Pipe tests under near-realistic stresses

Testing
a pipe until failure

For more than 100 years, concrete and steel reinforced concrete sewer pipes have been tested using the crown pressure test, which is designed to examine to the load bearing behaviour of concrete pipes. However, the crack behaviour of steel-reinforced concrete pipes which is recorded using this so-called ‚classical' method of investigation does not relate to practical conditions; the bonding effect between the concrete and the steel reinforcement is not taken into account and the crack widths are either under- or overestimated. With this in mind, a new testing method has been developed where the actual stresses on earth-covered reinforced concrete pipe can be simulated under near-realistic conditions.

For the first time ever, it is now possible to evaluate the crack formation of a reinforced concrete pipe under design-load conditions as part of a quality assurance system.

A prerequisite for the development and survival of a modern industrial company is a functional infrastructure with reliable supply and disposal networks. The condition of sewers is vitally important for the protection of soil and water. However, in the past, when laying large pipes made from steel-reinforced concrete, so-called 'initial damage' appeared in the form of surprisingly large cracks, in some cases immediately after or a few years after laying.

With this in mind and in view of future investment measures taken by the network operators (cf. [1]) the Department of the Environment in North-Rhine Westphalia, commissioned the IKT Institute for Underground Infrastructure to carry out a research project [2] for investigating the load-bearing and crack behaviour of large steel-reinforced concrete pipes when laid using the open-coverage method. For the first time, in a modified crown pressure test, near-realistic loads are applied which produce the same crack behaviour as that of pipes in the ground. In this case, both the moments and normal forces are measured where previously only the moment stress in the test cross section was taken into account in the 'classical' crown pressure tests. The risks of the design and production of the pipes are also recognized and, where necessary, special quality standards are derived for future construction projects. The important results are presented in the following.

Current technical status

In 2002, 137 manufacturers produced concrete and steel-reinforced concrete pipes which were designed for laying using the open-coverage or closed-coverage method in Germany. The specifications for the steel-reinforced concrete pipe produced include the condition, dimensional accuracy, strength, permeability to water and stability against chemical attacks. Along with the starting materials, the moulding and compaction process are crucial for to pipe quality [11]. The manufacturing process and the degree of mechanisation in the production process may differ from one pipe manufacturer to another. In terms of the production of concrete and steel-reinforced concrete pipes, there is a fundamental difference between methods which involve immediate demoulding and those where the concrete is hardened in the formwork (in-mould hardening).

In regard to the design, it is particularly noticeable that, unlike the normal requirements for reinforced concrete construction, there has so far been no minimum requirement in regard to reinforcement for crack width limitation in steel-reinforced concrete pipes (see German Industrial Standard DIN 4035 [3]). Since April 2003, however, DIN EN 1916 has also applied to the design of steel-reinforced concrete pipes of nominal sizes < 1750 mm [10]. This is destined to replace the German Industrial Standard DIN 4035 [3] from October 2004 at the latest and will also stipulate a minimum reinforcement for steel-reinforced concrete pipes for the nominal size under consideration. This minimum reinforcement is designed so that the permissible stresses which are applied during the crown pressure test can be absorbed. Pipes of nominal sizes > 1750 mm are only stipulated in the national preliminary standard DIN V 1201 [8] which means that there is still no obligatory European regulation for large steel-reinforced concrete pipes available to define a minimum reinforcement.

Steel-reinforced concrete pipes

According to DIN V 1201 [8], steel-reinforced concrete pipes must be made from quality-supervised construction materials. According to DIN EN 1916 [10], the 'classical' crown pressure test can be used as part of the quality assurance of the steel-reinforced concrete pipes produced. This test was derived from a testing method which was developed more than 100 years ago for testing concrete pipes (cf. Figure 1).

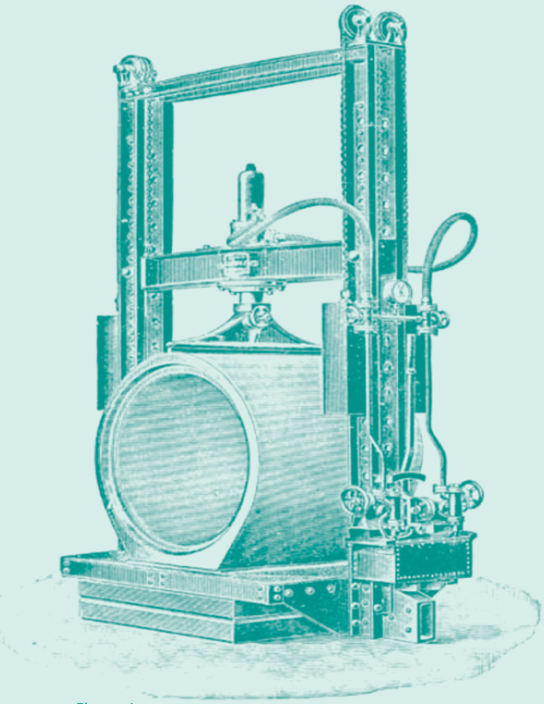

Figure 1:
„Koenen" hydraulic pipe tester from 1909 [6]

The original aim of these tests was to test the annular tensile bending strength of a concrete cross section and, therefore, the load-bearing behaviour of the concrete. The crack-distribution properties of the steel-reinforced concrete are basically not taken into consideration, which means that this method of testing is pushed to its limits for steel-reinforced concrete pipe. So, the standard cross section for the crack formation in the test in particular is 'normal-force free' in the pipe crown, although the pipe in the ground is always subjected to the effect of normal forces. In other areas of underground construction however, such as the testing of steel-fibre reinforced tubbings, tests with simultaneous moment and normal force loading have proved worthwhile (cf [17]).

Development of a modified crown pressure test

As a consequence, the crack behaviour of steel-reinforced concrete pipes should be observed under loads as they actually occur with pipes in the ground. A new testing method has been developed which is based on the experience gained from the 'classical' crown pressure test and simulates the loading to which pipes are subjected in practice as close as possible.

The classical crown pressure test according to DIN 4035 [3] is based on a test which was originally conceived for carrying out load-bearing capacity investigations on concrete pipes. The test is used to discover the edge fibre tensions under which a crack in the concrete structure develops and how the width of this crack develops as the load is increased. The special load-bearing and crack behaviours of steel-reinforced concrete are not taken into consideration during this test. Thus, the interactions between steel and concrete loading (bond) are not taken into account or the effect of the normal force/moment relationship on the crack development.

A preliminary study [3] has already shown that the stress distribution in the pipe wall can be influenced considerably by the choice of a modified experimental arrangement and adapted to the actual load conditions. While pursuing this topic further (cf [7]), the fundamental experimental setup shown in Figure 2 was suggested for the 'modified crown pressure test'. By introducing the horizontal forces in the area of the crossbar, the normal force in the pipe crown in particular increases so that realistic loading can be applied to this crucial test cross section.

It is still open to question, however, how the load conditions made up from vertical and horizontal forces are to be determined in individual cases for a realistic experimental procedure and how the test set-up can be designed and equipped with instruments. Standard crack areas for the evaluation were measured before the test set-up was designed and built on the basis of finite element calculations, so that the entire test arrangement and, in particular, that of the measurement instruments could be aligned to the crack behaviour.

The actual test parameters are specified in principle according to the actual design case to be tested in each case. In the test, the loadings which are actually expected are therefore produced in the measurement cross-section being examined. As one example within the scope of the project, the lateral pressure relationship $b = P_h/P_v$ was selected so that the load condition shown in Figure 3 was simulated in the test.

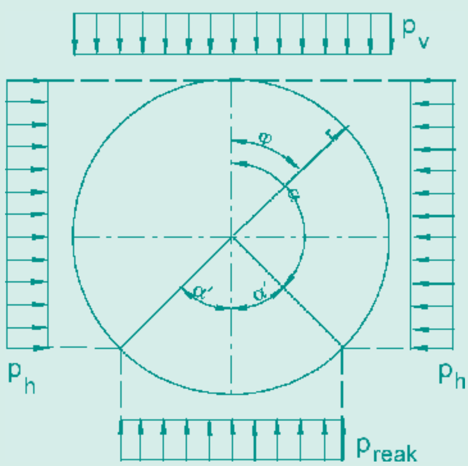

Figure 3: In-situ loading, example [9]

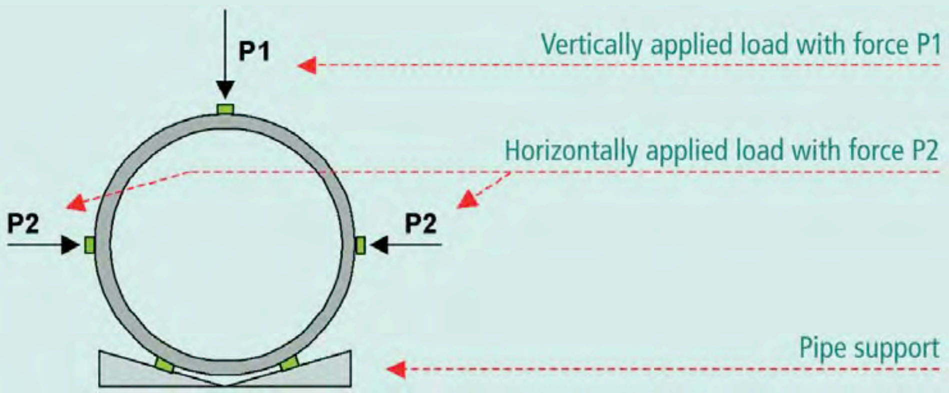

Figure 2: Schematic presentation of the test layout with applied load

In principle, the β ratio which corresponds to the in-situ load case is determined from the vertical force and horizontal supporting force as well as the standard pipe crown force as follows:

1. Determination of the maximum eccentricity for in-situ loading:

The in-situ loading (N/M distribution) is produced by the load conditions present in the installed state, e.g. as determined from permissible stress calculations on the annulus model. The eccentricity for this in-situ loading (e = M/N) is calculated in accordance with the angle at circumference. The maximum amount of eccentricity is a determining factor for the pipe circumference.

2. Determination of the load ratio β

The load ratio β in the crown pressure test gives the relationship between the horizontal supporting force and the vertical crown pressure force. For the 'crown pressure test' load case, the load ratio β is selected so that the maximum eccentricity in the test corresponds to the maximum value under in-situ loading. When considering internal cracking, the relevant cross section area is in the pipe crown but when considering external cracking, it is in the area of the crossbar. Figure 4 shows an example of the eccentricity distribution for any selected in-situ loading and the eccentricity distribution for the selected β-value in the crown pressure test with lateral support for internal crack investigation. The eccentricity at 0° in the crown pressure test in this case corresponds to the 180° value in-situ (standard bottom). Because the normal force within the area of the crossbeam is always large, the eccentricity of the external crack areas is affected less strongly by the choice of the supporting force.

3. Determination of the standard stress magnitude from in-situ loading

The determining factor is the maximum tensile stress on the internal or external surface of the pipe.

4. Determination of the standard crown pressure force

The magnitude of the crown pressure force which can be used to produce the loading which corresponds to the actual loads is determined for the selected β value according to 2 and the tension level according to 3. Figure 5 shows an example of the stress distribution for an in-situ loading and for the crown pressure test with lateral support using the standard crown pressure force. The tensions at 0° (test) and 180° (in -situ) correspond to one other.

In the result, the crack behaviour of the steel-reinforced concrete in the standard test cross section corresponds to the behaviour under design load. For practical application, this means that a direct comparison can be made between the supplied pipe quality and the specifications required under operating conditions for the first time.
A semi-non-destructive test is also possible, if the crack width is only to be examined at crack initiation. Thus, pipes which have already been tested could be approved for further in-situ use, if 'hairline cracks' only appear in the concrete after exceeding the initial crack load and no further load increase is applied during the test.

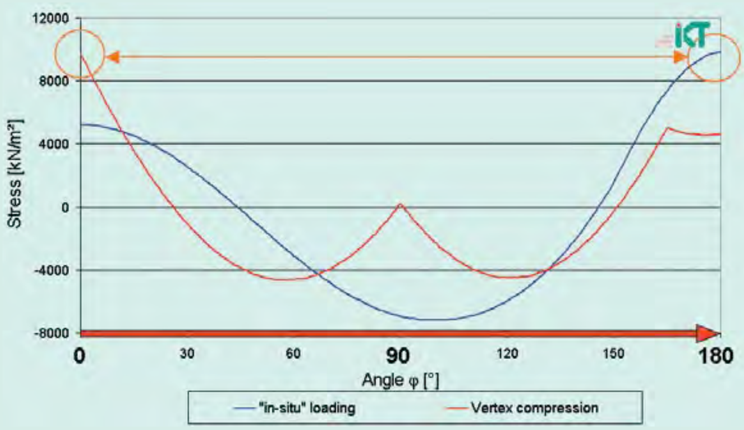

Figure 5: Coordination of the stresses in the standard cross section

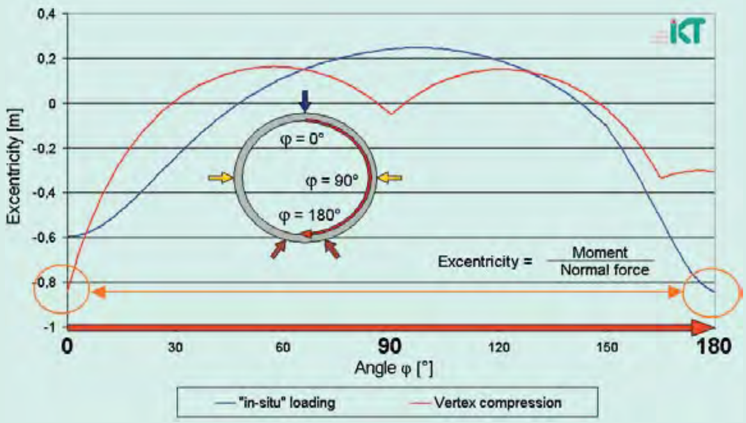

Figure 4: Determination of the load ratio β

Test results

The research project involved carrying out a total of 30 tests on pipes with different reinforcements produced via different manufacturing processes in order to optimise the test sequence and align the measuring program with the quality assurance requirements used in practice. Essentially, pipes were tested which had been

- immediately demoulded,
- hardened in the mould (in-mould hardening) or
- hardened in the mould (in-mould hardening) with concrete post treatment during the production process.

For pipes with nominal sizes > 2000 mm, the production method involved in-mould hardening which is the usual manufacturing variant for the range of observation adopted by the Emscher cooperative (see [15]). All pipe manufacturers which have production capacities for this nominal size range carry out hardening in the formwork (in-mould hardening). According to [15], all manufacturers questioned, which have a significant large-pipe production capacity (> 33 %), had set up their production facility expressly for in-mould hardening.

It should be possible to acquire initial information on qualitative crack behaviour, i.e. regarding the crack processes or crack development under load, by testing pipes which have been produced by different manufacturing methods. No information which could be evaluated statistically was expected on the relationship of the absolute crack widths on pipes produced by different manufacturing methods because of the usually large scatter (cf [14]) for the selected sample size. Steel-reinforced concrete pipes from only one manufacturer were used, so it is not possible to apply the quantitative information to other manufacturers or even other production processes.

Consequently, the investigation centred on the load-dependent recording of the crack development and the comparative interpretation of the characteristic cracking processes. However, this demanded a special outlay in regard to

- the design of the test set-up for the load-dependent lateral support for the pipe,
- the recognition of crack initiation in the standard crack by the application of numerous strain gauges, for example,
- the recording of crack width development in the standard crack by means of a video extensometer, for example.

In all cases, the position of the internal reinforcement corresponded to the specifications in the German Industrial Standard DIN 4035 [5], i.e. the permissible stresses under load were recorded and minimum reinforcement was not used (cf DIN 1045 [13]). The reinforcement on the pipe exterior involved three types of reinforcement with increasing degrees of reinforcement: I, design according to DIN 4035 [5]; II, degree of reinforcement according to interior reinforcement; III, minimum reinforcement according to DIN 1045 [4] for limiting the crack width w ≤ 0.2 mm. All the pipes were tested in a modified test setup with horizontal support based on the crown pressure test according to DIN EN 1916 [9] or DIN V 1201 [8]. After this test and quarter-rotation, some pipes were submitted to a classical crown pressure test without lateral support.

The following significant observations can be made from the tests:

- As expected, during a test with lateral support i.e. with moment and normal forces, the cracks opened more slowly as the load increased than during a test carried out in accordance with DIN EN 1916 [10] or DIN V 1201 [8] without lateral support. Figure 6 shows an example where the measured development of crack widths from tests with lateral support are compared with those without lateral support for crack widths up to 0.3 mm.
- In the pipe crown, cracks develop on the inside of the pipe which open continuously as the load increases. Individual cracks were restricted during all tests without lateral support, as they were in most cases for pipes which had been subjected to concrete post treatment with lateral support.
- Pipes without concrete post treatment with lateral support showed two to three parallel cracks one after the other. This load and crack behaviour dominated by bending moments and normal forces is oriented to the actual loads during installation on site and significantly improves the quality of the crack-width evaluation in comparison to bending moment loading alone in the crown pressure test according to DIN EN 1916 [10] or DIN V 1201 [8]. The pipes which were subjected to concrete post treatment during manufacture showed smaller crack widths than the pipes which were not subjected to concrete post treatment during manufacture for the same loading phases. By using small degrees of reinforcement, small crack widths initially developed and resulted in comparatively brittle failure under increasing load in some cases (see Figure 7). This type of behaviour brings the previous philosophy in regard to damage evaluation according to ATV M 149 [12] into question. Therefore, the relevant damage class is determined by the crack width on a steel-reinforced concrete pipe alone, i.e. independently of the method of manufacture and degree of reinforcement.

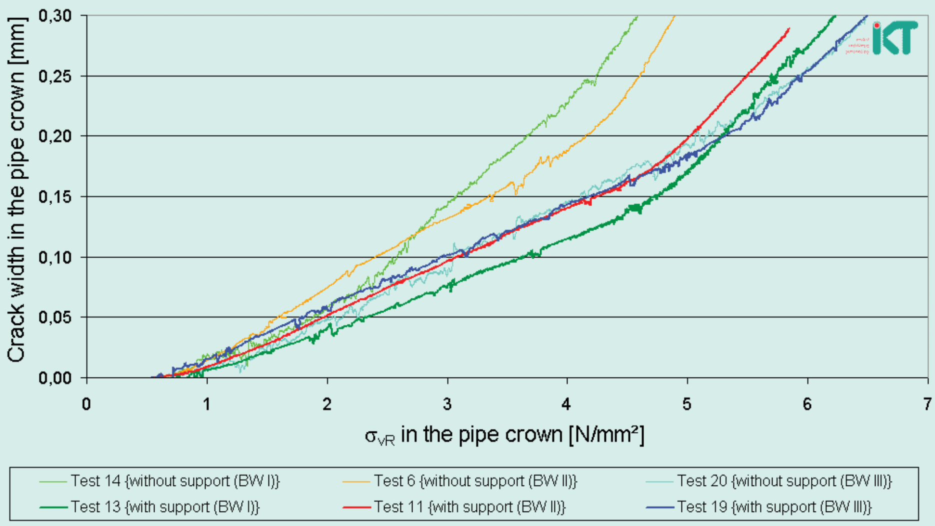

Figure 6: Crack development during tests on pipes cured in the mould
(BW I) Type I reinforcement, (BW II) Type II reinforcement, (BW III) Type III reinforcement

Figure 7: Testing a pipe to failure

- The crack width development can be reduced by both specifying a minimum reinforcement and improving the bond behaviour through concrete post treatment. However, a small degree of reinforcement cannot be compensated for by improved post treatment since this also reduces the load-bearing capacity; the post treatment merely affects the bond behaviour and therefore the crack width development.

Apart from the most important information gained about the test procedure, cracking and crack development described above, it was possible to draw other conclusions from further test observations.

- Depending on the manufacturing method, differences were found in the dimensional accuracy and the surface texture of the pipes. The pipes which were hardened in the formwork had significantly better properties than those which were immediately demoulded.
- In some cases, one possible weak point was found in the design of the lifting anchor system. If necessary, the extent to which the corrosion protection of the reinforcement or the water tightness of the pipes is impaired by this must be questioned.
- As well as the video measurement technique for crack recognition and pursuit, an ultrasonic measuring procedure was also used to discover whether it was possible to determine the depth of the crack. Meaningful results can only be obtained, however, by using very high resolution scanning at correspondingly high measurement cost. External cracks could neither be recognized nor measured from inside the pipe under the given boundary conditions.

Summary

For practical application, the following conclusions can be drawn from the results of the research project.

- In the 'classical' crown pressure test, the crack development in the pipe crown is overestimated because the effects of the normal force are missing. As a consequence, perfectly produced pipes are suspected of excessive cracking. On the other hand, pipes with bad bond properties may be unjustifiably promoted by reference to test conditions which are not in line with standard usage, based on the assumption that outside, such loads and the corresponding crack developments do not occur.
- The new modified crown pressure test allows the crack behaviour of steel-reinforced concrete pipes to be examined under near-realistic load conditions, i.e. moment and normal force loading, so that a pipe can be tested under actual design conditions. As well as concrete strength, crack development and bond behaviour between the steel and concrete can also be evaluated in line with standard usage.
- If the selected design conditions, such as the concrete covering and spacing of reinforcement layers, deviate substantially from the usual formulations for steel- reinforced concrete so that the applicability of the calculation is in doubt, supplementary investigations using the modified crown pressure test could provide additional security.
- If boundary conditions exist on the construction site other than those used in the structural analysis, such as the width, shape and depth of the excavation and the placement and pouring conditions, then a new structural analysis must be provided. If pipes are to be used which have already been manufactured and were originally intended for another load case, static load tests carried out on random samples using the modified crown pressure test could provide further security, since the actual crack behaviour of the pipes could be checked under the new design conditions.
- Cracks cannot be detected on the pipe exterior using justifiable means within the scope of the inspection so, for this layer of reinforcement with aggressive groundwater influence in particular, a minimum degree of reinforcement is advisable in each case.
- In-mould hardened pipes with concrete post treatment also developed only very small crack widths under large loads.
- An application of the damage classification system according to ATV - M 149 [12] hardly seems to be meaningful, particularly for in-mould hardened pipes with concrete post treatment since these pipes can develop small crack widths even under large loads.

In view of the results obtained from the research project, numerous questions which are still unanswered can also be identified. The following points can therefore be raised in regard to future research and test activities.

- In the investigation described here, the loads which were used in the modified crown pressure test were essentially designed for the standard internal pipe crown or bottom area for the initial crack. The supporting force also needs to be selected in relation to the cracking trend which arises in the in-situ state when examining the external cracks.
- In principle, the development of a comprehensive test program to simulate the entire static load history of a pipe (transport, structural condition and operation) for the modified crown pressure test would be advisable.
- Supplementary tests on pipes which have been removed from the ground, such as those recovered during the course of renovation, could provide information on the load-bearing behaviour of previously damaged or corroded pipes.
- The loading of steel-reinforced concrete pipes is possibly subject to numerous interactions and, therefore, complex damage mechanisms. Thus, dynamic loads, biochemical processes and the resulting changes in the load-bearing structure can affect or even accelerate each other. In particular, with difficult construction conditions, the effects of groundwater and various wastewater constituents, further investigations could be of interest in some cases here. As in the procedure described in [16], excavations of steel-reinforced concrete pipes with internal cracks after many years of use would be useful to better understand the crack behaviour on the pipe exterior under operating conditions and evaluate the risk of external cracking on the basis of internal cracks which have already been detected.

- In order to utilize the material properties of the steel-reinforced concrete better in sewer construction, new design rules, which are oriented to experience gained from handling water-impermeable concrete etc. could be worked out for the service load analysis.
- The updating of the test documentation as part of a random-sample-based quality assurance system for future construction projects could provide further knowledge on quality effects determined by production. The maximum delivery quality of a certain pipe manufacturer could also be determined by testing product samples (sample tubes).

Future IKT investigations are beginning – in close collaboration with interested network carriers.

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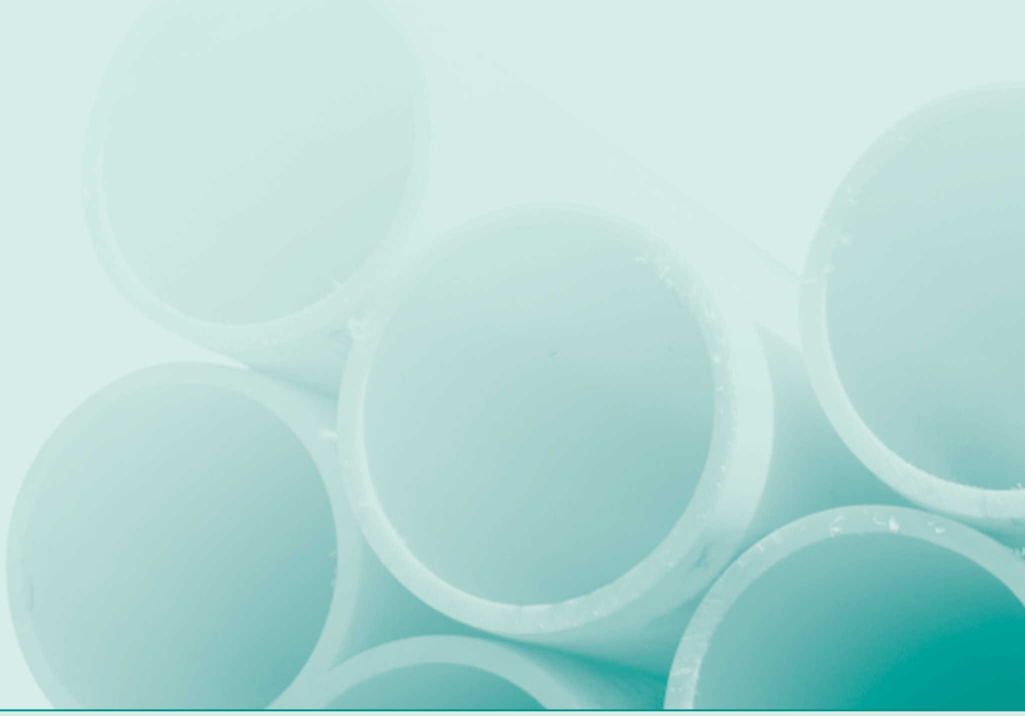

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ABOUT IKT

IKT - Institute for Underground Infrastructure is a research, consultancy and testing institute specialized in the field of sewers. It is neutral and independent and operates on a non-profit basis. It is oriented towards practical applications and works on issues surrounding underground pipe construction. Its key focus is centred on sewage systems. IKT provides scientifically backed analysis and advice.

IKT has been established in 1994 as a spin-off from Bochum University, Germany.

The initial funding for setting up the institute has been provided by the Ministry for the Environment of the State of North-Rhine Westphalia, Germany's largest federal state.

However, IKT is not owned by the Government. Its owners are two associations which are again non-profit organizations of their own:

a) IKT-Association of Network Operators: Members are about 100 cities, among them Berlin, Hamburg, Cologne and London (Thames Water). They hold together 66.6% of IKT.

b) IKT-Association of Industry and Service Providers: Members are about 60 companies. They hold together 33.3% of IKT.

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