CEMENT CONCRETE PAVEMENTS ON SOFT SOILS SENSITIVE TO DIFFERENTIAL SETTLEMENTS

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This paper deals with pavement desing on soft, compressible soils, and in particular with experiences made with cement concrete pavements (CCP) placed on such kind of soils. When dealing with this subject distinction must be made between:

1. Pavement design with respect to local influence of differential subgrade settlements affecting individual slabs, and
2. regionally influenced pavement structures.

Dealing with the first subordinate problem well tested technical solutions to prevent not only structural failures of the slabs, but also a severe reduction of riding quality and operational safety are described. The second subordinate problem deals with the phenomenon of pavements regionally influenced by the differential settlements of the soft, compressible soils on which they are placed, and describes the experiences made with a relevant number of CCPs placed on such soils in Switzerland. All mentioned Swiss pavements prove the soundness of the structural design philosophy, according to which the pavement structure's rigidity will minimize the effects of differential soil settlements to such an extent, that the magnitude of pavement deflection decreases with the creep modulus and the thickness of the pavement increasing. The most revealing example is supplied by the results gained from the observation of the long-term behaviour of the 7km (4.35 miles) long Swiss Interstate Highway N3 Flums-Sargans. These data permitted to determine the quantitative limits within which differential settlements may occur without affecting either the riding quality or the structural integrity of the pavement.

The most difficult problems engineers may have to face in road and airport pavement construction are those arising when dealing with the effects of soft, compressible or swelling soils prone to differential settlement and consolidation phenomena.

This paper deals with pavement design on soft compressible soils, and in particular with experiences made with cement concrete pavements (CCPs) placed on such soils. The engineer will be aware of afore mentioned phenomena:

A. When differential subgrade settlements occur locally i.e. within a restricted area underneath approx. one single slab. These are called local differential settlements (Figures 1 and 2).

B. When the effects of consolidation, and also those of differential settlements, affect several slabs lengthwise we speak of regional differential settlements.

A. Sphere of influence of local settlements

Figure 1. Cross section of a slab placed on soils of different kinds.

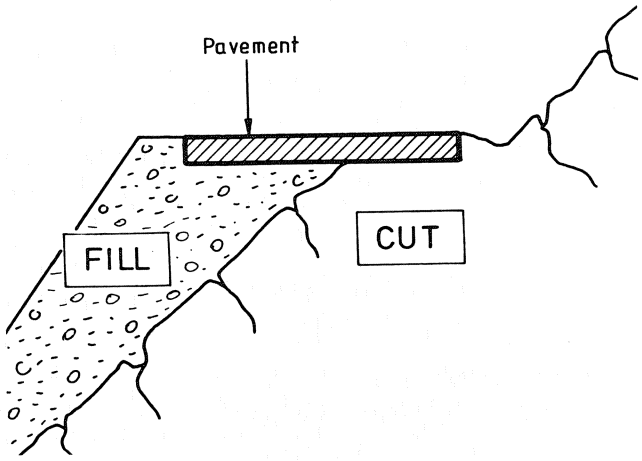
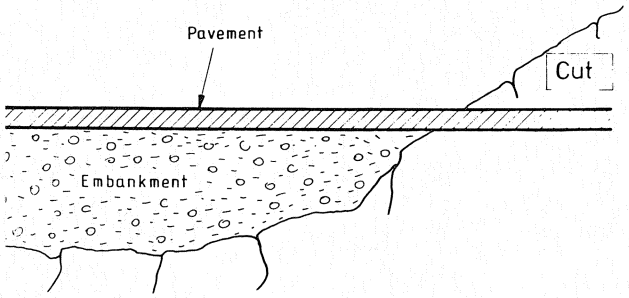


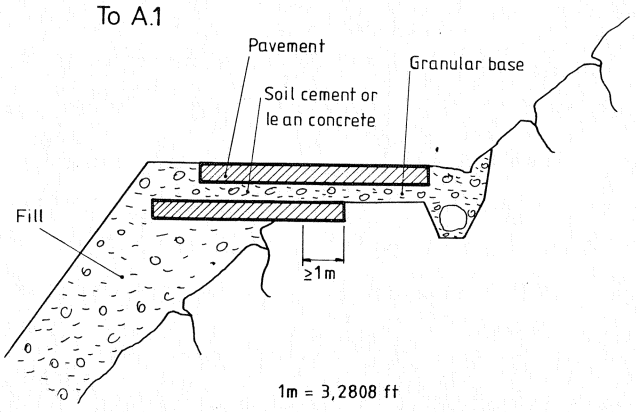
Figure 2. Longitudinal section of a slab placed on soils of different kinds.



It is generally known and therefore mentioned here merely for completeness sake that rigid pavements require a homogeneous base to achieve satisfactory long term behaviour. This has also been confirmed by extensive research effected by the Bundesanstalt für das Strassenwesen/BAST, Cologne, during the 1960's and by the pertinent recommendations subsequently issued (1).

The following construction method has been successfully applied on many pavement construction sites in hilly and mountainous topography in Switzerland (Figure 3).

Figure 3. Cross section of a pavement placed on different kinds of bases.



Should, in spite of all precautions taken, transverse or longitudinal cracks develop in such a pavement, this does not necessarily mean that repairs are due. Such cracks may not even affect either the ridability or the durability of the road concerned. A crack of mentioned type is shown in Figures 5 and 6.

Structural condition of the affected slabs:

1. Longitudinal cracks (< 2 mm = 4 in) but:
2. no visible damages,
3. no significant alterations of the load bearing capacity,
4. no repairs required to this day,
5. no rehabilitation will be required in the near future.

Figure 4. Longitudinal section of the pavement shown in Figure 3.

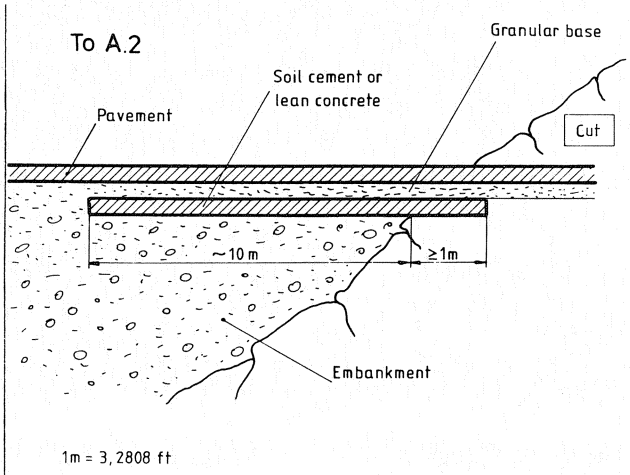
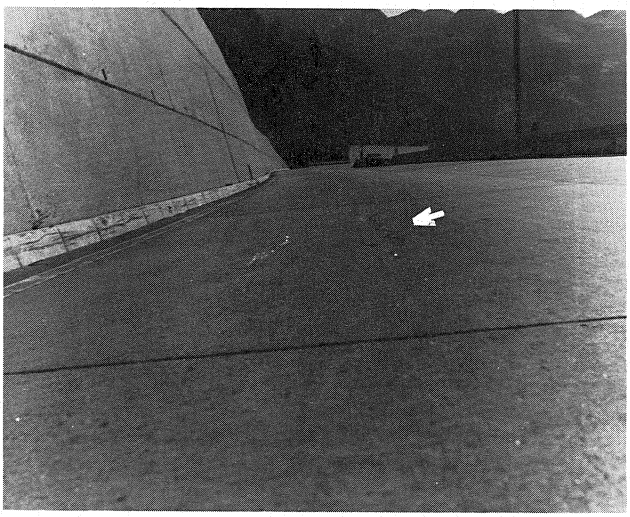


Figure 5. Overall view of a crack which appeared 2 years after pavement construction in 1967. Shot taken by the author on 21 August 1980.



Between the behaviour of cement concrete pavements (CCP) and of asphalt concrete pavements (ACP) placed in areas subject to local transverse differential settlements an interesting difference exists. In CCP slabs mentioned phenomena merely produce:

1. a longitudinal crack, and
2. a slow tilting downwards of the slab segment placed on the softer base soil (Figure 7).

According to the effect achieved Q, the shear force remains effective, and the riding quality is not affected at all.

Assessment of the admissible settlement δ (Table 1)

With $\varepsilon_{tu\ creep} \cong 0.30$ o/oo

$\delta_{admissible} \cong 0.30$ mm/m = 0.003 in/1 in (1)

Figure 6. Close up of the crack shown in the preceding figure, also taken by author. Present serviceability index of pavement: >3.9

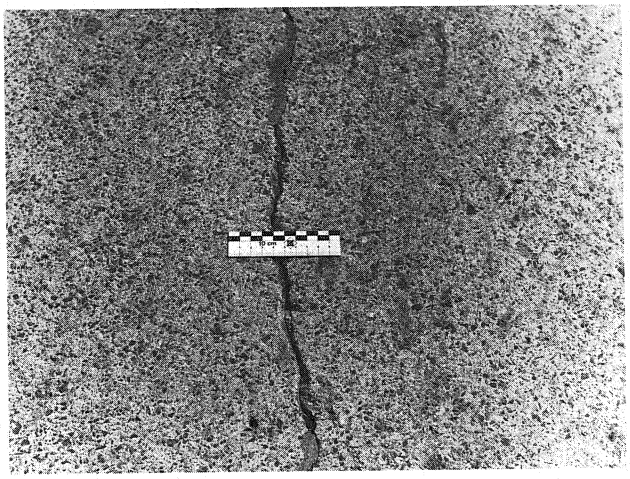
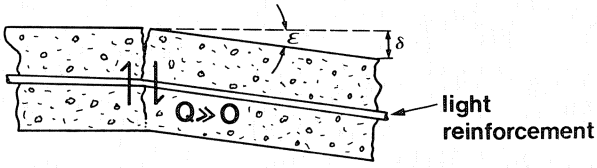


Figure 7. A lightly reinforced CCP slab a segment of which, placed on softer base soil, tilted.

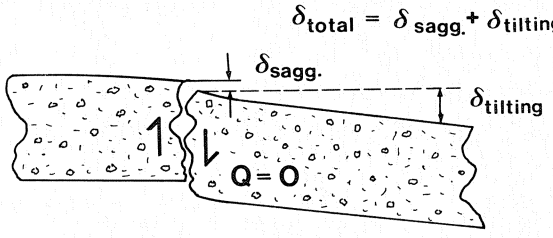


In the same conditions the ACP not only shows:

1. Cracks in the structure, and
2. tilting

but the pavement segment placed on the softer soil may possibly be subject to sagging (Figure 8).

Figure 8. An APC pavement the segment of which, placed on softer base soil, tilted and sagged.



As a result the riding quality of such a pavement is considerably impaired (Figure 9)

Figure 9. The considerably impaired riding quality of an ACP.



Design principles applicable in the case outlined in A.

1. A permanent base of the greatest possible homogeneity and compactness is of paramount importance.
2. No abrupt change of the type of base.
3. The absolute load bearing capacity of the CCP support, expressed by a deformation modulus E; k is irrelevant to the long term behaviour of the pavement.
4. A light slab reinforcement is however to be recommended.

B. Regional settlements affecting larger areas.

Literature dealing with design principles and/or with experiences made in this field is rather scarce. In almost all known cases the soft compressible soil is either removed and replaced by other materials (sand, gravel-sand), or bridge systems are built across such areas. It is generally postulated that such soils really require flexible pavements. It will be shown that such a postulate is erroneous from the standpoint of the structural engineer (though acceptable to the engineer in charge of road maintenance), and the many years experience with rigid pavements placed on such soils in Switzerland, will confirm this.

B.1 Fundamentals. On the subject of subgrade conditions, the long term behaviour of which is affected by consolidation phenomena (Figure 10), a first statement of principle applies: the primary consolidation phase requires relatively little time, whereas the secondary one extends itself over longer periods of time (e.g. years).

A second statement deals with the structural design premises of road construction. The author proceeds from the assumption that "structural design" in mentioned field means the "design of functional pavements". This implies that alterations of the grade line may be tolerated provided the operational traffic safety, the riding quality and the long term behaviour of the pavement structure (durability, maintenance needs and costs) are not affected. In other words: when roads are constructed on soft soils (which are therefore not replaced by

other materials) or when bridges are being built over such areas, grade line changes are not to be excluded. It is therefore up to the engineer to see to it that, in spite of these modifications, the standards set for operational safety and riding quality are still met.

(Functional) design criterion implies achieving the riding quality according to the following equation (2):

$$\frac{\Delta}{L^{1/2}} \leqq k \qquad (2)$$

in which

k = determinated value of the interaction between vehicle and pavement surface.

Δ = deflection amplitude of the pavement surface.

L = ondulation wavelength

Figure 10. Time settlement curve of compressible soils.

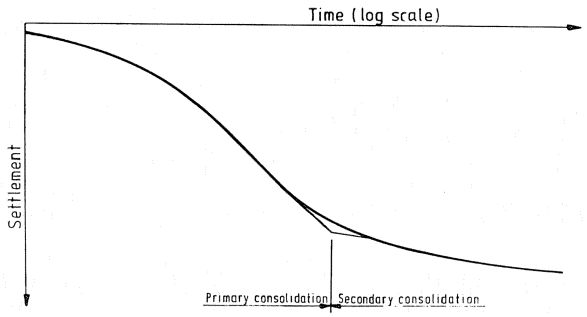
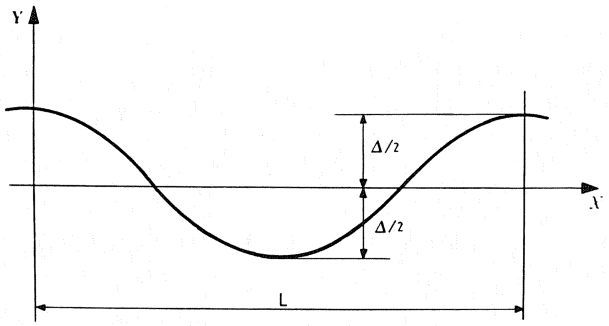


Figure 11. Pavement deflection curve.



Hence to meet requirements resulting from the equation (1), the aim of the structural design must be:

1. The selection of the appropriate materials, and
2. the determination of the structure and the thickness of each layer (this in view of the flexural thickness).

Thus the engineer is offered a real possibility to minimize Δ by solving the following complementary problems:

Effects due to soil type	Solution
Primary consolidation	is forced or cushioned by special soil mechanic measures or provisions
Secondary consolidation	Design of pavement structure: -selection of materials -sequence of layers to improve the flexural stiffness and to minimize " $\Delta_{secondary}$ "

Please note:

- "Δ" is positively affected by pavement, base and subbase courses. Hence it is possible to modify the differential settlement by achieving a pavement of the appropriate rigidity. The full amplitude of the (soil) settlement will not be reflected on the smooth pavement surface until termination of its anticipated service life.
- The duration of the consolidation ($t_{consolidation}$), however, cannot be steered by the road pavement, base and subbase courses. Subject to the functional criterion (riding quality) and the subsidiary systems of soil and pavement structures, a design technique in principle according to (3) and Figure 12 will result.

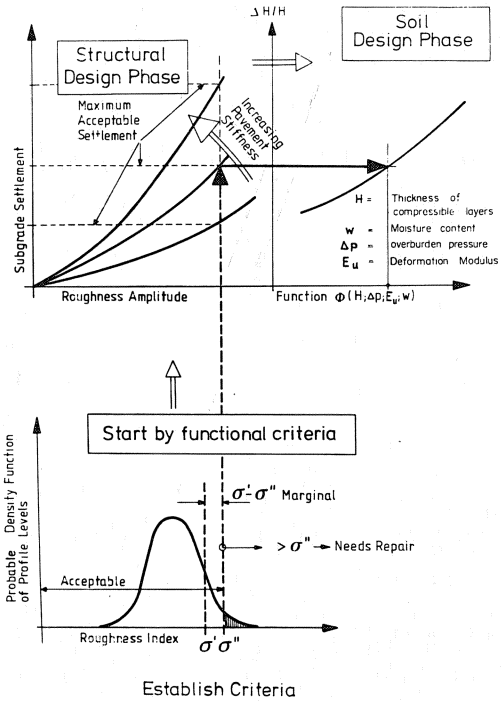
B.2 Experiences made on the Swiss Interstate Highway N3 Flums - Sargans. Since the end of the 1920's more than 20 road- and airport construction projects have been realized in Swizerland on soft compressible soils, according to technical studies and recommendations of Betonstrassen AG, who was also entrusted with their supervision. During the decades of service life, the performance under traffic of all those pavements deserve the qualification "excellent", and the maintenance costs required were minimal. The most recent and spectacular amongst mentioned projects has been the construction of the 7 km (4.35 miles) long Flums -Sargans section of the Interstate Highway N3 linking Zurich to Sargans. This section crosses the Seez Valley plain, the soil of which shows following characteristics:

1. Random scattering on the whole route of disparate soil types, the bearing capacity of which runs from poor to extremely poor.
2. Peat layers up to 8 m (314.96 in) thick.
3. Considerable compressibility under the pavement dead load and long term consolidation.
4. Easy propagation and poor dampening of vibrations.

5. None of the 2 compressible peat layers have been replaced by other materials.
6. Close vicinity of the National Railroad Line built for train speeds of 120 km/h (74.55 m/h) (Figure 13).
7. Very short construction time (2 years).
8. The highway section was opened to traffic provided with the permanent pavement.

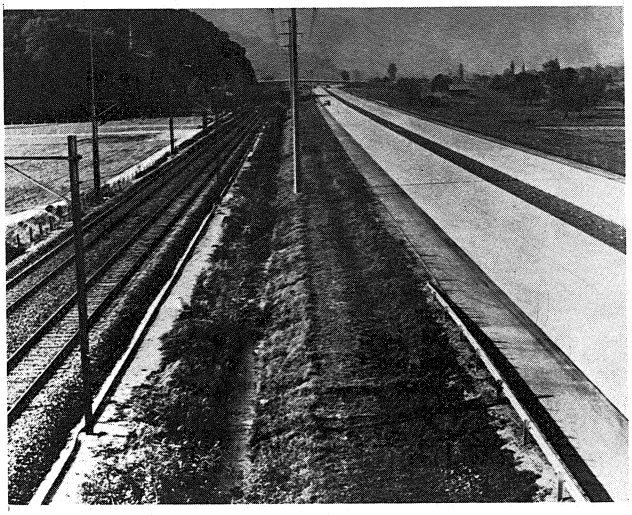
As a result of geotechnical and engineering studies, a sandwich structure was chosen (Figure 14, 10, p. 13) showing the following features:
1. High flexural stiffness
2. Lowest possible embankment thickness to shorten consolidation processes as much as possible.
3. The inertia of the mass of pavement, base and subbase courses suffices to meet the impact of vibrations.
4. In addition to its contribution to the stiffness of the structure, the cement stabilized course first placed not only functioned temporarily as a road for site traffic, but it also increased the compactibility of the embankment materials placed on top, thus achieving:
- increased compactness at placing
- increased internal friction angle, and
- increased stiffness, thus a higher modulus of deformation .

Figure 12. Relationship settlement to roughness amplitude.



The section under discussion was opened to traffic in November 1970. As expected, pronounced post construction settlements occurred on the whole length of the route subgrade, bringing about alterations of the pavement grade line (Figure 15). Amongst others a considerable settlement depression came into being after km 190 on the Flums-Sargans carriageway of the Highway N3, having a chord length of approx. 80 metres (87.44 yds) and a depth of approx. 40 cm (15.75 in) (Figures 16, 17). The development of this most dramatic depression due to differential settlement of the subgrade soil on which a CCP has been placed, was closely followed and measurements taken yielded following information:
1. Long term settlements took place between November 1970 and November 1979 (Figure 15).
2. A riding quality (present serviceability index) as shown in Figure 18.
3. The grade line of the depression is shown in Figure 19 and the tilting angles between the concerning slabs are tabulated in Table 2.
4. The longitudinal evenness of the slabs concerned (measured by means of a planograph) are shown in Figure 19.
5. The type of contraction joints (Figure 20)
6. The condition at the joints of the sides of those slabs subject to the most pronounced tilting (w_{max}) (Figure 21).
7. The joint arrisses of the slabs subject to the most pronounced tilting, hence nearest to each other (in the concavity due to the depression) were carefully examined on 13.8.1980 to locate eventual compression damages. The result was entirely negative no compression damages having been found.
8. Furthermore no blow-ups appeared during the 9 years this section is in operation.

Figure 13. Swiss National Railroad Line adjacent to the Swiss Interstate Highway N3 Flums-Sargans (10, p. 14)

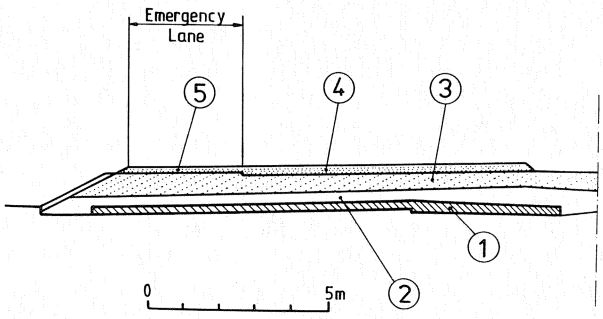


C. Summary and Conclusions

When dealing with CCP on heterogeneous, soft, compressible soils prone to differential settlements, distinction must be made between:
1. Local influences within the radius of approx. one slablength, and
2. regional influences affecting more extensive pavement areas.

The deformation characteristics pertinent to either type of influence are significantly different.

Figure 14. Sandwich structure section selected for the Highway N3 Flums - Sargans.



1 Cement stabilized material
2 Embankment
3 Untreated gravel base
4 Cement concrete pavement
5 Bituminous pavement

Figure 15. N3 Flums-Sargans: Alterations of the pavement grade line due to subgrade settlements.

Table 1. Ultimate compressive strain (ε_{cu}), resp. tensile strain (ε_{tu}) for cement concrete.

a.) $\varepsilon_{cu\ elastic} \cong 3$ o/oo (7)

$\varepsilon_{tu\ elastic} \cong 0.15$ o/oo (8)

b.) The corresponding strains due to creep:

$$\varepsilon_{creep} = \varepsilon_{elastic} \cdot \varphi_{\infty} \quad (3)$$

φ_{∞} = final creep value $\cong 2$ (9)

$\varepsilon_{cu\ creep} \cong 6$ o/oo

$\varepsilon_{tu\ creep} \cong 0.30$ o/oo

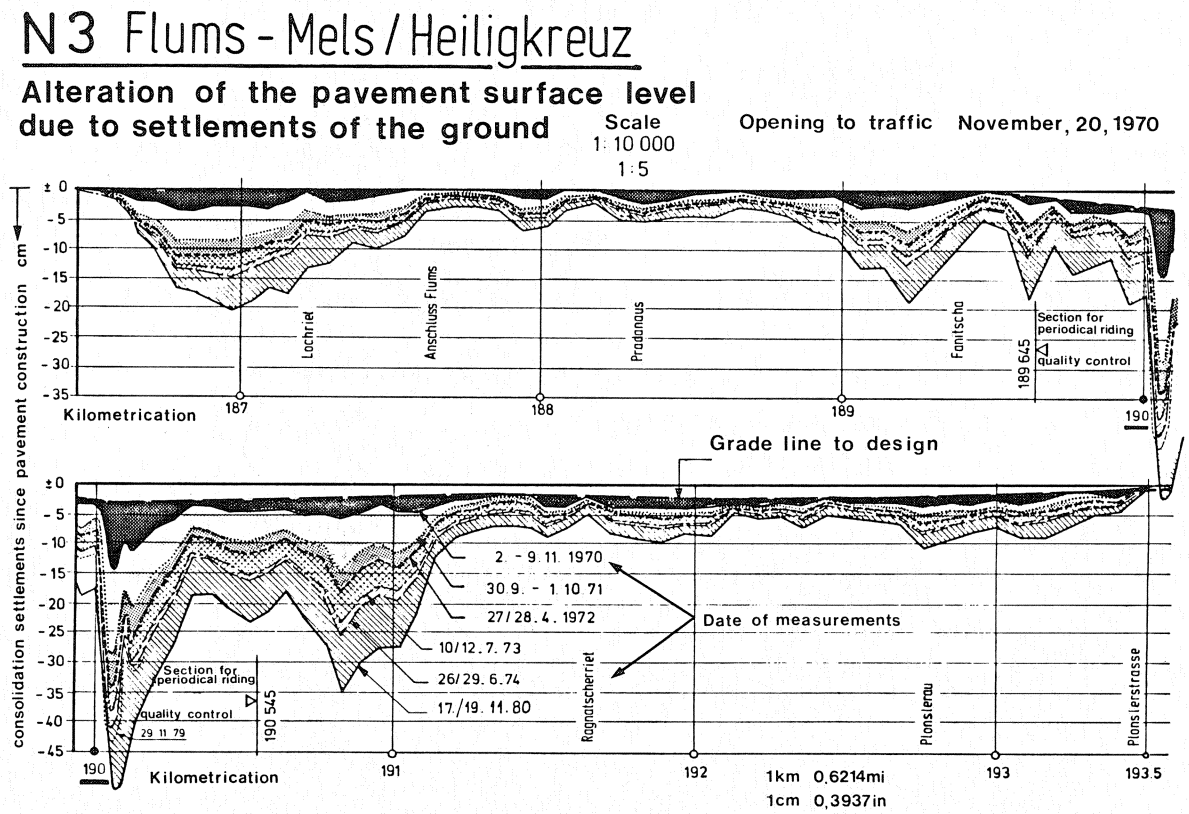


Table 2. Slab-tilting angles between adjacent slabs. (Data taken from Figure 19).

Carriageway Zurich - Chur		Carriageway Chur - Zurich	
Slab No.	Rotation angle (Reference = 100 g)	Slab No.	Rotation angle (Reference = 100 g)
1883 1882	+ 0.19	1411 1412	+ 0.33
1882 1881	- 0.07	1412 1413	+ 0.18
1881 1880	- 0.09	1413 1414	- 0.12
1880 1879	0.21	1414 1415	0.05
1879 1878	0.20	1415 1416	0.34
1878 1877	0.20	1416 1417	0.34
1877 1876	0.07	1417 1418	
1876 1875	0.15	1418 1419	
1875 1874	0.09	1419 1420	
1874 1873	- 0.13	1420 1421	0.19
1873 1872	+ 0.16	1421 1422	- 0.05
1872 1871	+ 0.23	1422 1423	± 0.00
		1423 1424	+ 0.31

Figure 16. Depression "Stofel" on the Interstate Highway N3 Flums-Sargans. (Photo Betonstrassen AG of 13 August 1980).



Figure 17. Another shot of the same depression. (Photo Betonstrassen AG of 13 August 1980)



Figure 18. N3 Flums-Sargans: Riding quality

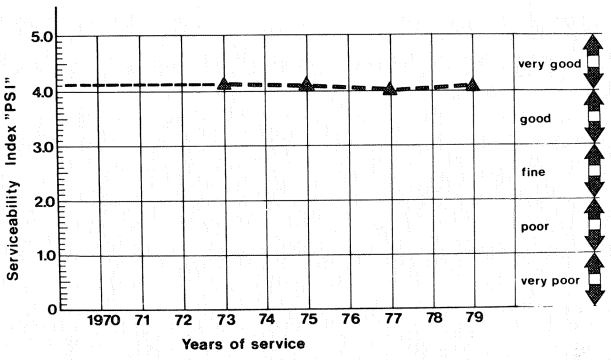


Figure 19. Pavement grade line at the "Stofel" depression and some slab-surface measurements taken by the planograph in longitudinal direction.

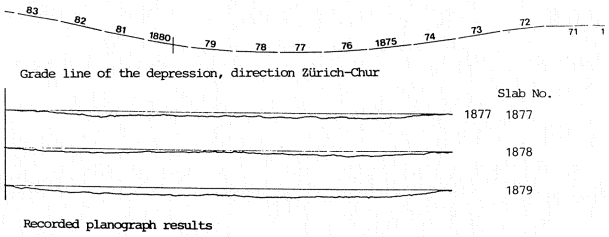
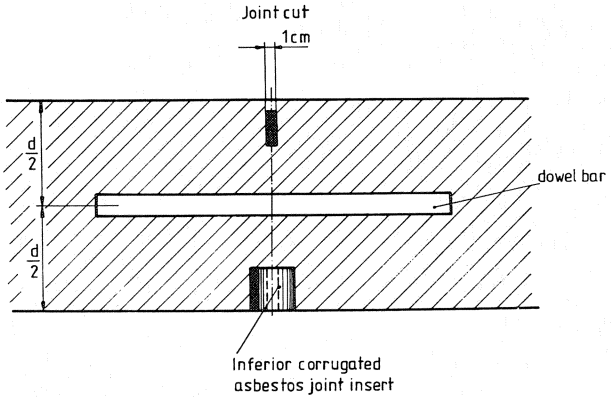
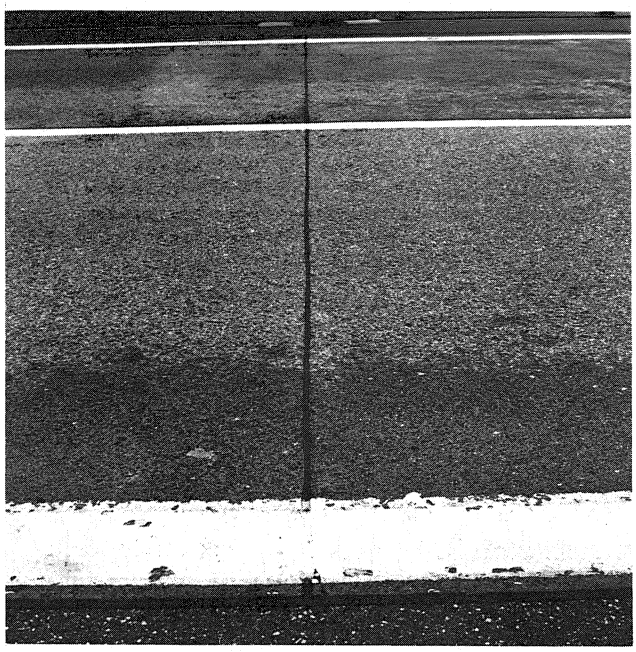


Figure 20. Type of contraction joint on the N3 Flums - Sargans



1cm = 0,3937 in

Figure 21. Condition of the joint arrisses of the slabs subject to the most pronounced tilting. (Phot taken by Betonstrassen AG on 13 August'80)

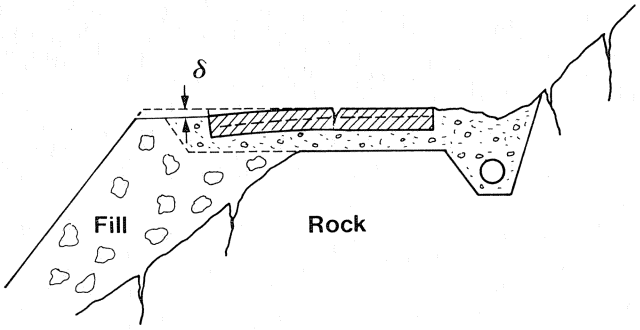


Shape of the deflection curves. Case C.1.

The deflection curve due to post-construction fill settlements affecting approx. one slablength is shown in Figure 22.

Figure 23 shows an elastically coupled slab series developing a catenary curve due to regional post-construction settlement (case C.2)

Figure 22. Deflection curve due to post-construction settlement.

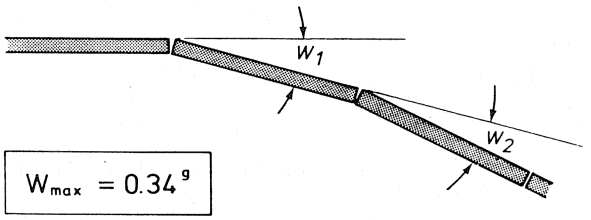


If $\delta > \varepsilon_{ultimate\ tensile\ strain}$ → CRACKING

$$\delta_{admissible} = f\ (\varepsilon_{tu}\ ;\ \text{max. admissible joint faulting effect}) \quad (4)$$

Due to δ → Slab warping

Figure 23 . Elastically coupled slab series developing a catenary curve due to regional post-construction settlement.



$W_{max} = 0.34^{g}$

$\delta_{admissible\ in\ the\ longitudinal\ section} = f\ (\text{structural integrity; operational safety})$ (5)

Applied to the section Flums-Sargans equation (5) yields:

$\delta_{max} = 3.35\ cm/_{6.25cm}\ (132\ in/_{256\ in})$

being $w_{max} = 0.34^{g}$

referred to the slablength of 6.25 metres (246 in).

Experiences made at the depression "Stofel" of the N3 Highway section Flums-Sargans, show that several criteria are involved when assessing $w_{admissible}$ and $\delta_{admissible}$.

1. The criterion "riding quality", determined by means of the "neuer Winkelmesser ISETH" shown in Figure 24 (4, p. 11).

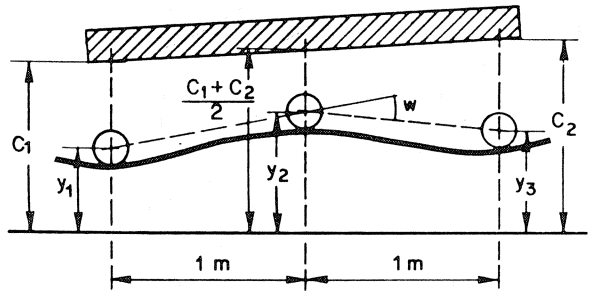
Figure 24 . New ISETH evenness measuring equipment.



A sketch representing the method according to which the evenness is measured with the new ISETH equipment is shown in Figure 25 (4, p. 12).

Figure 25 . Diagram of the method of evenness assessment with the "neuen Winkelmesser ISETH"

$$w\ [‰] = 2y_2 - y_1 - y_3$$



$$\left(w_{max.\ on\ N3\ Flums\text{-}Sargans}\right) = 5.34\ ‰ \ll w_{admissible}$$

2. Criterion "operational safety". Already in the planning stage care must be taken that sufficient surface drainage is provided, even if depressions should appear, to prevent water collecting conducive to hydroplaning.

3. Criterion "structural safety" of the CCP-slabs. In the case of the N3 Highway section Flums-Sargans no damages at all due to slab tilting (lengthwise) have been found after almost 10 years service.

According to the experiences pertinent to the afore named "Stofel" depression, due to post-construction settlement, the maximum admissible degree of differential settlement $\left(w_{admissible/max}\right)$, in C.1, can be defined as follows:

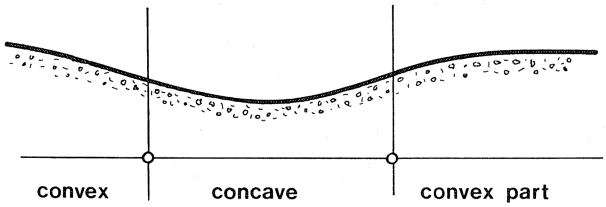
1. From the point of view "riding quality":

$$6\ ‰ < w_{admissible/max} < 10\ ‰$$
(for Switzerland)

$$6\ mm/metre\ (0.006\ in/1in) < \delta_{admiss./max.} < 10\ mm/metre\ (0.01\ in/1in)$$

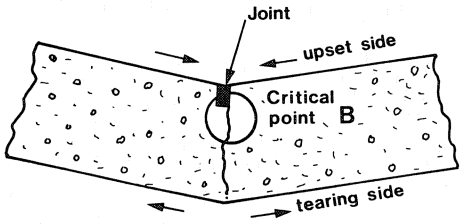
2. From the viewpoint "structural soundness": the general deflection curve of a depression due to post-construction settlement is shown in Figure 26.

Figure 26. General deflection curve of a depression.



The critical condition at the convex and at the concave parts of the depressionis shown in Figure 27.

Figure 27. Critical points of the depression shown in Figure 26.



$\varepsilon_{critical\ for\ the\ whole\ deflection\ curve} = \varepsilon_{cu} = 6\ ‰$

$$\delta_{admissible\ structurally} \leq 6\ mm/metre\ (0.006\ in/1in)$$

Hence and finally

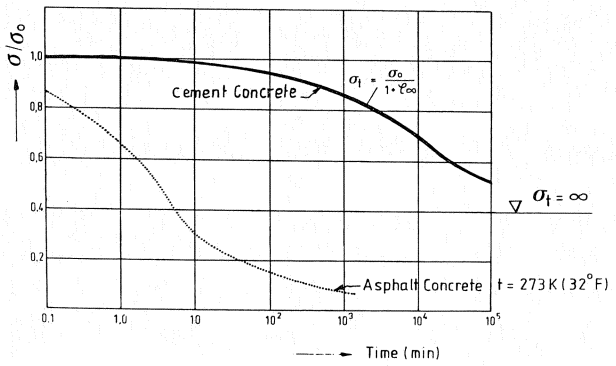
$$\delta_{admissible} \cong 6 - max.\ 10\ mm/metre\ (0.006 - max.0.01\ in/1in.)$$

In the case C.1 the CCP requires special remedial steps (see Figures 3, 4 and pavement design princi-

ples).

In the case C.2 the CCP (rigid pavement) is highly suitable,compared with a flexible pavement, for the reasons that, unlike bituminous material, cement concrete offers high resistance under long term loading (creep processes) (Figure 28) (5, 6).

Figure 28. Master curves of stress relaxation for Asphalt and Asphalt-Concrete



In view of the slow development of long term deformation processes a "creep modulus" (E') applying to the materials concerned has to be introduced into the structural design procedure. For cement stabilized materials and cement concrete

$$E' \sim \frac{E}{3}$$

applies. Note the influence of the temperature on the relaxation process of bitumen bound materials, the creep resistance of which decreased still more rapidly at high temperatures during tests. This actually means:

The pavement structure rigidity will minimize the effect of differential settlement in the subgrade. The magnitude of pavement deflection decreases with the increase of the creep modulus and the pavement thickness. The rigid pavement spans a bridge over non homogeneous terrain areas, thus forcing the creation of an "average" soil behaviour pattern similar to the premises of the pertinent design methods based on the theory of elasticity.

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