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Application of Steel Fibre Concrete for Underwater Concrete Slabs

H. Falkner* & V. Henke

Institute for Building Materials, Concrete Construction and Fire Protection (iBMB), Technical University of Braunschweig, Germany

Abstract

In the heart of Berlin, the area of the Potsdamer Platz is being developed into a new multi-functional town centre. As most of the buildings reach far below the ground-water level, the construction of deep building pits becomes necessary. Due to special underground conditions and environmental protection requirements, sealing injection layers cannot be carried out for the deeper parts of these building pits. The remaining solution is to erect an underwater concrete slab, back-anchored by tension piles. These building pits are of a very irregular shape with extremely high water pressure on the concrete slab. In order to increase the overall safety of this construction, steel fibre concrete instead of plain concrete was used for these slabs, thus leading to a robust and ductile construction. This paper gives a short description of the building method, the tests carried out concerning the load carrying and deformation behaviour of such a slab and the additional tests undertaken on the building site to solve remaining questions about the underwater concreting technology of steel fibre concrete. © 1998 Elsevier Science Ltd. All rights reserved.

Keywords: steel fibre concrete, underwater concreting, steel fibre concrete slab, deep building pits.

GENERAL

One of the first huge construction measures in the centre of Berlin is the erection of a new multi-functional town quarter in the area of the Potsdamer Platz on a large building site extending over an area of more than 70000 m^2. Development of this area is carried out by *debis*, a subsidiary company of Daimler Benz. This new town centre will not only provide offices, housing, shops and shopping-centres, but also hotels, theatres and cinemas.

The dimensions of this *debis* project, with a length of approximately 560 m and a width of up to 280 m are remarkable. The whole construction has to be carried out in one single building pit. Figure 1 shows a section and a plan-view of this building pit. This building project, with foundation depths between 9 and 18 m, has had to be founded in the ground-water, with the ground-water table approximately 2 to 3 m below the surface. At the same time a connection of this building project with the new railway station Potsdamer Platz is planned. This station has in parts a foundation depth of up to 20 m into the ground-water and poses a special challenge to the planning engineers and the construction companies.

As Berlin draws its drinking water from this ground-water reservoir, any encroachment into the fragile ground-water balance has to be avoided. For this reason any ground-water lowering must, on principle, be excluded. Furthermore, all building materials used must not lead to any kind of ground-water contamination. Ground injection methods are only allowed if the materials used are hygienically safe and do not lead to any ground-water contamination.

*To whom correspondence should be addressed.

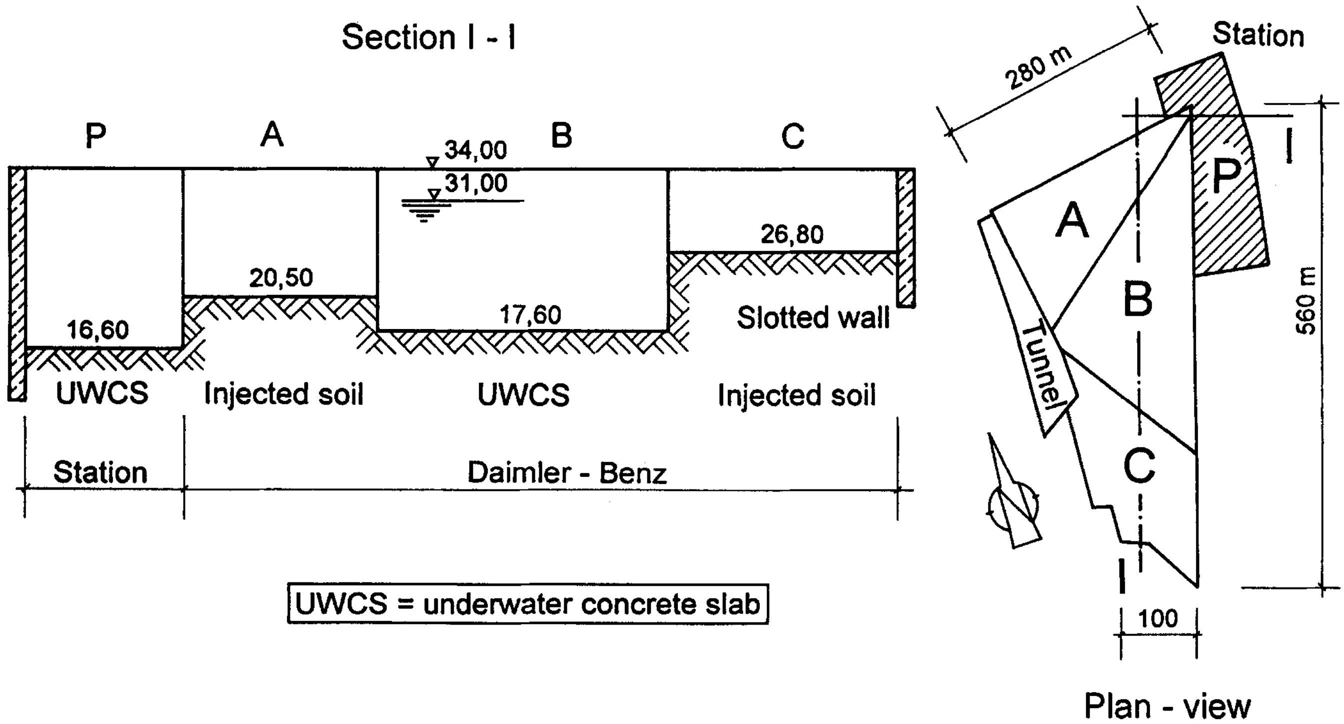

Fig. 1. Section through the building pit 'Potsdamer Platz'.

For depths of up to 10–12 m, it is possible to construct a 'dry building pit' with an artificial or natural sealing layer and deep sheet piling or slotted walls. For greater depths a different construction method has to be used; underwater excavation after the erection of the sheet piling or slotted walls with the subsequent placement of a back-anchored underwater concrete slab (see Fig. 2).

For construction of a dry building pit with an underwater concrete slab according to Fig. 2c, the following construction steps are necessary:

- driving of the sheet piling or construction of the slotted wall;
- excavation of the building pit to the ground-water level;
- setting of the anchors for the surrounding walls. Additional anchors below the outside ground-water level would affect the very stringent watertightness requirements;
- further underwater excavation down to the required level;
- driving of the tension piles from a pontoon, in this case steel profiles as vibration-injected piles;
- concreting of the underwater concrete slab; for the first time steel fibre concrete was used for such an extensive slab instead of plain concrete
- pumping out of the building pit, after hardening of the underwater concrete slab;
- if necessary, local defects have to be sealed by injection with cement grout.

The underwater excavation took place with large floating dredgers in the construction section B of *debis*. This first artificial lake created here covered an area of approximately 20000 m^2. This lake is enclosed by 1.2-m thick slotted walls or sheet pile walls with a steel section depth of 1.0 m. The underwater concrete slab, with a thickness of 1.2 m, is anchored by approximately 2000 tension piles; each pile with a length of 17 m carries a tension force of up to 1500 kN. The overall buoyancy force for this building pit amounts to 3000 MN. Figure 3 shows this artificial lake.

STEEL FIBRE REINFORCED CONCRETE SLABS

For the time being, the verification of such an underwater concrete slab is based on a simple computational model. It is normally assumed that the external loading is carried by spatial arches within the slab towards the anchoring points of the tension piles, whereas the resulting

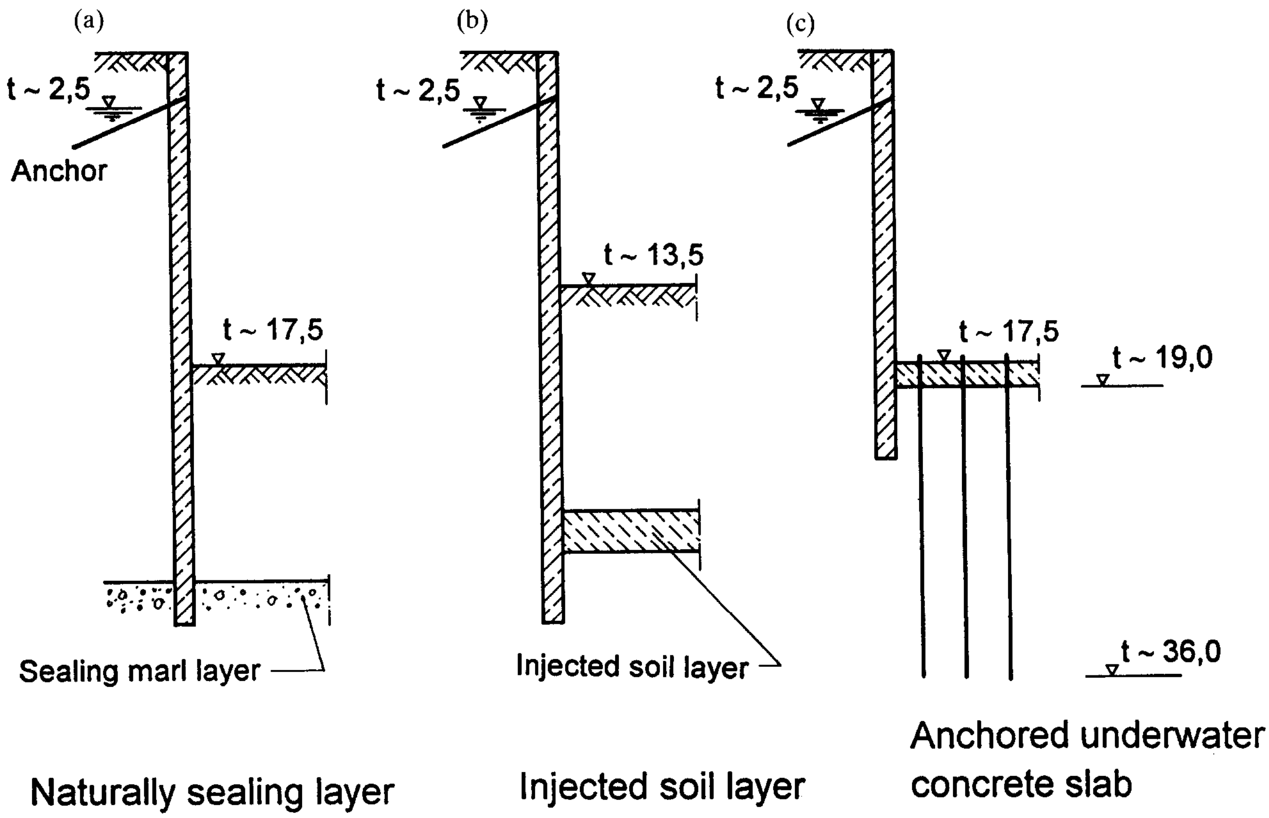

Fig. 2. Construction principles for deep building pits.

horizontal force is balanced by the external earth and water pressure on the surrounding walls. These anchoring points are normally considered to be fixed (see Fig. 4). The verification of the serviceability and overall stability is assumed to be fulfilled if the concrete compres-

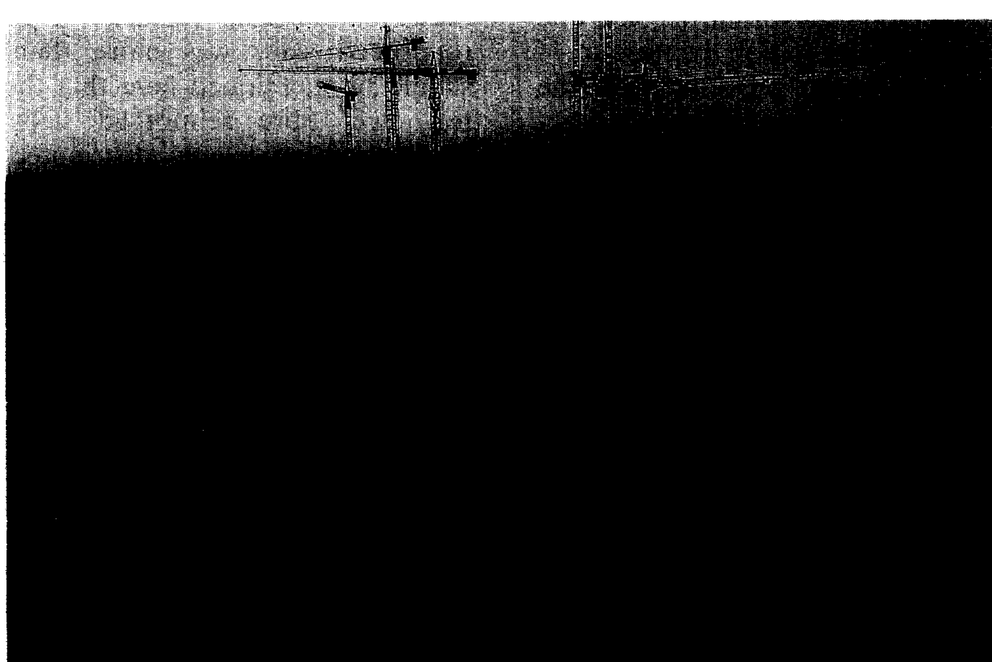

Fig. 3. View of the building pit B: 'Lake *debis*'.

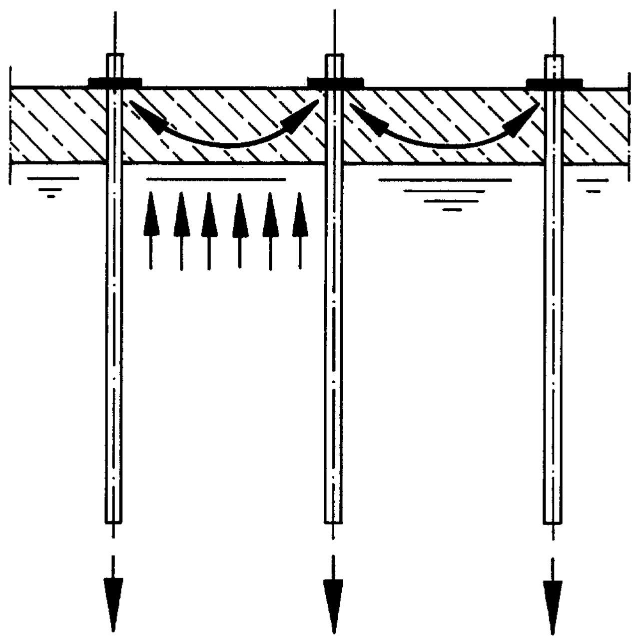

Fig. 4. Simple computational model for the verification of underwater slabs.

sion stresses within the arch or under the anchorage points remain within the allowable stress limits for the concrete used.

Such a simple computational model is normally sufficient for the successful erection of underwater slabs in smaller, straight building pits. For large-area building pits with irregular shapes and misalignments within the slab, as is the case for the building pits shown in Fig. 1, it has to be assumed and was shown by calculations that bending moments within the slab due to a different load deformation behaviour of 2000 tension piles, water pressure and the external normal force are unavoidable. Therefore, it was intended to avoid the brittle behaviour of a plain concrete slab and to obtain a robust and ductile construction.

From the experience gathered from tests on steel fibre reinforced industrial floors,[1] which showed very ductile and redundant load carrying and deformation behaviour, the possibility to replace the plain concrete by a steel fibre reinforced concrete slab was considered at the Institute for Building Materials, Fire Protection and Concrete Construction (iBMB) at the Technical University of Braunschweig, Germany. A steel fibre reinforced concrete slab, providing an immensely increased deformation capability, would be far more suited to counteract the deformations to be expected in this building pit.

Tests on plain and steel fibre reinforced concrete slabs

In order to carry out additional laboratory tests on larger-scale test specimens, funds were made available by *debis*, in order to examine the load carrying and deformation behaviour of these slabs. These tests were carried out at the iBMB laboratory.[2] The set-up for these tests is shown in Fig. 5.

The tests were carried out on one plain and two steel fibre reinforced slabs with dimensions of 3×3 m and a thickness of 280 mm. One important feature of these tests, the simulation of an evenly distributed high water pressure, was realized with the simple, but reliable, concept of a layer of cork plates underneath the test specimen. The load was applied by nine hydraulic jacks as shown in Fig. 5. For the first fibre-reinforced slab the fibre content was 60 kg/m^3 DRAMIX 60/0.8 and for the second 40 kg/m^3 DRAMIX 50/0.6.

The result of these tests can be summarized as follows. The ultimate load-bearing capacity of the plain concrete slab was reached by exceeding the tensile strength of the concrete. At this point an unannounced and sudden failure occurred, the slab broke up into several pieces (see Fig. 6).

In comparison to this brittle failure, the fibre reinforced slabs showed an entirely different behaviour. It can be seen from Fig. 7 that, in comparison to the plain concrete slab, the ultimate load-bearing capacity of the steel fibre reinforced slabs was more than doubled. It should be mentioned here that the tests on the two steel fibre reinforced slabs had to be stopped at an evenly distributed pressure of 525 kN/m^2, as the ultimate capacity of the hydraulic jacks was reached. The deformability of the slabs is indicated by the measure Δs (see Fig. 7), the deformation difference between the centre (A) and edge (B) of the slab.

One other important aspect is the high deformability of the steel fibre reinforced slabs. It can be seen from Fig. 7 that the deformation of these slabs reached during the test is four to five times larger than the deformation of the plain concrete slab. This means that steel fibre reinforced concrete slabs have extremely ductile deformation behaviour, which, as different deformations due to ground movements in such a large building pit cannot be excluded, will add to the overall safety and reduce or even exclude

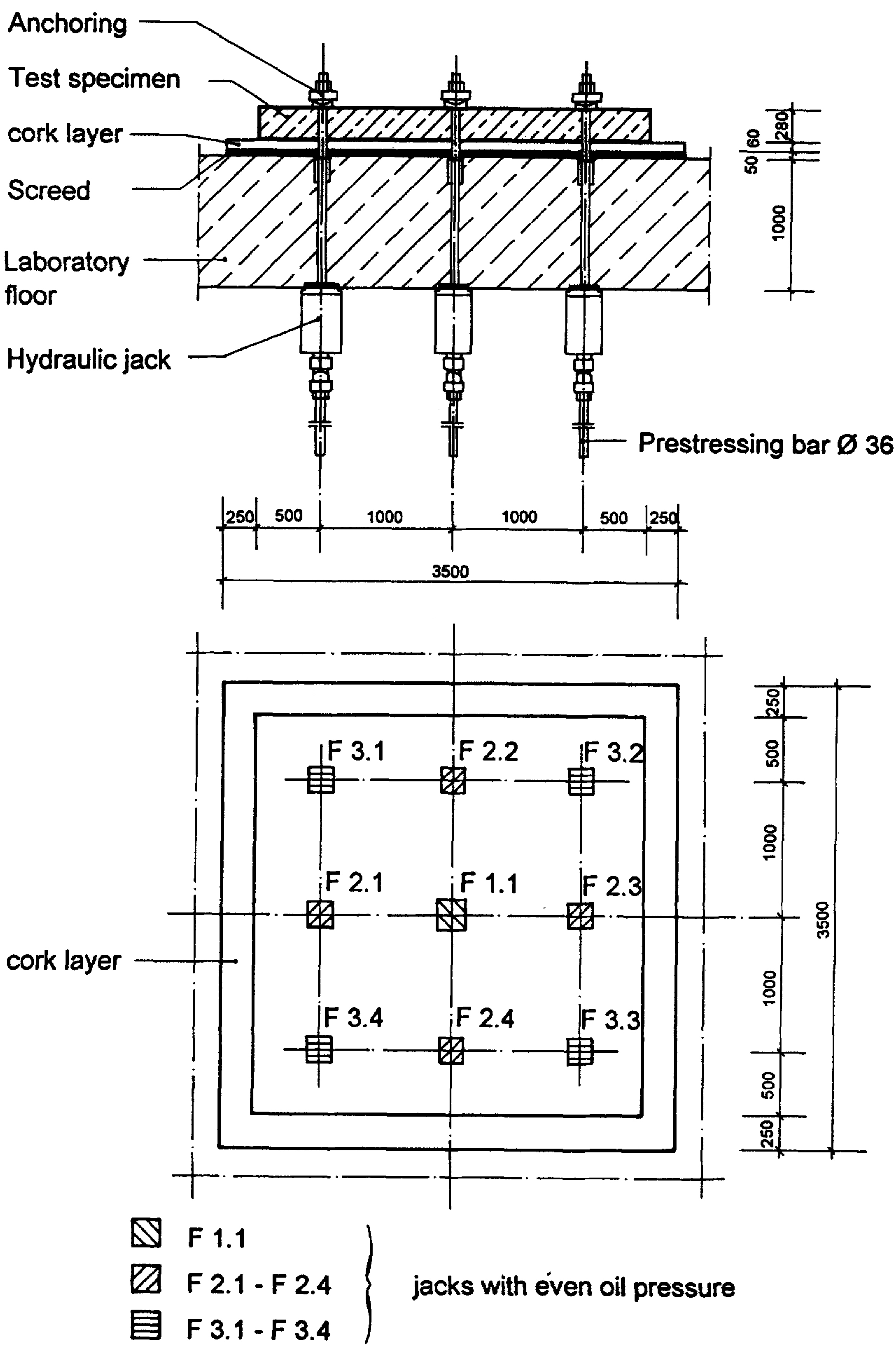

Fig. 5. Test set-up for plain and steel fibre reinforced concrete slabs.

Fig. 6. Remains of the plain concrete slab after failure.

the risk of sudden failure. Other tests, carried out with a single load in the middle of the slab (not included in this paper), led to a deformability which was 10 to 15 times higher than with a plain concrete slab.

These results showed clearly that steel fibre-reinforced concrete slabs have an inherent additional redundancy and therefore possess a higher degree of safety performance in practice. The fibre reinforced slabs did not break into several pieces; on the contrary, they could be lifted as a whole from the test floor. One of the fibre reinforced test slabs can be seen in Fig. 8, where the yield lines are clearly recognizable.

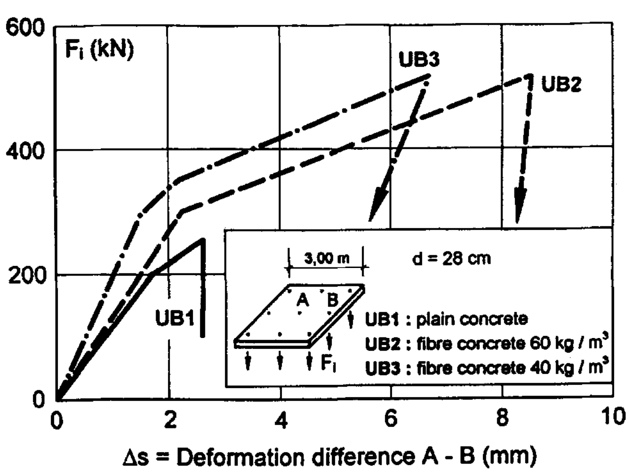

Fig. 7. Results of test loading slabs with plain and steel fibre concrete.

From this yield line pattern a simple model was developed for the dimensioning of these slabs.

The slab UB3 (40 kg/m^3) in comparison to slab UB2 (60 kg/m^3) showed better load-carrying behaviour, which can be explained by the higher total amount of the finer steel fibres, even if the mass of the fibre was reduced. Based on these findings, it was finally decided to use this amount and kind of steel fibres for the underwater concrete slabs.

APPROVAL FOR SPECIAL CASES

Under German building regulations, building materials or construction methods which are not covered by the normal building regulations and/or codes have to be approved under the so-called 'special case approval regulations'. This procedure makes sure that these new building materials or methods conform with the regulations in existing codes.

In this context, and as there was no previous experience about the handling of steel fibre concrete under such extreme conditions (most of the concreting took place in winter and early spring 1995/96), it had to be proven in this context in a large-scale test under building site conditions that steel fibre concrete could be produced and placed underwater, satisfying all concrete technology and procedural engineering

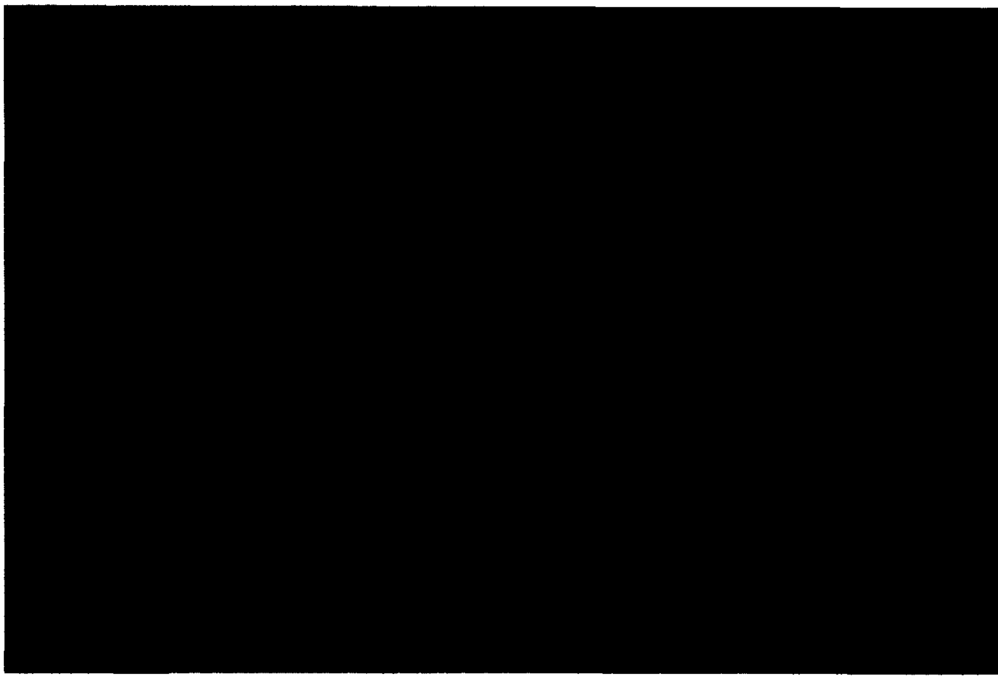

Fig. 8. Specimen with 40 kg steel fibre reinforcement.

conditions. This large-scale test was carried out in late autumn 1995. The following conditions for a special case approval had to be met:

- The long pumping distances of over 150 m and the placing underwater enable proper concreting of the underwater slab, especially with regard to the enclosure of the tension pile heads.
- The material properties of different concrete mixes used had to be checked in such a way that a decision about the final concrete mix can be carried out with regard to the concrete material and workability properties.
- The tests had to be carried out for steel fibre concrete as well as for a normal concrete, used as a reference concrete.
- For each concrete mix one large test specimen including two pile heads had to be concreted underwater and recovered after the concrete had hardened.
- These test specimens had to be sawn apart, in order to check for proper enclosure of the pile heads.
- The concrete mix should show a very low heat of hydration and take the sulphate content of the ground water into account.

Figure 9 shows the steel container of one test specimen with the two heads of the tension piles prior to lowering into the building pit. The cross-section of these steel containers was 1.2 × 1.2 m, with a total length of 4 m.

Altogether, six of these underwater concreting tests, together with an additional four pumping tests, had to be carried out. The six underwater concreting tests were necessary as, even though these tests were planned on the basis of extensive preliminary laboratory tests with regard to the concrete properties, composition and slump, some of the first mixes showed an extremely high retarding time. Even if these concretes reached their intended strength (C 20/25) in the end, such unpredictable behaviour could not be tolerated.[3] Therefore, these tests proved to be extremely valuable, as they showed the behaviour of the different concrete mixes under building site conditions in comparison to defined laboratory conditions.

For the underwater concrete slab the following mix (see Table 1) was finally chosen, as it showed a tolerable heat of hydration and an intended regarding time of 24 h.

As mentioned already, it had to be proven that the heads of the tension piles were totally encased by the steel fibre concrete and that there was an even steel fibre distribution over the cross-section. Therefore, the test specimens had to be cut through the pile head with a diamond bandsaw. Figure 10 shows the cross-section through such a test specimen. Close inspection showed that the pile head was properly enclosed by the steel fibre concrete. An even fibre distribution over the cross-section was achieved and no disintegration of the concrete structure during the hardening time occurred.

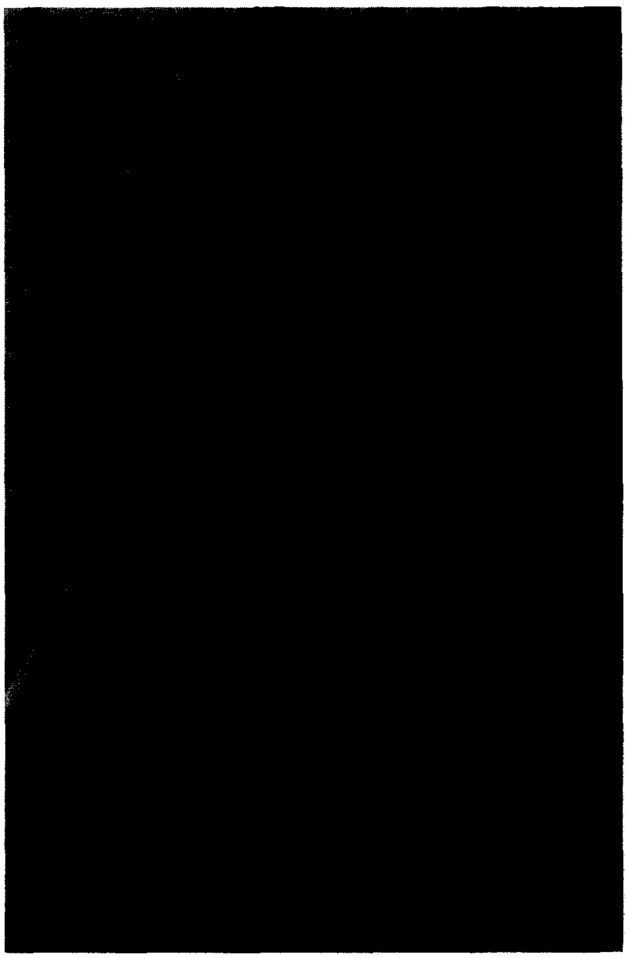

Fig. 9. Steel container with two pile heads for the large-scale test.

Table 1. Final concrete mix proportions

Grade	C20/25
Cement	32.5 R, 280 kg/m^3
Aggregates	0–16 mm
Fly ash	220 kg/,^{3}
Water	197 l/,^{3}
w/c ratio	0.7
w/(c+f)	0.39
Fibres	DRAMIX 50/0.6, 40 kg/m^3
Fluidifer	Fk88, 1.5%
Regarder	Retard 360, 0.4%
Spread	67 cm (on 'German Table')

EXECUTION

The concreting of the underwater concrete slab was carried out in 18 sections. For each section approximately 1500 m^3 of steel fibre concrete had to be poured underwater in a 10-h shift. Altogether, 30000 m^3 of steel fibre concrete were needed for the underwater slab of this building pit.

The different sections were separated by sheet piles, equipped with grouting hoses for cement injection. After hardening of the concrete and before pumping out the 350000 m^3 of water, these joints between the sections of the underwater concrete slab and the sheet piling were injected with a cement grout in order to secure the watertightness of these joints, as the very stringent watertightness conditions of the overall building pit had to be met. This measure proved very successful, as hardly any leaking of these joints later occurred. The overall leakage rate of this building pit was only one-third of the allowed rate. Figure 11 gives a view into the

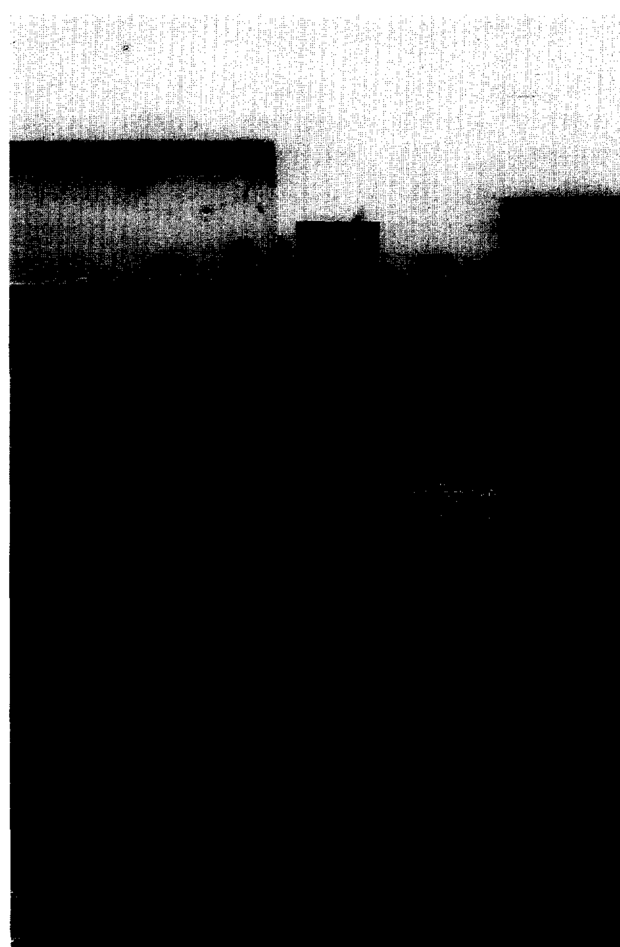

Fig. 10. Cross-section of a test specimen.

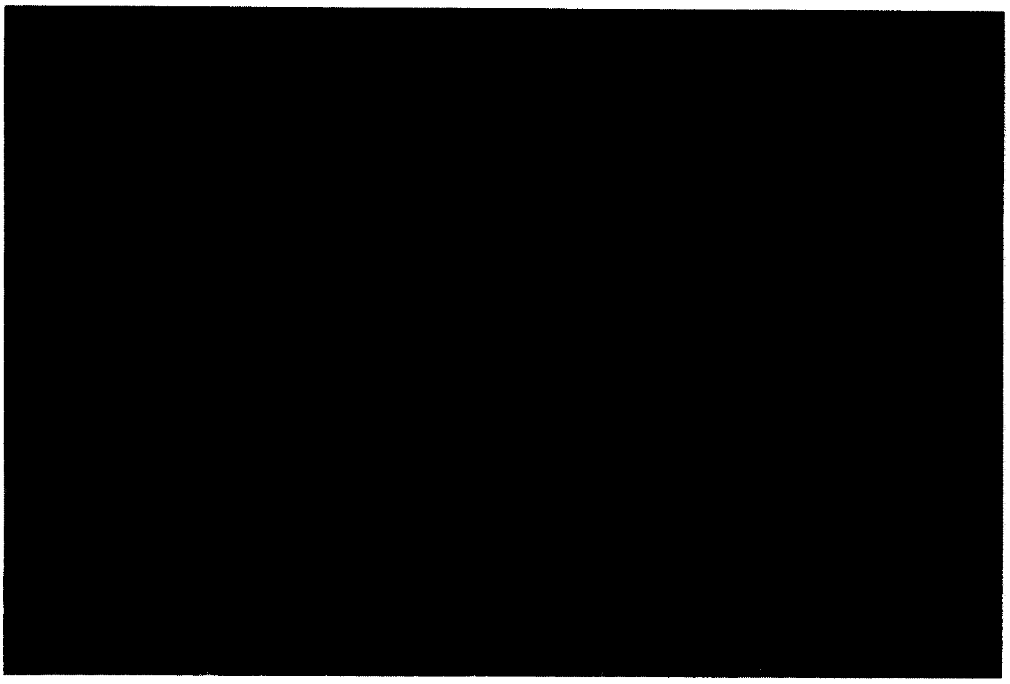

Fig. 11. View into the dry building pit.

successfully completed dry building pit. During the whole construction process, each phase was monitored by an extensive measurement programme.[4]

CONCLUSIONS

For the first time an underwater concrete slab of such dimensions has been constructed. The positive test results in the laboratory as well as on the building site convinced all parties involved in this project (planning engineers, construction companies and building authorities) that the use of steel fibre concrete would contribute considerably to the overall safety of this construction measure.

The large-scale test on the building site proved to be especially valuable, as it provided the opportunity to study the behaviour of different concrete compositions under building site conditions. In addition, these tests allowed the verification of the stringent quality control programme which had to be established in order to control all stages of the concreting, starting with the aggregate supply and finishing with the properties of the fresh concrete arriving on the concreting pontoon.

The final result, a dry building pit which fulfilled all requirements, shows that the use of steel fibre concrete for such an underwater concrete slab provides a new concept which, as more and more buildings have to be founded far below the ground-water table, will contribute to the overall building safety. If dimensioned properly, such a steel fibre-reinforced concrete slab can be constructed for the same cost as a thicker, plain concrete slab.

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