 hours.

2.5 Control testing during construction phase

2.5.1 In-place recycled sub-base layer with cement

The in-situ compaction achieved varied between 98% and 101% standard Proctor (DIN 18127/ASSHTO designation T 99).

2.5.2 In-plant cold recycled base layer with foamed bitumen

Indirect Tensile Strength (ITS) with briquettes manufactured to Marshall compaction

Specimens sampled from the job site were taken to the laboratory in air tight containers, and prepared in the same manner as the mix design testing. Marshall briquettes were manufactured to determine the Indirect Tensile Strength. Bitumen extraction and grading tests were carried out.
The in-situ compaction achieved varied between 98.6% and 103.4% standard Proctor (DIN 18127/ASSHTO designation T 99).

2.5.3 In-plant cold recycled base layer with bitumen emulsion

Indirect Tensile Strength (ITS) with briquettes manufactured to Marshall compaction

Specimens sampled from the site were taken to the laboratory in air tight containers, prepared in the same manner as the mix design testing. Briquettes were manufactured and the results of tests undertaken indicated that the strengths achieved from the mix design were exceeded. The in-situ compaction achieved varied between 98.6% and 103.4% standard Proctor (DIN/ASSHTO designation T 99). Bitumen extraction and grading tests were carried out.

2.5.4 Asphalt wearing course

Samples were taken from the field and tested at the supplier’s laboratory with the following results:

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total bitumen content</td>
<td>5.68% by mass</td>
</tr>
<tr>
<td>Density at 25°C</td>
<td>2,622 g/m³</td>
</tr>
<tr>
<td>Bulk density at 25°C</td>
<td>2,717 g/m³</td>
</tr>
<tr>
<td>Voids at 25°C</td>
<td>3.5 Vol-%</td>
</tr>
<tr>
<td>Marshall-stability</td>
<td>14.3 kN</td>
</tr>
<tr>
<td>Marshall-flow</td>
<td>4.1 mm</td>
</tr>
</tbody>
</table>

These results indicate that the asphalt wearing course is within the specified values and thus in order in terms of quality of mix. Visually the compacted asphalt wearing course was well graded and compacted adequately.
2.6 Pavement structure monitoring

Cores were extracted after 3 months and tested for ITS und UCS (fig. 54 - 57). Results of these tests are shown below in fig. 58 and 59.

![Fig. 54: Core foamed bitumen](image1)
![Fig. 55: Core bitumen emulsion](image2)

![Fig. 56: Cross section foamed bitumen](image3)
![Fig. 57: Cross section bitumen emulsion](image4)

The access road to the quarry will be monitored over time to assess the long term behaviour of the pavement.
3 Glossary of terms

CBR = California Bearing Ratio
CSIR = Council for Scientific and Industrial Research, South Africa
DCP = Dynamic Cone Penetrometer
\( E_{v1} \) = E-Modulus, achieved in the DCP-test
\( E_{v2} \) = E-Modulus, achieved in Static Plate Bearing test
ITS = Indirect Tensile Strength
MDD = Maximum Dry Density
OMC = Optimum Moisture Content
RStO = Richtlinien für Straßenoberbau
UCS = Unconfined Compressive Strength
4 Appendix
Publication in “Straße + Autobahn 55 (2004), Nr. 5”
(5 years after the project was completed)
Cold Recycling Construction Methods Put To the Test – Results of the Nauberg Project

Ernst Neußner, Bernd Grätz and Steffen Riedl

Cold recycling (the CR construction method) becomes ever more popular internationally and ever more important from both, technical and economical viewpoints. In May 1999, the access road to the “Nauberg” quarry in the Westerwald region was successfully rehabilitated with the cold recycling construction method. Over the past 5 years, annual control measurements were carried out on this highly stressed road. The following report provides details about the execution and the good results of this project.

1. A look back and the background of this project

Cold recycling construction methods with bitumen-cement mixtures have been in use worldwide for approx. one decade, mostly in the States of Saxony, Saxony-Anhalt and Thuringia [1 to 21]. All the same, a certain reserve regarding these construction methods is still noticeable in many places, both on the part of the clients and on the part of the construction industry.

Major reasons for this are, above all:
- A lack of experience on the part of clients and construction companies.
- Doubts with regard to the performance level when compared to asphalt base course layers and hydraulically bound base course layers.
- Necessary investments in construction machinery (e.g. cold recyclers, cold mixing plants) meeting high performance requirements with regard to the quality level to be achieved and the prevention or reduction of risks, because conventional cement-stabilizing machines are less suitable for this purpose.
- Competitive drawbacks, because the cold recycling construction methods can, as a rule, only be introduced into the competitive procedures by means of secondary offers.
- The assessment of bitumen-cement mixtures with regard to test engineering.
- The lack of technical rules and regulations.

The following should be noted concerning the two latter points:

Initially, the Roads Department of the Saxon State Ministry of Economics and Labour prepared the “Richtlinie Komplexrecycling im Straßenbau” (Guideline on complex recycling in road construction), and numerous projects have been carried out in accordance with this guideline in the New German States.

The Forschungsgesellschaft für Straßen- und Verkehrswesen (FGSV = Research Institute for Roads and Traffic) has since designed the “Merkblatt für Kaltrecycling in situ im Straßenoberbau” (M KRC = Bulletin on the in-situ cold recycling of road pavements). It was published in 2002 and takes into account German as well as foreign experiences. Regarding the bituminous binding agents, both of the above mentioned rules and regulations concern themselves, for the present, to the application of bitumen emulsions. A supplement to the M KRC in the form of a working paper is presently being prepared for the application of foamed bitumen. Company-specific publications may be used for the time being.

Cold recycling construction methods have gained particular importance in recent years in connection with the reuse of existing substances containing pitch (construction methods using pitch bitumen or pure road pitch), in particular for the following reasons:
- No water pollution hazards due to the bleeding-proof incorporation of road construction materials containing pitch.
- Prevention of vapours that irritate the respiratory passages or are carcinogenic, and prevention of fumes.

Cold recycling construction methods do, however, have a much more widespread field of possible applications.

In addition to technical and economical issues, the main advantages of applying these construction methods consist in the saving of resources and in minimizing any negative influences on environment and traffic, namely:

- Precept of waste avoidance and reuse in the sense of the “Kreislaufwirtschafts- und Abfallgesetz” (KrW-/AbfG = Recycling Management and Waste Avoidance and Management Act).
- The main mass of the mineral aggregate lies in the pavement to be rehabilitated, which results in less material transports and, therefore, less fuel consumption, less air pollution, less nuisance due to noise and dust as well as a reduced traffic volume and strain on the road.
- Energy savings due to cold processing, in particular with bitumen emulsions.
- Shorter construction times.

A lasting and increasing interest in cold recycling construction methods will, however, only be given if a high quality and profitability can be guaranteed. Experiences and results in connection with the rehabilitation of road pavements are, therefore, all the more important. For this purpose, test and trial sections are set up in addition to general applications in order to obtain assessment criteria that are as comprehensive as possible. The results of such projects are particularly significant in cases where the per-
formance capacity of the construction methods and pavements in question is proved under unfavourable and extreme local conditions. This article reports on the production and performance of an access road to a quarry, which was set up as a test section [22, 23].

2. Selection and initial condition of the test section

Considering the above-mentioned targets, an access road in need of rehabilitation, which leads to a quarry and from a ready-mix concrete mixing plant seemed to be particularly suitable. Transports to and from the premises take place, e.g. of construction materials from the quarry and the ready-mix concrete plant or of cement and natural sand to the concrete mixing plant or of used materials and excavation masses intended to backfill the quarry. This results in the desired, very high strain on the road. The road showed numerous damages, making extensive rehabilitation measures inevitable (Figs. 1 and 2). The road section is approx. 1,000 m long and 5.1 m wide. An approx. 100 m long stretch on the way out is particularly critical, since it shows a longitudinal incline of up to 6% in connection with a narrow bend. The engineering firm Nies in Cologne was assigned to carry out the preliminary investigations, mix designs and tests during and after the construction. These will be dealt with in sections 3 and 4 of this report.

3. Assessment and rehabilitation proposal

The following preliminary investigations were carried out in order to prepare a rehabilitation proposal:
- The structure of the existing pavement and the condition of the subsoil and subgrade respectively were determined by means of test pits.
- The bearing capacity of the subsoil was established by both, the dynamic cone penetrometer and the static plate bearing test. They produced the following values: CBR 25%, $E_{\text{0,2}}$ 100 MN/m².

3.1 Mix design

The mix design was carried out according to [24 to 30]. Marshall specimens were tested to establish the indirect tensile strength without and after soaking in water. The specimens, which had a diameter of 145 mm, were subjected to tests to determine their unconfined compressive strength and indirect tensile strength without soaking in water at the designated testing age. The mix design differentiates between standard class B 80 foamed bitumen and the addition of bitumen emulsion U 70 k.

3.2 Mix formulas for the execution of the work

Cement-stabilized base course layer: milled material 0/22 mm, average gradation, consisting of gravel base course material + milled asphalt, added cement 2.0% by mass, water content $w_\text{Pr} = 6.4\%$ by mass.

Cold recycling base course layer with foamed bitumen: asphalt granulate containing pitch 0/22 mm + 2.0% by mass crushed basalt sand 0/1 mm + 2.0% by mass cement + 2.5% by mass foamed bitumen, optimum compaction water content $w_\text{Pr} = 5.7\%$ by mass.

Cold recycling base course layer with bitumen emulsion: The formula is equal to the characteristics described above. A slow-breaking bitumen emulsion VIALIT U 70 k KRC was used, heated to approx. 40-45°C. Its water content was taken into account when proportioning the bitumen emulsion.

A long-lasting and economical solution had to be found to restore the pavement to a perfect condition, combined with the shortest possible construction time. These requirements could be met with cold recycling construction methods, which would thus be exposed to a performance test not only with regard to the traffic load, but also with regard to the other unfavourable initial conditions.

The rehabilitation was carried out in accordance with the following work steps (Fig. 3):
- In order to create a foundation of...
maximum evenness for the cold recycling layer with bitumen-cement mixtures, it was planned to stabilize the existing pavement down to a total depth of 19 cm by scarifying and mixing it with cement.

- A 15 cm thick cold recycling layer with bitumen-cement mixtures was to be placed on top of the hydraulically stabilized layer. Most of the aggregate mass of the cold recycling layer consisted of asphalt granulate containing pitch, which had accumulated at a renewal project on the motorway A45.

- Subsequent to the application of a tack coat, a surface course of only 4 cm thickness consisting of asphalt concrete 0/11 S was to be placed on top of the cold recycling layer.

4. Composition of the construction material mixtures, execution of the work and results

4.1 Construction material mixtures

The stabilization was effected by a Wirtgen recycler WR 2500 and a Wirtgen slurry mixer WM 400. 2% to 3% by mass water and 2% by mass cement were added. The mix design showed that a sufficient degree of stability would be achieved with a cement content of 2% by mass.

In order to be able to compare cold recycling layers with different types of bituminous binding agents, it was planned to produce approx. 2/3 of the 1,000 m long road with foamed bitumen and approx. 1/3 with bitumen emulsion. The different binding agents were to be proportioned in such a manner that the construction material mixtures of both sections would contain identical proportions of bitumen and cement.

The cold processing in-plant of both types of mix was carried out with the Wirtgen cold mixing plant KMA 150. The cold mix was placed by a road paver Vögele Super 1800 with high-compaction screed. It was compacted by a 12-ton vibrating roller and a 7-ton tandem roller. Subsequent to the application of a tack coat on the cold recycling base course layer, a 4 cm thick surface course consisting of asphalt concrete 0/11 S was also placed with the road paver Vögele Super 1800.

4.2 Execution of the work

A number of unfavourable influential factors occurred during the execution of the work:

- The compaction equipment was not used in an optimum manner.
- The cement content of both, the cement-stabilized layer and the cold recycling layer was chosen at the lower limit.
- The nominal layer thicknesses were not achieved.
- Low temperatures when placing the cold recycling layers.
- The surface course was placed immediately, which is particularly unfavourable for the section recycled with bitumen emulsion.

The scarified existing pavement was stabilized with cement on 8th May 1999. The following machines were used: cold recycler WR 2500 and mixer WM 400; rollers: vibrating roller (12 t) and tandem roller (7 t). The layer thickness after compaction was approx. 18 cm. The work was carried out within one day. Set compaction degrees were measured within the limits of DPr = 98% to 101%. According to plan, the cement-stabilized base course layer was exposed to heavy traffic for the period of one week. Apart from surface wear, no damages were found.

On two thirds of the road, cold recycling material with foamed bitumen was then placed on 14th May 1999. On the upper third of the road, cold recycling material with bitumen emulsion was placed on 15th May 1999. A tack coat of approx. 0.4 kg/m² had previously been applied on the entire area. The following machines were in operation: mobile mixing plant KMA with 150 t/h, road paver Vögele Super 1800 with high-compaction screed, three rollers of the above mentioned configuration. Layer thickness after compaction: d = 12 cm. The set compaction degrees for both sections were DPr 98.6% to 103.4%.

The asphalt surface course type AB 11S with a layer thickness of 4 cm was placed on 16th May 1999.

4.3 Check testing

Material samples for check testing were taken during the execution of the work. 20 cores (of 150 mm diameter) were taken three months later. The compaction degrees of all cores were determined with the average values: indirect tensile tests of Marshall specimens with 145 mm diameter without and after soaking in water. Core samples were tested to establish the indirect tensile strength at 5°C and 20°C.

Fig. 3: Structure of the road pavement prior to and after the rehabilitation
and the unconfined compressive strength at free lateral expansion. Two cores each were subjected to the freeze-thaw test with 10 cycles between -25°C and +20°C in accordance with the so-called “warm wet feet” formula to allow the permanent capillary absorption of water. According to the check tests both, the requirements of the corresponding rules and regulations as well as the target values of the material characteristics were met. The elution test for environmental compatibility in accordance with the “Richtlinien für die Standardisierung des Oberbaues von Verkehrsflächen, Ausgabe 2001” (RSIO 01 = Guidelines for the standardization of the pavement of traffic areas, edition 2001), Fig. 7 shows the traffic load by the end of 2003 in 10-ton axle passages and the categorization of the construction classes in accordance with RSIO 01. As a result, the traffic load to this point corresponds to construction class III. Fig. 8 compares the rehabilitated pavement to the pavements of the construction classes III and II of the RSIO 01. According to this comparison, the total thickness of the bound layers corresponds to construction class III, whereas it falls short by 4 cm when compared to construction class II. A fundamental difference between the various designs shown in Fig. 8 is, however, the fact that the rehabilitated pavement does not possess a binder course between the base course and the surface course layers, as is the case with the pavements of the construction classes II and III. Since the shear stress maximum, which was calculated by means of the half-space theory, is below the surface course due to vertical wheel loads, the omission of the binder course in the rehabilitated pavement means that the cold recycling layer must absorb the maximum shear stresses. Additional, very high stresses from braking and centrifugal forces arise on a section with an incline of up to 6% in front of a narrow bend. Further extreme conditions are the climate and untended drainage channels. Unfavourable climatic conditions prevail in the winter period due to the harsh Westerwald climate (approx. 450 m above sea level). Inhomogeneous subsoil conditions and a strong lateral afflux of water must be assessed as particularly unfavourable. In conjunction with the completely neg-

5. Exposure of the road to strain

Extreme circumstances are, in particular, due to the high exposure of the road to strain. The road is mainly travelled by fully loaded heavy commercial vehicles, some of them with axle loads exceeding the permissible maximum limits. The advantage of using this section as a test section is the fact that both, the delivery of mineral aggregate and concrete as well as the supply of backfill for the quarry and of sand and cement for the production of the concrete are precisely weighed and documented. From this information, the axle passages are calculated in accordance with the “Richtlinien für die Standardisierung des Oberbaues von Verkehrsflächen, Ausgabe 2001” (RSIO 01 = Guidelines for the standardization of the pavement of traffic areas, edition 2001). Fig. 7 shows the traffic load by the end of 2003 in 10-ton axle passages and the categorization of the construction classes in accordance with RSIO 01. As a result, the traffic load to this point corresponds to construction class III. Fig. 8 compares the rehabilitated pavement to the pavements of the construction classes III and II of the RSIO 01. According to this comparison, the total thickness of the bound layers corresponds to construction class III, whereas it falls short by 4 cm when compared to construction class II. A fundamental difference between the various designs shown in Fig. 8 is, however, the fact that the rehabilitated pavement does not possess a binder course between the base course and the surface course layers, as is the case with the pavements of the construction classes II and III. Since the shear stress maximum, which was calculated by means of the half-space theory, is below the surface course due to vertical wheel loads, the omission of the binder course in the rehabilitated pavement means that the cold recycling layer must absorb the maximum shear stresses. Additional, very high stresses from braking and centrifugal forces arise on a section with an incline of up to 6% in front of a narrow bend.
lected maintenance of the drainage channels and the soft shoulders, this leads to an accumulation of standing water (Fig. 9). At times, the water level rose as high as the top edge of the pavement. This condition continued until a thorough maintenance of the drainage channels was carried out in 2003.

6. Results from cross section measurements

A geodetic measurement of the stretch was carried out for subsequent observations, and ten cross sections of 5 to 6 m width were installed, secured by embedded, dowelled machine bolts type M24. The measurement was carried out in three passes, in conjunction with deflection measurements. No changes in the level were noticeable during the observation period of approx. 4 years. In a 90° bend with an ascending grade of approx. 6%, however, one measuring bolt was extrac-
	ed from the dowelled joint due to cornering forces, a fact demonstrating the magnitude of the induced forces and the resulting shear stresses. According to the longitudinal profile, partial sections display ascending grades between 6% and 8%.

7. Measurement, calculation and assessment of the bearing capacity

The bearing capacity was measured at three different times of measurement using the Falling Weight Deflectometer (FWD). Approx. 300 FWDs are used worldwide to establish the bearing capacity [31]. The FWD is a dynamic method of measurement, which uses a falling mass to transfer a momentum to the pavement surface, similar to the dynamic traffic load. The method of calculation of the bearing capacity and the two layer moduli is described in [32]. The bearing capacity (elastic length) \( l \) and the layer modulus \( M_0 \) are calculated from the FWD measuring data without knowing the layer thickness \( H \). [33] defines the bearing capacity as “mechanical resistance of a road pavement against short-term deformations”. To assess the bearing ca-

pacity at the three times of measurement, the parameters elastic length \( l \) and layer modulus \( M_0 \) are entered into the “provisional assessment diagram” displayed in Fig. 10.

The FWD measurements were carried out in both directions of the access road (uphill and downhill) at 19 stations each in the right tracks. The temperature was 15°C (1st measurement in September 1999), 9°C (2nd measurement in March 2001) and 20°C (3rd measurement in September 2003). When comparing the calculated parameters and the “provisional assessment diagram”, it becomes ob-

vious that three bearing capacity parameters of the uphill measurement are in the transition zone between sectors I and IV (these parameters can be attributed to one measuring station) and all other bearing capacity parameters of the uphill measurement are in sector I. Except for one measuring station, the bearing capacity of the entire pave-

Fig. 7: Traffic load and construction classes

Fig. 8: Comparison between the rehabilitated pavement and pavements in accordance with RStO 01

Fig. 9: Standing water

Fig. 10: Provisional assessment diagram
ment is, therefore, assured. This measuring station is localized by means of the “bearing capacity curve”. The bearing capacity curve is the graphical representation of the parameters bearing capacity (elastic length) $l$ and layer modulus $M_0$ of the half-space above the measuring stations. Fig. 11 exemplifies the bearing capacity curve for the uphill direction.

Fig. 11 shows that the measuring spot with the lowest bearing capacity (transition zone from sector I to sector IV) is located at station 235 m. The bearing capacity curve further shows that:

- the layer modulus $M_0$ is distributed very inhomogeneously across the section;
- the bearing capacity $l$ is distributed more homogeneously across the section;
- the chosen layer structure will lead to a homogeneously distributed bearing capacity and thus to a homogeneously distributed load of the pavement.

The bearing capacity curve also permits conclusions with regard to the bearing performance of the pavement. [33] defines the bearing performance as “change of the bearing capacity depending upon the time and/or the traffic load”.

Fig. 11 shows that between 1999 and 2003
- the bearing capacity $l$ has not significantly changed.
- the layer modulus $M_0$ has decreased in the area between station 700 and station 850 at the time of the third measurement when compared to the first two measurements.
- the layer moduli $M_0$ are otherwise within a small range, depending upon the time.

After approx. 4 years, the good bearing capacity that was achieved when rehabilitating the pavement of the access road to the Nauberg quarry has practically not changed.

8. Concluding assessment of the Nauberg project and other rehabilitation projects

The intention of this reconstruction project was to give general proof of the performance capacity of cold recycling construction methods with bitumen-cement mixtures and, in particular, to answer the question as to whether these construction methods are capable of meeting the properties expected from base courses and binder courses with regard to bearing capacity and resistance to permanent deformation.

The good results are due to the fact that, because of their thickness and composition, cold recycling layers with bitumen-cement mixtures have a high bearing capacity potential. Their cement content should, however, always be lower than the bitumen content. Moreover, these layers are resistant to deformation without the tendency to shrinkage cracks that is known from purely hydraulically bound layers. Due to the resulting plate-like distribution of the load, inhomogeneities of the base are better compensated for, and the pavement area lying underneath the cold recycling layer is subjected to a reduced load.

In addition to the Nauberg test section, further rehabilitation projects using
cold recycling construction methods have meanwhile been carried out in Rhineland-Palatinate and North Rhine-Westphalia. The good results achieved on all of these projects significantly contribute towards dispelling doubts. They should also give reason to critically question the application examples detailed in the “Merkblatt für Kaltrecycling in situ im Straßenbau” (M KRC = Bulletin on the in-situ cold recycling of road pavements). For the construction classes III to V and depending upon the deformation modulus of the base, the M KRC always calls for one or more asphalt layers in the form of a levelling, base and/or binder course between the cold recycling layer and the surface course layer.

Hence, the structural designs of the pavements presented in the application examples of the M KRC have a larger overall thickness than those of the test section described and of other rehabilitation projects that have been carried out in the meantime, for example:

- Renewal of the K 99 Straßenhaus – Oberhonnewel in 2000: Construction class V:
  5 cm surface course layer 0/11 S
  20 cm cold recycling layer with foamed bitumen
- Renewal of the L 275 Asbach – Buchholz in 2002:
  Construction class VI:
  5 cm asphalt concrete 0/11
  20 cm cold recycling layer with foamed bitumen and cement
- Renewal of the L 256 Breitscheid – Fernthal
  Construction class IV:
  5 cm surface course layer 0/11 S
  20 cm cold recycling layer with emulsion
- Renewal of the L 126 Lanzenbach
  Construction class VI:
  4 cm asphalt concrete 0/11 S
  4 cm asphalt binder course 0/16 S
  20 cm cold recycling base course layer with foamed bitumen and cement

Here, it must be considered that the application examples detailed in the M KRC have their roots in an early stage, in which specifically proven values concerning the bearing capacity performance of cold recycling construction methods, in particular those using bitumen-cement mixtures, were not yet available. Due to the experiences gained with the Nauberg project and other projects, it is suggested to verify the examples given in the KRC, in particular with a view to the fact that layers between the cold recycling layer and the surface course layer can be omitted. If, in individual cases, doubts should remain, increasing the thickness of the cold recycling layer should be preferred to a layout calling for one or more intermediate layers. The risk of rutting is also reduced by omitting intermediate layers. Simultaneously, the risk of possible failures of the adhesion between layers is reduced, since there are less layers and layer levels. A prerequisite for the omission of intermediate layers is, however, that the cold recycling layer is produced sufficiently even and true to line and level. Furthermore, an adequate adhesion between the cold recycling layer and the surface course layer must be assured. In case of less strict demands on the evenness, e.g. on rural roads, a surface treatment (single or double) or a cold asphalt surface dressing can be proposed in lieu of a surface course consisting of rolled asphalt.

9. Concluding remark and future prospects

The experiences with cold recycling construction methods, gained internationally and nationally over many years, must be judged as good. With a careful preparation and execution of the construction project, the risks are no higher than those of the traditional construction methods, so that doubts due to basic considerations will be unfounded in the future. The experiences present a sufficiently broad basis for planning and executing rehabilitation projects using cold recycling construction methods with bitumen-cement mixtures. Both, bitumen emulsion and foamed bitumen produced directly during the mixing process can be considered as suitable bituminous binding agents.
Since the kind and the extent of road damages tend to grow continuously due to the increasing age and load of the road pavements, but the financial shortages continue or even increase at the same time, the repair of damages is more often than not restricted to the simplest methods. This entails ever shorter rehabilitation intervals and the accompanying traffic obstructions, whilst the extent of the structural damages increases at the same time. Due to their technical, economical, traffic-relevant and environmental advantages, cold recycling construction methods are considered as a particularly suitable alternative with a good long-term performance, mainly for the rehabilitation of country and district roads within the context of the so-called improvement of existing roads, to the conventional rehabilitation and renewal methods, such as the removal of the existing pavement and reconstruction of the layer structure (inlay) or the reinforcement with thicker asphalt packages (overlay).
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