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Bonded Concrete Bridge Pavements in Switzerland

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Bonded cement concrete pavements have been successfully constructed on more than 150 long, medium, and short bridges in Switzerland during the past 15 years. Traffic in Switzerland never rolls directly over the bridge structure (the deck) but always over a bridge pavement (overlay) instead. The concrete used in bridge construction is generally not proof against combined frost-thaw-salt action. The abundant use of deicing chemicals in winter increases the risks of damage to structural concrete and steel reinforcement. In addition, today's road traffic (a) subjects carriageways to horizontal shearing forces, (b) demands high standard riding quality of pavements, and (c) results in pavement wear caused by abrasion (pronounced wear in the case of studded tires). The criteria required of bonded concrete bridge pavements in Switzerland are presented. The results of on-site measurements taken on 13 test bridges prove that (a) crack-free bonded pavements perceptibly increase the bending stiffness of bridges and (b) use of bonded concrete pavement allows economies in longitudinal steel reinforcement of 7 percent or more depending on the bending stiffness of the bridge and up to 40 percent in transverse reinforcement if the pavement is fully bonded to the bridge deck. Rules to be followed in construction of such bridge-deck pavements are also given.

The subject of bridge pavement construction in Switzerland is conditioned by three factors: (a) the extraordinary relief of the earth's crust in Switzerland, (b) developments in bridge construction, and (c) significant changes that have occurred in the past 15 years in the realm of keeping roads serviceable (i.e., snow- and ice-free) in winter.

TOPOGRAPHY

The Swiss road construction engineer has to face an exceptionally dynamic relief of the earth's crust. This results in the large number of bridges found in very small geographic areas of the country. Bridge requirements per route kilometer in Switzerland are as follows:

1. In mountainous regions, 0.55 to 1.55 bridges/route-km (2 to 10 percent of route length);
2. In hilly regions, 0.30 to 0.60 bridge/route-km (5 to 28 percent of route length); and
3. In the plains, which are crossed by streams, canals, and lakes, 0.5 to 0.75 bridge/route-km (0.5 to

13 percent of route length).

These characteristics make Switzerland a classic bridge-building country.

DEVELOPMENTS IN BRIDGE CONSTRUCTION

Prestressed concrete, which came into use in Swiss bridge construction around 1960, made it possible to achieve practically crack-free structures. The prestressed concrete system, however, requires high-grade steel reinforcement, which is more vulnerable to the action of corrosive agents.

ROAD SERVICEABILITY IN WINTER

Since about 1965, deicing salts (mainly of the sodium chloride group) have been used to keep Swiss roads snow- and ice-free in winter. No sufficient frost-resistant concrete has yet been achieved in Swiss road construction. Inspections of concrete roads in Switzerland have shown that

1. No frost damage was found on such roads before deicing salts were frequently used (1960) and
2. Random scaling damages started to appear on these pavements around 1965 as a result of the extensive use of deicing salts.

In relation to concrete durability, therefore, frost-thaw-salt impact is stronger than frost impact. As a result, empirically proved air entrainers have to be added to all cement concretes used in Swiss pavement construction, and compliance is checked by means of stringent quality controls (11).

BRIDGE-DECK-OVERLAY CONSTRUCTION CONCEPTS IN SWITZERLAND

Bridges are not operated unpaved in Switzerland. This seems to be a significant difference between Swiss con-

Figure 1. Pore distribution, morphology, and frost-thaw-salt resistance of concrete for two bridges.

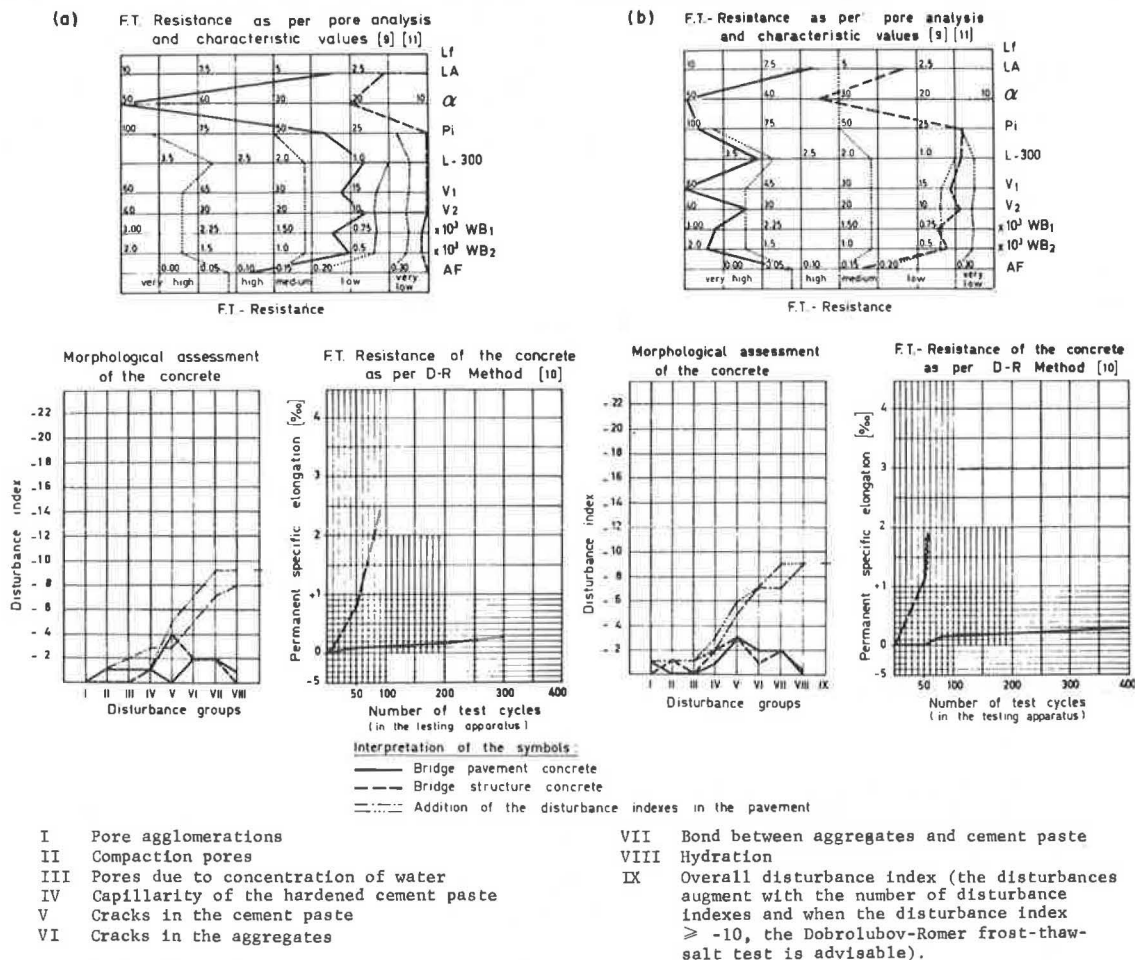
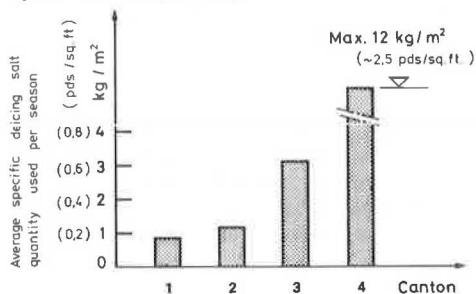


Figure 2. Quantities of deicing salts used per season by four districts (cantons).



struction concepts and those applied, at least until today, in the United States. The Swiss concept—that bridge traffic should roll over proper pavements—is based on several considerations.

The road-pavement performance demanded by modern traffic requires that particular attention be focused on the horizontal forces caused by vehicle braking and acceleration. To counteract these forces, resistance is required against (a) pavement surface deformation, which mainly occurs in pavements made of thermoplastic materials; and (b) skidding. Other resistant properties required in a pavement are

1. Riding quality (on which heavy demands are made),

2. Imperviousness to climatic (frost-thaw) influences,
3. Resistance to abrasion, and
4. Resistance to corrosion caused by deicing agents.

In the past, the concrete used for bridge construction (including the bridge deck) was non-air-entrained, and its resistance to frost-thaw-salt effects was generally poor. Figure 1 shows pore distribution, morphology, and frost-thaw-salt resistance for two bridges. Figure 2 shows in detail the quantities of deicing salts used.

Because the surface on which the traffic rolls is the only part of the bridge directly exposed to these forces, in Switzerland and throughout Western Europe the bridge structure is protected by means of a specially designed element: the pavement. The major bridge paving systems used are shown in Figure 3. An examination of these systems, which differ in principle from one another, reveals the following facts:

1. The construction of an overlay (bridge-deck pavement) adds weight (permanent load) to the structure.
2. In the stress analysis by the bridge design engineer, all unbonded overlays mean dead weight. Although such systems create a certain load distribution according to their stiffness, they do not contribute to load bearing.
3. In the case of a shear-resistant bond (the cement concrete pavement system shown in Figure 4), the pavement not only adds additional weight to the bridge structure but also considerably increases its transverse and longitudinal stiffness.

Therefore, in any comparative economic study of bridge construction systems, it is necessary to prove to what extent a pavement type contributes not only to the durability of the bridge structure but also to its load-bearing capacity. In this way, possible savings in steel reinforcement can be determined.

Bonded Paving Systems

The two bonded paving systems shown in Figure 4 require placement of the pavement at different stages of construction. The system referred to as monolithic requires placement of the pavement while the deck is still plastic. Although this approach is sound from an engineering viewpoint, it is hampered by (a) the impossibility of slipforming and (b) the difficulty and the cost of conventional placement (by means of a paver moving on rails), which is thus feasible only on short bridges. In the two-layer system (Figure 4), pavement is placed after hardening of the deck concrete. Because of the feasibility and the moderate placement costs of this system, more than 150 bridges of all sizes [none shorter than 300 m (986 ft)] have been paved according to this method in Switzerland during the last 15 years.

Stress

The characteristics of the transverse and longitudinal stresses for the two static bridge-deck conditions to be analyzed—unpaved and paved—are shown in Figures 5 and 6 (1). In the figures, $\sigma(g + V\infty)$ = stresses caused by dead weight and prestressing; $\sigma(g + V\infty + p)$ = stresses caused by dead weight, prestressing, and traffic load; and d_b = concrete pavement thickness. The paved and unpaved conditions differ from one another in the levels of S_1 and S_2 (safety factors) of the neutral axes in the cross section, shown in Figure 6. Figure 7 shows moment of inertia with and without concrete pavement in the Felsegg Bridge over the Thur River (12).

As a consequence of the shear-resistant bond between the pavement and the bridge deck, deformation of the bridge deck causes stresses in the pavement (Figures 5 and 6), a factor that must be considered in designing an overlay.

CRITERIA FOR TWO-LAYER PAVING SYSTEMS

The suitability of the two-layer paving system shown in Figure 4 is determined by whether (a) there is sufficient permanent bond between the pavement and the bridge deck and (b) the pavement offers sufficient protection to the structural reinforcement against the corrosive action of deicing agents.

Fatigue Tests

Fatigue tests have been conducted at the Swiss Federal Materials Testing Institute (EMPA) (2, 3) for the purpose of determining

1. The efficiency of the bond between the bridge deck and the pavement under repeated loadings and
2. The ultimate strength of the bond.

These tests complement on-site load tests conducted on the St. Margrethen twin bridge (4). The aim of the EMPA tests was to clarify the behavior of the combined system—the pavement and the bridge deck on which it has been placed—under any number of traffic load cycles.

Models

Figure 8 shows the two mock bridge-deck slabs that, with their respective pavements, were constructed in the laboratory. Each was as thick as a normal, paved bridge deck. The pavement of slab 1 was designed without considering any load-bearing participation. It was only meant to function as a pavement and, in the structural design, its weight was considered as a permanent dead load. Slab 2, on the other hand, was designed as a genuinely combined system (bridge deck with bonded cement concrete pavement). The concrete pavement was considered not only a dead weight but also an agent cooperating with the bridge deck to bear traffic loadings. For this purpose, steel reinforcement was designed for the pavement with additional reinforcement over the midcolumn to resist the negative bending moment.

Procedure

In selecting the disposition and the size of the test loads, care was taken to approximate as closely as possible the conditions of the in situ bridge structures. A strip load of 19 Mg (21 tons) was applied to each slab at a cyclical frequency of 4 Hz (equivalent to approximately 250 cycles/min). Stronger loading demands than would occur in reality were intentionally made on the test slabs for greater certainty in the results.

Results

Under the stresses caused by 2 million load cycles, the bond remained unaffected. One of the two test slabs was also submitted to another 2 million loading cycles (the total load of which was 125 percent of the original load) and then to a further 2 million cycles (the total load of which amounted to 150 percent of the original load). Even after the last test, the bond did not appear to be weakened.

Tests to determine the ultimate strength of both slabs yielded the following factors of safety (S): $S_1 = 5.2$ (slab 1) and $S_2 = 4.0$ (slab 2). The safety factor can be defined as follows:

$$S = (P_u + P_p)/(N + P_p) \quad (1)$$

where

- P_u = ultimate load,
- P_p = equivalent load expressing the influence the permanent load of each whole slab exerts on the respective N location, and
- N = traffic load [19 Mg (21 tons)].

Shearing Stresses in the Bonding Zone

In a load-bearing construction system consisting of two bonded, load-bearing elements that resist shearing strengths, it is important to determine the shearing stresses in the contact zone. If interdependent dilatation exists by definition in either one of the bonded elements, stresses caused by shearing forces cannot be measured but can only be assessed in theory. This also applies to residual stresses caused by shrinkage with and without creep effects.

Maximum shearing stresses (τ) of 2.95 and 2.72 MPa (428 and 395 lbf/in²) respectively were assessed in the two test slabs after cracking had occurred, under carrying load and dead weight, by determining the course of the transverse strength according to the elastic or plastic method (3). Data produced by other authors on cracking caused by shearing force (τ rupture) in bonded

Figure 3. Three major bridge-paving systems used in Switzerland.

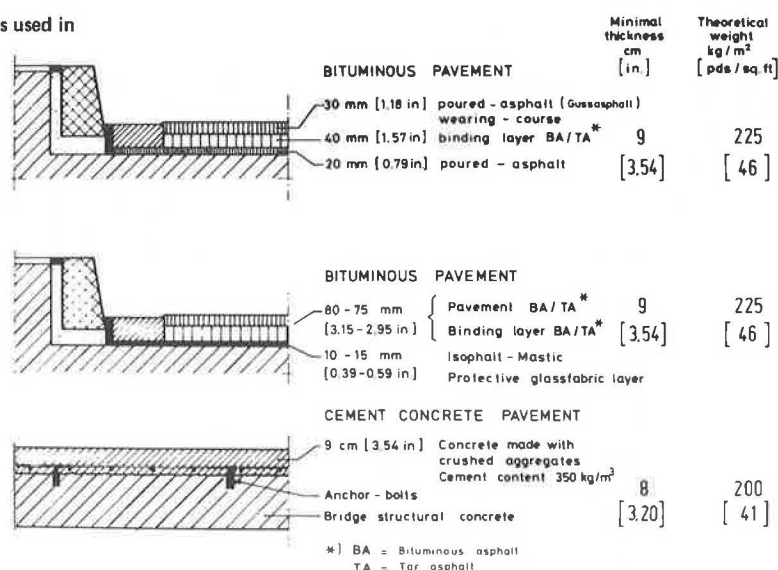


Figure 4. Two systems of bonded concrete pavement construction.

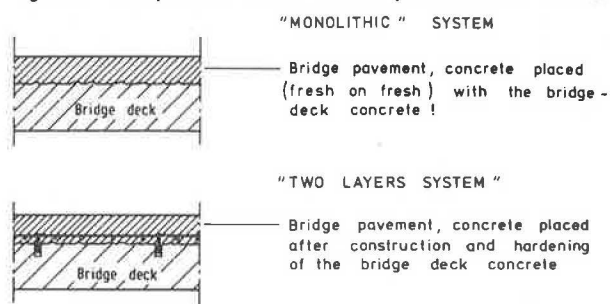
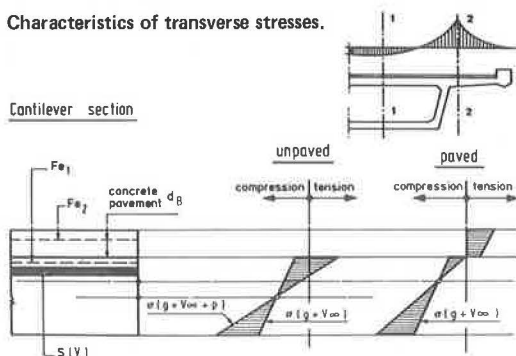


Figure 5. Characteristics of transverse stresses.



systems with cracked cross sections contradict these findings. The table below gives test results reported by various other sources for the shearing strength of bonded concrete elements of different ages (1 MPa = 145 lbf/in²):

Source	Shear Strength (MPa)
ACI-ASCE (4) (smooth to rough bonding surface)	0.55 to 2.21
Hanson (5) (smooth to rough bonding surface)	2.07 to 2.45
Saemann and Washa (6)	2.45
Basler and Witta (7)	2.45

To assess the actual bonding strength in bridge structures, values obtained from uniaxial strength measurements have been published by Wilk (8). These

Figure 6. Characteristics of longitudinal stresses.

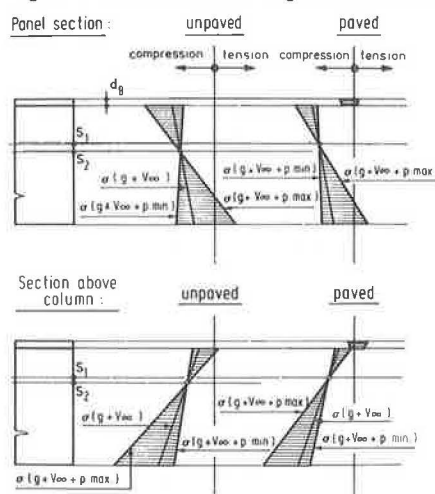
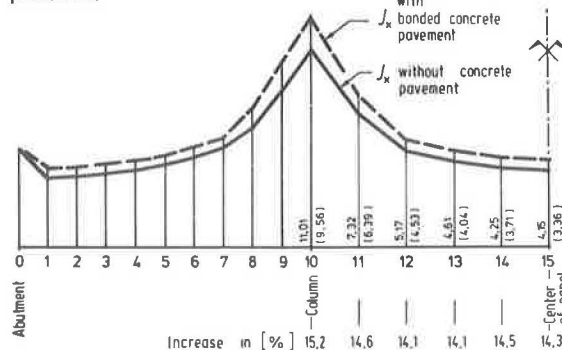


Figure 7. Moment of inertia with and without concrete pavement.



values were obtained from EMPA tests on 7.2-cm (2.8-in) diameter cones. The tests were made to establish the uniaxial tensile strength of the bond when it is not influenced by anchors. The results are shown in Figure 9. Figures 10 through 13 show some interfaces of fractures that resulted from the same tests.

Corrosion Tests

Except for some light damage caused by scaling, no other damage was found on the bridge pavements constructed according to the two-course bonded construction system (Figure 4). These results show that efficient protection is provided by the two-course system against the corrosive action of deicing agents.

Quantitative data on the sealing efficiency of concrete pavements were obtained by taking drilled-out test cores, each of a diameter $\phi = 7.2$ cm (2.83 in), from eight bridges (Table 1) at the end of the winter of 1974 and measuring their specific chloride contents at various depths. The range of the values measured is shown by the hatched zone in Figure 14, which indicates that the highest chloride content measured in the contact zone does not exceed 0.025 percent by weight—the limit set by German Industrial Standard Specifications (DIN) No. 1045 for the chloride content in prestressed concrete. This is of primary importance in view of the fact that, immediately underneath the pavements, bridge decks in Switzerland are generally constructed with non-air-entrained concrete and in most cases, therefore, are without frost-thaw-salt resistance. This is proved by the results of many microscopic pore analyses, morphological examinations of concrete struc-

Figure 8. Disposition of loads on two test slabs.

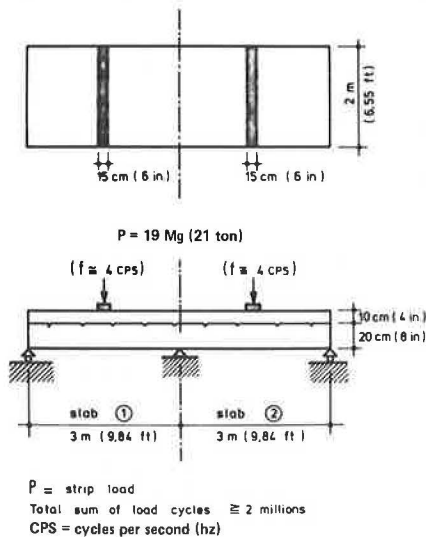


Figure 9. Distribution of uniaxial tensile strength (β_z).

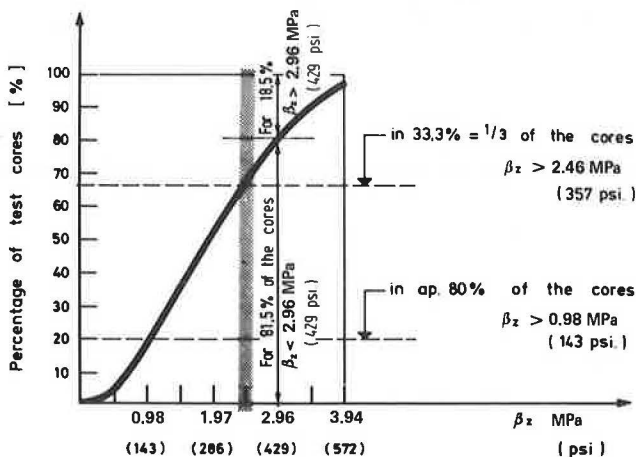


Figure 10. Results of uniaxial tensile strength tests: rupture running across whole mortar course [$\beta_z = 0.69$ MPa (100 lbf/in²)].

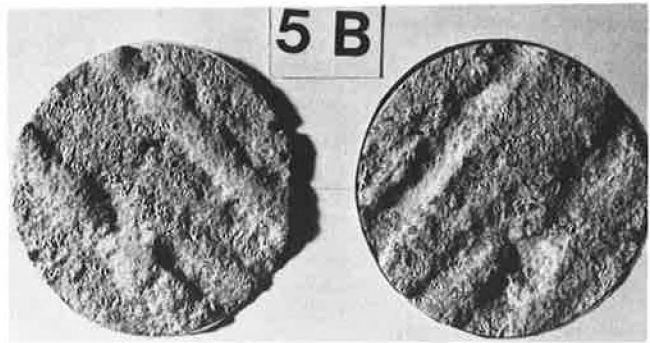


Figure 11. Results of uniaxial tensile strength tests: rupture running across whole mortar course [$\beta_z = 1.08$ MPa (157 lbf/in²)].



Figure 12. Results of uniaxial tensile strength tests: rupture running across many coarse and fine aggregates with no fine mortar in contact zone [$\beta_z = 2.38$ MPa (345 lbf/in²)].



Figure 13. Results of uniaxial tensile strength tests: characteristic surface of rupture [$\beta_z = 3.04$ MPa (441 lbf/in²)].

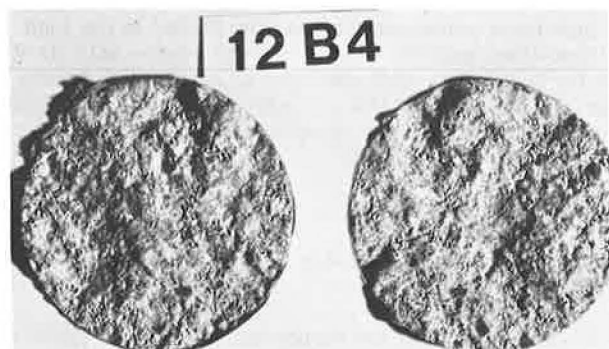


Table 1. Location and construction data for bonded cement concrete bridge pavements on which corrosion tests were conducted.

Bridge or Viaduct	Construction Period	Length of Bridge (m)	Pavement Thickness (cm)	Spacing of Transverse Joints (m)	Age of Pavement at First Salt Treatment (years)
Rheinbrücke N13 Grisons, St. Gall	1962	210	8 to 10	5	1
Zwillingsbrücke N13, St. Gall	1962 to 1964	125	8 to 10	5 to 6	1
Lehnenviadukt N13, St. Gall	1962 to 1964	800	8 to 10	5 to 6	1
RA No. 20, Pont de Larrevoin	1964 to 1965	212	8 to 10	8	1
Kanalbrücke N1, Aargau	1966 to 1967	110	8 to 10	5 to 6	1
Goldachviadukt N1, St. Gall	1971 to 1973	480	8 to 10	Day joints only	1
Nönnentobelbrücke T13, St. Gall	1972 to 1974	140	8 to 10	No joints	1
Attinghausenviadukt N2, Uri	1973	160	8 to 10	No joints	1

Note: 1 m = 3.3 ft; 1 cm = 0.39 in.

Figure 14. Chloride content limits measured in concrete pavements of eight bridges.

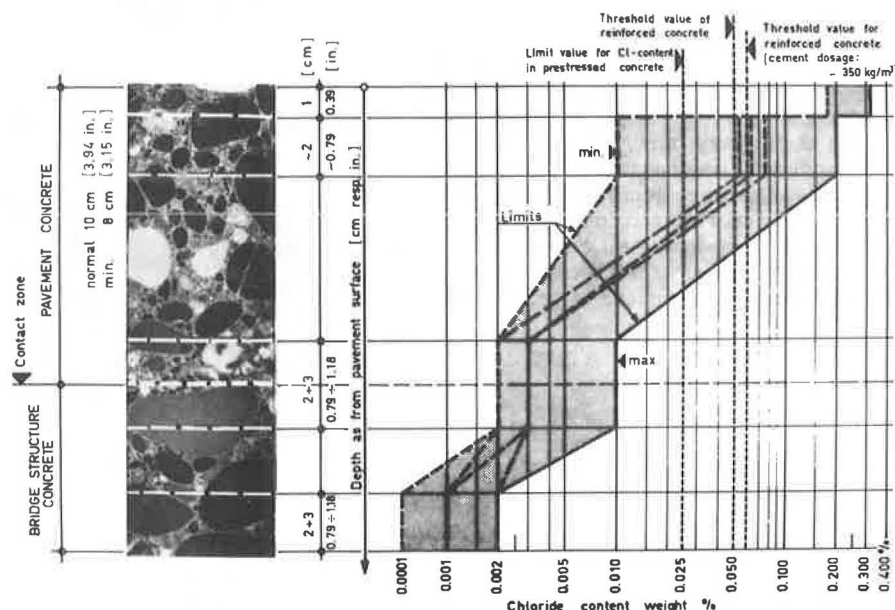
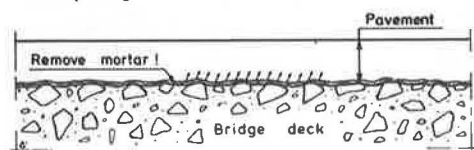


Figure 15. Desirable roughness of bridge surface before paving.



ture (i.e., of the quality of the bond between aggregates and matrix and cracks and capillarity), and tests of frost-thaw-salt resistance using rapid cycles according to the Dobrolubov-Romer (D-R) method (Figures 1 and 2). These three types of tests and their results are discussed elsewhere (11).

In morphological analysis, the higher the total index number for a certain structure, the higher is the loss in frost-thaw-salt resistance. In the rapid-cycle (D-R) test for frost-thaw-salt resistance, concrete is frost-thaw-salt resistant if the permanent longitudinal dilatation of its prismatic test specimen reaches 1 percent after 360 or more cycles.

CONSTRUCTION RULES

Rules for constructing bonded bridge-deck pavement are as follows:

1. The surface of the structural concrete of the

bridge deck must be absolutely sound, show a high degree of roughness (Figure 15), be scrupulously clean, and be kept wet for 48 h before pavement construction.

2. The deck must not be vibrated during paving (for instance, by heavy vehicle traffic) because concrete passes through a very critical phase during the first 4 to 12 h after placement. At this stage, deformation capacity is at its absolute minimum (Figure 16), and any disturbance causing deflections stronger than those allowed can result in irreversible fractures.

3. Immediately before the concrete pavement is placed, the bridge-deck surface is treated with a synthetic resin emulsion (on a polyvinyl or latex base) to decrease the elasticity modules below their normal level in the contact zone and thus reduce the stresses caused by differential shrinkage (16). Mortar left after the removal of the coarse aggregates from the pavement concrete is then rubbed into the bridge deck surface by means of brooms. The thinner the cement paste coating is, the better the bond will be (Figures 9 through 12).

4. To counteract the effect of the shearing stresses caused by shrinkage and creep, the pavement panels are fastened to the bridge by means of 2 to 3-m (6.5 to 9.8-ft) anchors placed along their edges (Figures 3, 4, and 17).

5. The pavement thickness must not be less than 8 cm (3.15 in.).

6. In zones of negative flexural moments, the pavement reinforcement must be increased according to careful calculations.

7. Adequate bridge pavement curing is of primary

Figure 16. Capacity of strain at failure of freshly placed concrete.

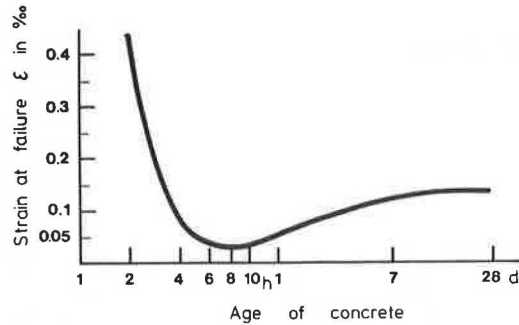
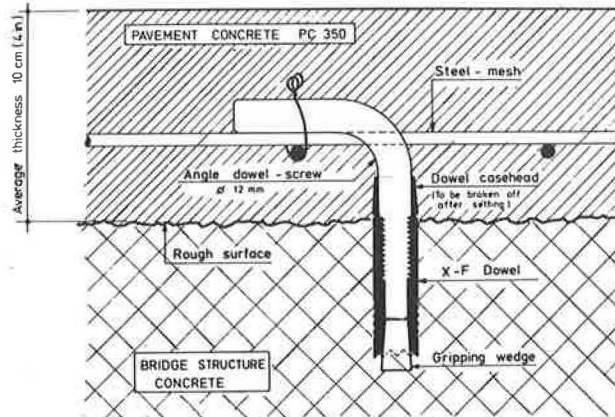


Figure 17. Type of anchor used to fasten pavement panels.



importance. In addition to the application of a curing compound, it is advisable to protect the concrete for at least 48 h after placing by means of wet burlap.

CONCLUSIONS

Fatigue tests confirmed the results of previous on-site measurements (12, 13, 14), showing that, in the case of a two-course bonded paving system subject to the maximum cyclical static loading allowed, the pavement will always perform its share of the load-bearing function of the structure—provided, of course, that the technical rules (4) have been observed during construction. This joint load bearing by the bridge and the pavement must therefore be fully considered in structural design.

Bridges must be designed with full knowledge of all the advantages offered by a bonded pavement. In its turn, the pavement must be designed according to its load-bearing contribution to the bridge. Because of its load-bearing capacity, a bonded pavement offers cost-saving possibilities that cannot be offered by pavements constructed according to other design systems (14). In fact, bridge construction costs, which of course vary according to the project design and the longitudinal and transverse stiffnesses required (Figure 7), could at times be reduced by an amount equivalent to the paving costs.

Protection of the bridge structure by a frost-thaw-salt-resistant pavement of the best possible impermeability is needed. Measured chloride contents and penetration depths (8) indicate that bonded concrete pavements offer effective and durable protection against frost-thaw-salt penetration without the use of special insulation layers.

The long-term behavior of the bond in certain bridge structures can be controlled by means of ultrasonic equipment (15).

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