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Strength and Behaviour of Repaired Concrete Bridge Decks

Comportement et résistance de dalles de ponts en béton, après réparation

Festigkeitsprobleme reparierter Fahrbahnplatten aus Beton

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SUMMARY
Deteriorated concrete due to mainly de-icing salts and freeze-thaw cycles is nowadays removed from concrete bridge decks in Sweden by using the water-jet technique. It is shown that a repaired concrete bridge deck can resist stresses due to differential shrinkage because of the favourable effects of concrete creep. It is necessary to carry out removal, casting and compacting operations carefully and to make sure that all loose particles are removed from the surface before casting of the new concrete topping. Composite concrete slabs fulfilling these demands have developed as high ultimate loads as homogeneous slabs.

RÉSUMÉ
La technique du jet d'eau sous pression est employée en Suède pour nettoyer les dalles de ponts de bétons détériorés suite à l'action des sels de déverglaçage et à l'action des cycles gel-dégel. Après réparation, un tablier de pont en béton peut résister aux contraintes dues au retrait différentiel grâce aux effets favorables du fluage du béton. Il est nécessaire de réaliser avec soin les opérations de nettoyage, de coffrage et de compaction et de s'assurer que toutes les particules ont été enlevées de la surface du joint de bétonage. Les dalles de bétons composites réalisées selon cette méthode présentent une résistance ultime semblable à celles de dalles homogènes.

ZUSAMMENFASSUNG
Hauptsächlich durch Tausalz und Frost-Tauwechsel beschädigter Beton von Fahrbahnplatten wird heute in Schweden mit Hilfe der neuen Waterjet-Technik entfernt. Es wird hierin gezeigt, dass eine reparierte Fahrbahnplatte aus Beton den durch unterschiedliches Schwinden verursachten Spannungen wegen der günstigen Effekte des Betonkriechens widerstehen kann. Voraussetzung ist ein sorgfältiges Arbeiten beim Entfernen, Betonieren und Verdichten, damit die Fuge vollständig frei ist von losen Partikeln. Verbundplatten, die diese Forderungen erfüllen, haben ebenso hohe Bruchlasten erreicht wie homogene Betonplatten.

1. INTRODUCTION - IDENTIFICATION OF THE PROBLEMS

Increasing traffic loads combined with de-icing salts and repeated freeze-thaw cycles have caused extensive damage to bridges in Sweden and abroad. Deterioration starts at the surface and progresses into the structure with carbonisation and with increase in chloride content. The deteriorated concrete has to be removed and replaced by a new concrete topping, which leads to a composite concrete structure. In order to ensure full structural interaction between old and new concrete it is necessary to have good bond between them.

Concrete removal by means of high pressure water-jets is a new technique. The use of the water-jet technique - also called hydrodemolition - has increased rapidly in recent years. The water-jet technique creates a clean and rough contact surface. It is furthermore believed that the technique does not induce any microcracks into the remaining concrete. Thus the new technique ought to further a good bond between old and new concrete.

Since 1982 the bond between old concrete and a new concrete topping has been studied at the Department of Structural Mechanics and Engineering, Royal Institute of Technology in Stockholm. Tests on beams [6] and slabs [8] have been carried out in order to study the behaviour and load-bearing capacity of composite concrete structures.

According to the Swedish "Regulations for Concrete Structures" BBK 79 [1] a composite concrete member may be designed as a monolithic member only if there is reinforcement or a compressive force passing across the contact surface (in CEB [2] and FIP [4] called interface). Traditionally the shear capacity is ensured by stud bolts. Showing that shear capacity is ensured without stud bolts will lead to a considerably more economical solution for repairing bridge decks.

Differential shrinkage is an additional loading case to be considered for a composite concrete structure such as a repaired concrete bridge deck consisting of concrete cast at two different times. Differential shrinkage is the difference between shrinkage strains of new and existing concrete. In order to estimate the residual stresses caused by differential shrinkage it is necessary to study not only concrete shrinkage but also concrete creep. Since both concrete shrinkage, concrete creep and concrete strength are dependent on time, the effects of the differential shrinkage have been studied theoretically as functions of time and compared with the test results in [7] and [8].

2. THE BOND BETWEEN OLD AND NEW CONCRETE

Briefly it can be said that the bond between old and new concrete is dependent on the strength of the old concrete, the properties of the new concrete topping, the treatment of the contact surface, how the topping is cast and the curing conditions. All of these causes are in turn dependent on a number of factors. Extensive investigations are needed to determine the influence of the numerous factors completely.

In this study different kinds of contact surfaces have been investigated. The water-jet technique has been compared with the traditional method of concrete removal by means of a pneumatic hammer and with sandblasting. The differences between the three methods are mainly roughness differences and differences in the extent of induced microcracks.

After terminated tests pull-off tests were carried out in order to determine the tensile strength of the bond between old and new concrete. In the case of an contact surface chipped by a pneumatic hammer the mean value of the failure stress was about 1 MPa. The explanation of the rather low tensile strength is probably that the chipping induces microcracks in the residual concrete. In the cases of water-jetted or sandblasted contact surfaces the mean value of the failure stresses was more than 2 MPa. The standard deviation was less and the number of failures at the contact surface was smaller in the case of the rough water-jetted contact surface, why it can be concluded that the probability of a good bond is the greatest if the contact surface is water-jetted. On the other hand the results imply that less importance ought to be attached to the influence of the roughness on bond.

Further information about the influencing factors has been obtained from field tests. A total number of more than 150 pull-off tests on twenty bridges are reported and discussed in [8]. The obtained failure stresses varied mainly between 1 and 2 MPa, but some very low values have also been found. Two main causes have been noticed for the low pull-off strengths: (1) Loose particles and dust from the removal of deteriorated concrete had not been completely removed and (2) compacting of the concrete topping had been bad. The use of the water-jet technique leads to a very rough surface. Consequently, the compacting is particularly important in order to prevent the creation of air pockets in the surface depressions.

The shear strength of the bond between the old and new concrete is often more interesting than the tensile strength. In order to determine the shear strength, a number of cylinder cores were drilled out of the concrete slabs. The cylinders were loaded to failure by a torsional moment. The obtained failures stresses were about 4 MPa. If similar results can be obtained in field it ought to be possible to permit shear stresses between old and new concrete in a repaired concrete bridge deck equal to the current design concrete tensile strength. Some preliminary results from field tests show failure stresses varying between 3 and 4 MPa.

3. EFFECTS OF THE DIFFERENTIAL SHRINKAGE ON COMPOSITE CONCRETE STRUCTURES

3.1 Tests on beams

Four composite concrete beams of different length were tested. The two longest beams (6 and 8 m) were supported on air-bags and the other two (1.1 and 2.1 m) were simply supported on three rigid supports.

A repaired concrete bridge deck was simulated as follows. The top surfaces of the four beams, all more than two years old, were chipped by a pneumatic hammer resulting in rough surfaces on which the concrete toppings were cast. The ratio between the depth of the topping and the total depth of the beam was in all cases 2/7 and the total depth was 0.35 m. The tests were carried out outdoors in a tent between September 1983 and November 1984. [7] deals with the test results in detail. The most important results were that no failures occured at the contact surfaces and that no cracks could be seen on the test beams.

3.2 Tests on slabs

The tests consisted of five composite concrete slabs. The lower parts of the composite slabs were cast followed seven months later by the concrete toppings. The ratio between the thickness of the topping and the total thickness of the slab was in all cases one third and the total thickness was 0.15 m. The square slabs were free at the edges and simply supported at the corners. The side length was 2 m. Two slabs had water-jetted contact surfaces, two had contact surfaces chipped by a pneumatic hammer and one had a sandblasted contact surface. The tests were carried out indoors between November 1985 and May 1986. Detailed test results are reported in [8]. Nor in these tests did differential shrinkage cause any visable cracks.

3.3 Strains and deflections

Since no visible cracks occured in the tests, un-cracked state has been considered. The tests show that strains and deflections due to differential shrinkage of a composite concrete slab or beam can be predicted by assuming perfect bond between old and new concrete, a linear relationship between stress and strain, a constant rectangular distribution of differential shrinkage. Furthermore, concrete creep has to be taken into account.

Since concrete shrinkage is strongly dependent on the water cement ratio and the cement content, the agreement between tests and theory is best if measured free shrinkage is used as indata instead of any empirical shrinkage function - like CEB [2] and [3] - which neglects these dependences. If the differential shrinkage is based on the free shrinkage of reference prisms the influence of member size on shrinkage has to be taken into account.

According to the tests on slabs the discrepancy between tests and theory is about 20 per cent. Since the agreement is fairly good, the theoretical model has also been used in order to estimate normal stresses.

3.4 Normal stresses

To explain the observed absence of cracks the concrete creep has to be considered. An accurate calculation demands that the time is divided in time steps. At every time step the existing stresses are compared with the available strength. Such a calculation with creep and shrinkage according to CEB [3] shows that the greatest tensile stress is lower than the tensile strength of the concrete topping. If the creep on the other hand is neglected the calculated stress will be about three times greater. Similar results have also been obtained using creep and shrinkage based on experimental data.

The risk of cracks caused by the differential shrinkage is reduced if the concrete structure is kept wet after casting of the concrete topping. The wetting will reduce the shrinkage and the maximum stress will occur at a later time when the concrete strength will be higher. A calculation with creep and shrinkage according to CEB shows that seven days of wetting will reduce the ratio between maximum stress and strength with 30 per cent.

3.5 Shear stresses

In FIP [4] a method is given estimating shear stresses. The method is based on results from *Jonasson* [5]. The resultant of the normal stresses on one side of the interface leads to shear stresses, concentrated to the ends of the beam. A triangular shear distribution is assumed. The distribution has its maximum value at the end and zero at a distance of three times the thickness of the new concrete topping. The method can in princip also be applied to slabs, which has been done in [8].

Calculations of maximum shear stresses at the contact surface of the test beams [7] show - for both studied theories - that they are much less than the tensile concrete strength. Their effects on the principal stresses have been estimated at 10 per cent and thus they can be neglected in practice. Estimates for the test slabs have given similar results [8].

4. LOAD-BEARING CAPACITY AND DEFLECTIONS OF COMPOSITE CONCRETE STRUCTURES

4.1 Load-bearing capacity of beams and slabs

In a primary investigation at the Department of Structural Mechanics and Engineering composite concrete beams of old and new concrete were simply supported and subsequently loaded to failure by a central single load. Composite beams with a chipped, rough contact surface reached as high ultimate loads as homogeneous beams. *Silfwerbrand* [6] has reported the test results.

The load-bearing capacity of the test slabs described in section 3.2 has been investigated as well. The slabs were free at the edges and simply supported at the corners. The five composite concrete slabs and two homogeneous reference slabs were loaded subsequently to failure by a central single load. The slabs contained only bottom reinforcement.

The measured ultimate loads of the composite slabs were as high as the ultimate loads of the homogeneous slabs. This statement is even valid for the composite slab with a sandblasted contact surface. All the slabs showed similar yield line patterns. The measured yield loads were 15 to 25 per cent higher than the corresponding calculated load.

4.2 Deflection

Mid-span deflection was measured in all tests. All data show similar relationships between load and deflection. The measured values correspond fairly well to the theoretically determined ones which was expected but nevertheless had to be confirmed before application in practice.

5. FATIGUE TESTS

The number of vehicles passing a bridge during its lifetime often exceeds one million and sometimes even ten and one hundred millions. Hence it follows that it is important to consider fatigue. At the primary investigation at the Department of Structural Mechanics and Engineering [6] fatigue tests on beams were carried out. According to the test results there is no evidence that a properly cast composite concrete structure with a rough contact surface has less resistance to fatigue than a homogeneous one. The number of tests was, however, small.

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