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Measurement of strains and temperature responses in reinforced concrete walls

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Measurement of strains and temperature responses in reinforced concrete walls

When concrete sets, the added cement reacts with the water in an exothermic reaction, i.e. heat is released. In the setting phase (hydration), various chemical processes run at different speeds and also interact.

Introduction

The concrete is soft in the initial stage and it expands as a result of being heated. If the concrete building component is a wall on a foundation, later cooling creates tensile stress, especially at the foot of the wall where the base plate interferes with deformation. This can produce cracks, which can cause problems, particularly if the structure must be watertight. The walls of settling basins are typical examples of building components which need to be impermeable to water. Settling basins are given a fill test to check for leaks. Existing cracks are revealed by the damp lines along the cracks **(Figure 1)**.

Fig. 1: Hydration cracks in a settling basin during fill test

Hydration, stress and strain

The following theoretical model should help to make clear the distribution of strain and stress: imagine a concrete wall, the temperature of which is lowered by a specific amount. The wall should be able to expand freely in all directions; constant strains will therefore become apparent over the entire wall without creating stresses. At its base point, the wall should now be moved to its original position, i.e. the foot of the wall must be stretched longitudinally.

This stretching corresponds to the deformation hindrance caused by a normally powerful base plate, the temperature of which does not change. As a result of this stretching, the greatest strains and therefore stresses will become apparent at the foot of the wall. The strains will lessen towards the top of the wall. The diagram in **Figure 2** illustrates this effect, which can also be seen from the measured strain responses in **Figure 7** (see page 5).

During setting, the material properties of the new concrete change continuously: elasticity, compressive strength and tensile strength, relaxation capacity and breaking elongation. Together with heat loss and static constraints, these variables produce constantly changing stress conditions in the concrete building component. It is a very complicated procedure to assess this problem using a computer. Research programmes are running at several universities both at home and abroad, to try to understand the problem by computation.

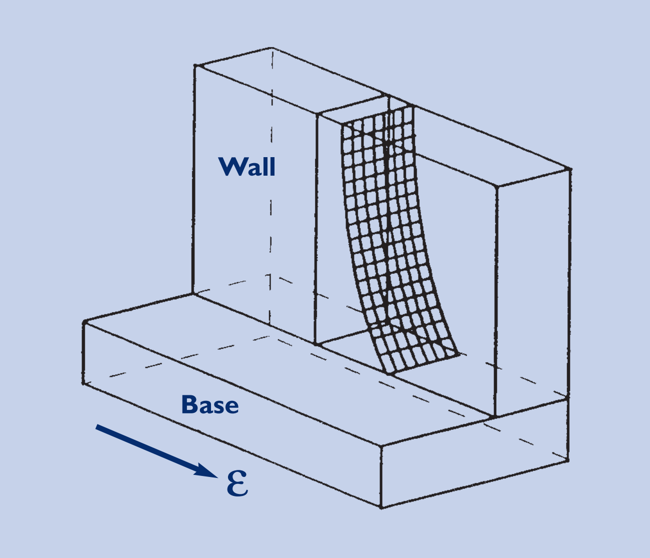


Fig. 2: Diagram of strain distribution caused by a drop in temperature in a wall

Over the last few years in the Berlin area, new settling basin constructions have had the scientific accompaniment of a Technische Universität Berlin research programme. The remit was to take and evaluate measurements at walls and base plates for settling basins and to undertake more extensive analytical studies to prevent hydration cracks.

The first measurement was taken in 1990 at the Ruhleben clarification plant. For this measurement, the temperatures inside the reinforced concrete wall were taken starting at the time of concreting. The reinforced concrete walls were provided with a system of cooling pipes to reduce temperatures **(Figure 3)**.

The aim of the research project was to study the complicated setting action in concrete and develop a method of preventing hydration cracks in settling basins.

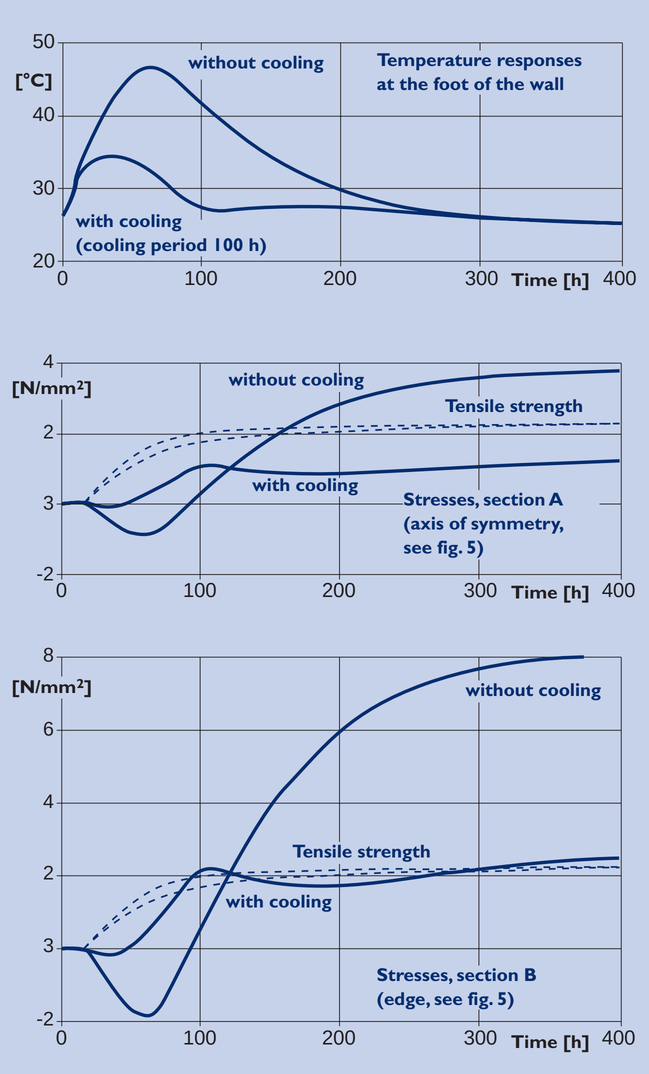
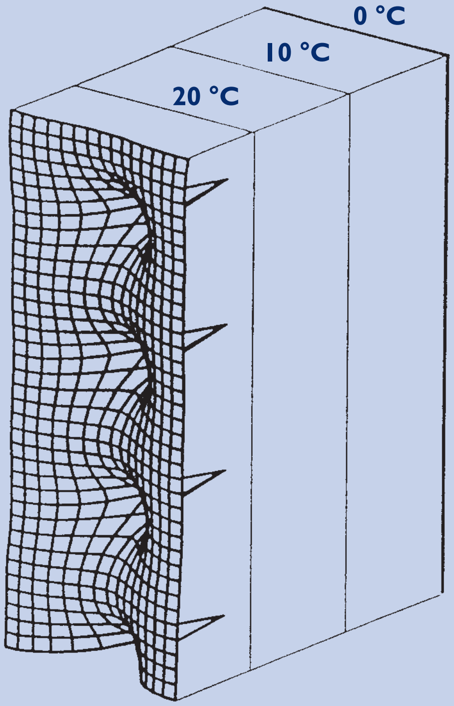
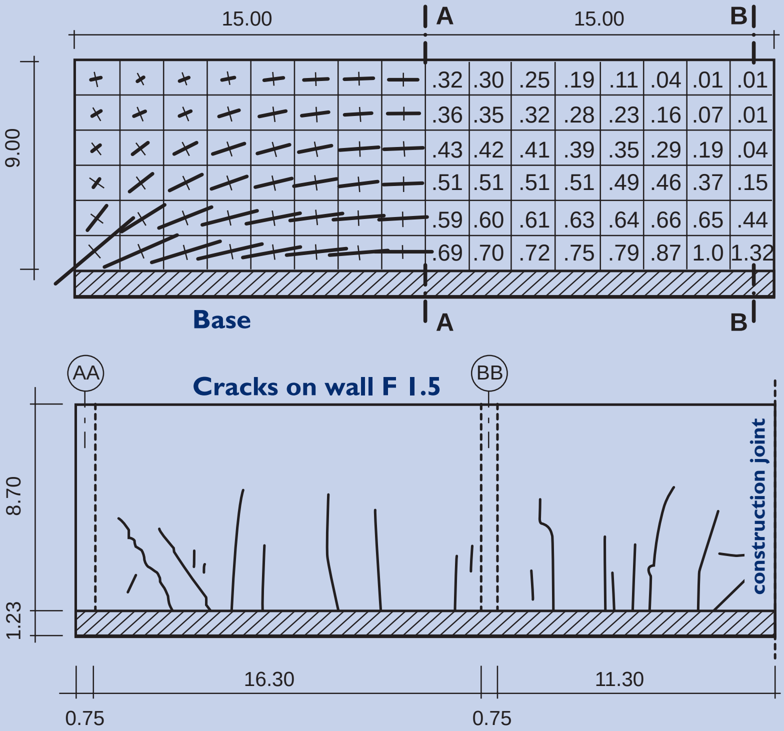


Fig. 3: Temperature and stress responses of a wall with and without cooling pipes





.32	.30	.25	.19	.11	.04	.01	.01
.36	.35	.32	.28	.23	.16	.07	.01
.43	.42	.41	.39	.35	.29	.19	.04
.51	.51	.51	.51	.49	.46	.37	.15
.59	.60	.61	.63	.64	.66	.65	.44
.69	.70	.72	.75	.79	.87	1.0	1.32

Fig. 4: 3D diagram of the temperatures of a wall with cooling pipes

Fig. 5: Direction of principal stress with values in a wall, resulting from a drop in temperature and the cracks in a wall of the Ruhleben clarification plant

The measurement of temperature and strain responses was used to verify computer generated computational models **(Figure 4)**. The computational models could then be used to study the effect of various measures to reduce tensile stresses in concrete walls. In a scheme specifically created for this purpose, the wall cross-section is divided into finite elements and the temperatures of each element are ascertained, allowing for the heat gain from hydration, the heat losses from the cooling pipe and the constraints at the surface of the wall. In a second step, stresses are calculated from the temperatures, allowing for relaxation and the “plate effect” of the wall **(Figure 5)**.

As a result of these measurements, it was discovered from a computer simulation of the temperature and stress conditions that:

1. the cooling period was too long; cracks were virtually “cooled into” the walls.
2. pre-heating the foundation level before concreting was good for preventing cracks.

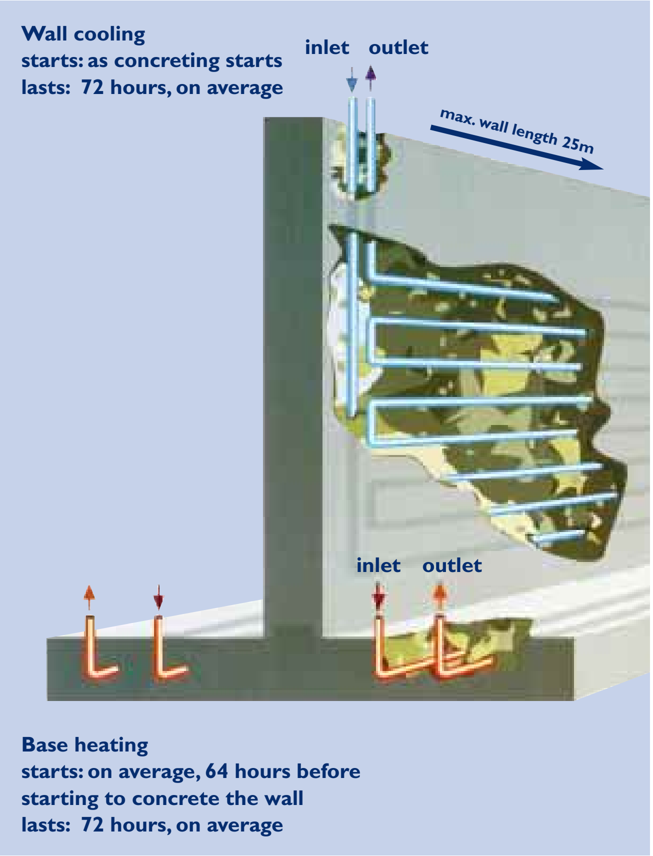


Fig. 6: Diagram of base heating and wall cooling

Armed with this knowledge, a method was developed for the construction of two further clarification plants, Waßmannsdorf II and III, to the south of Berlin, which it was hoped would prevent cracks altogether. Hot water flowing through internal pipes heats the base plate for at least three days before concreting the wall, causing it to expand. When the accompanying wall is concreted, the base heating is turned off; the base plate contracts as it cools, which prestresses the wall on top, to prevent tensile stress occurring. Cold water running through internal pipes cools the freshly concreted wall, to keep down the temperatures in the fresh concrete and the tensile stresses. **Figure 6** shows the chosen design for base heating and wall cooling. The calculated model was tested by taking extensive temperature and strain measurements in the walls and base plates.

As an example, **Figure 7** shows typical temperature and strain responses for a settling basin wall which has been neither cooled nor had its base plate heated. You can see the rapid rise in temperature in the wall caused by hydration heat during the first 1.5 days. The still largely soft fresh concrete and the large relaxation capacity mean that the increase in temperature only creates a slight strain (pressure). The later drop in temperature attracts attention because of the greater strain (tension), which can exceed breaking elongation and lead to cracks. The increase in strains from top to bottom is easily detectable.

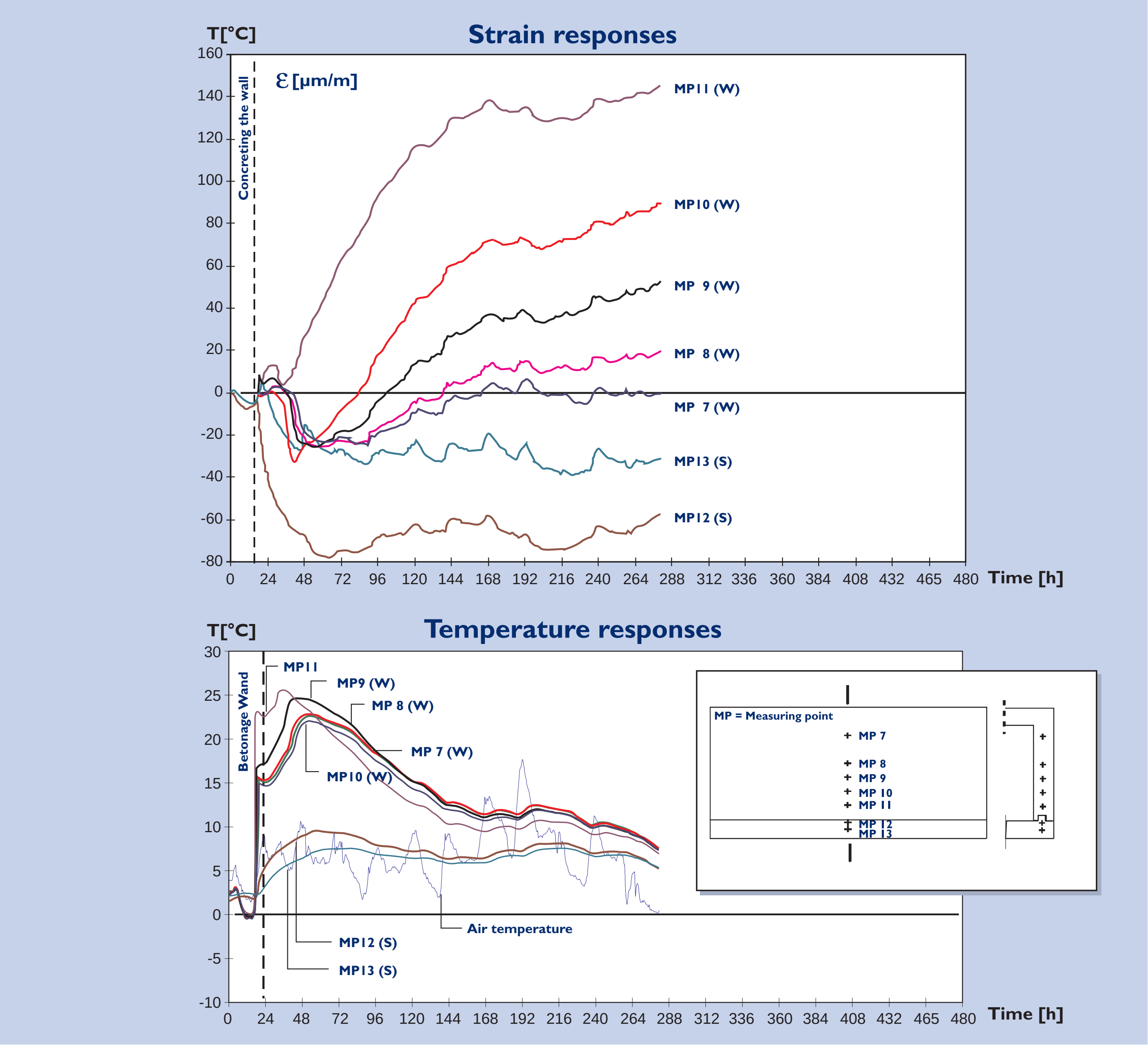


Fig. 7: Measured temperature and strain responses in a wall

Fig. 8: Site of the Wassmannsdorf clarification plant near Berlin

Figure 8 shows some settling basin walls. The real sizes of the settling basins in Waßmannsdorf can only be appreciated by an aerial photo, which would then not show any details; we have therefore reproduced this site photo as an example.

2 Equipment and measurements in Ruhleben and Waßmannsdorf

The block diagram in **Figure 9** shows the measurement setup. All the devices have been housed in a roofed cubicle.

We chose as the measuring instrument the UGR 60 made by Hottinger Baldwin Messtechnik (HBM), which was a new arrival on the market. This measuring instrument does not have any control elements, it is simply programmed to measure by a computer; the measured values are accepted by the computer after measurement. The UGR 60 (no control panel, no display field, just computer controlled) was later converted to a UPM 60 (the same measuring instrument with a control panel and an additional manual measurement option). The reason for this was that there were no visual signals on the UGR 60 when programming and measuring. Neither was it possible to carry out quick check measurements by hand.

Measurements were made at two major construction sites. The cranes had powerful electric motors which were located right next to the measurement cubicle. An electronic counter was therefore set up to generate a reset pulse for the measuring instrument and the computer every thirty minutes. The line frequency was used as the time base in this electronic counter and this proved to be extremely stable, at least in the initial measurement run in Ruhleben. In Waßmannsdorf, the time intervals were not precisely 30 minutes (differences per day up to approx. ± 30 secs.); the reason for this was that the supply network frequency was not stable.

This reset circuit rebooted the operating systems of both the IBM-compatible computer and the UGR 60 measuring instrument before measurement was carried out. It was feared that the high inductance switching of the crane motors would cause voltage peaks in the power supply system and thus immobilise the instruments, but this risk was virtually eliminated; only single measurements could be lost, in other words, one per 30-minute cycle, which could be disregarded and which also occurred during site operation.

A further advantage of this reset circuit became obvious in rough site operation. In this situation, it often happens that the power supply is interrupted because, for example, construction workers simply pull a power cable or the feed of a subdistribution out of a socket in a site distributor if they want to plug in an electric tool. When they later plug the power cable to the measurement system back in, the operating system is immediately rebooted and a measurement is automatically taken; the counter in the reset circuit immediately continues to count in thirty minute cycles; there is merely a time shift and possibly a gap between measured values which is longer than 30 minutes.

The DIL-switches on the back of the UGR 60 are always set to a cold start for this type of device programming. In Ruhleben, only the temperatures were measured. In Waßmannsdorf, as well as the temperatures, strains in the quarter bridge circuit were also measured. For each ten strain gauges (S. G.) a high-precision comparator resistor had to be temperature stabilised, to prevent any measurement errors being caused by temperature drift. This was achieved by using an existing thermostat, which kept a water bath at a constant temperature of 40 °C.

To monitor whether the UGR 60 measuring instrument was measuring perfectly, 2 × 120-ohm precision resistors (dummys) were measured at the last two available S. G. channels.

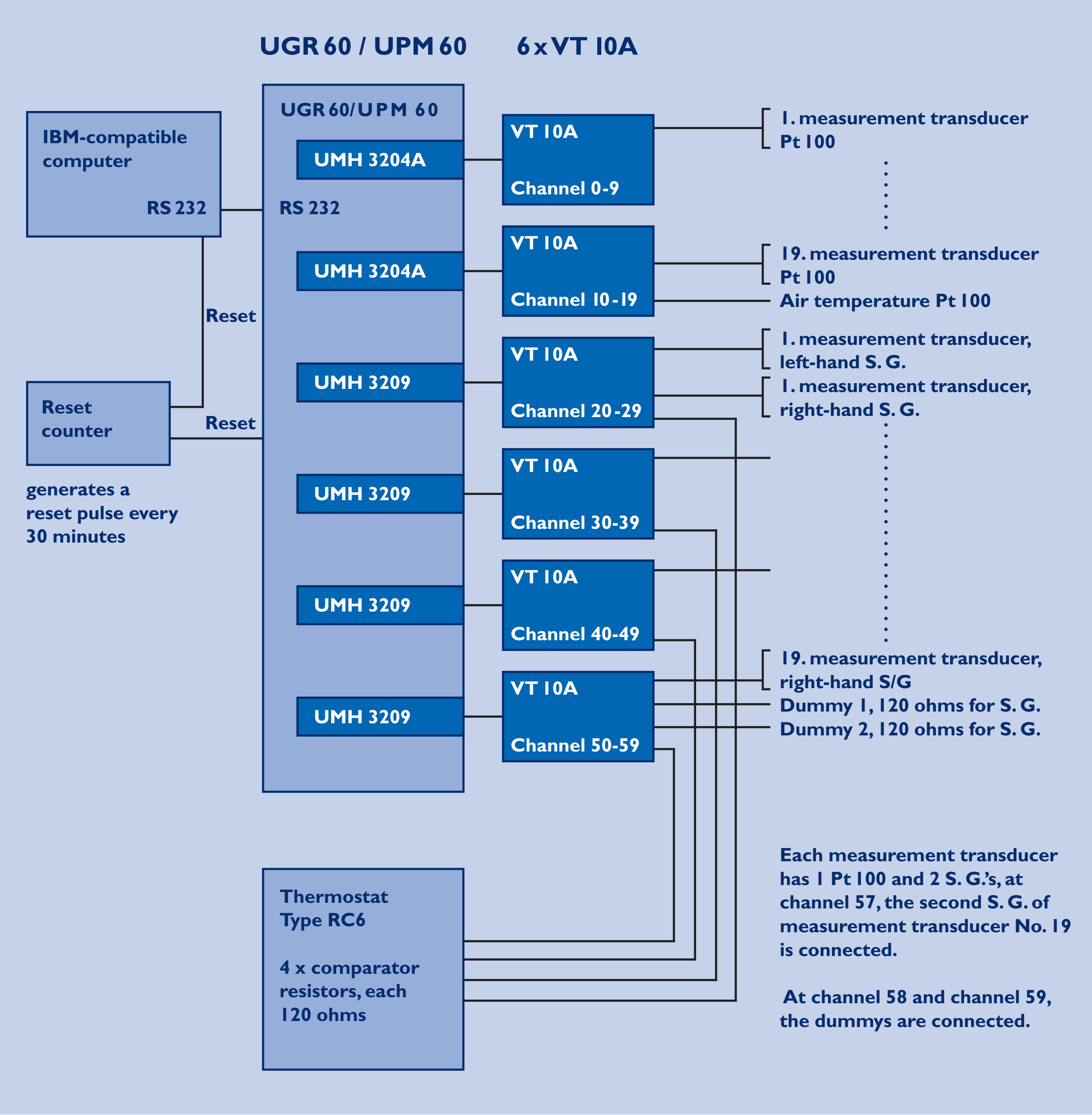


Fig. 9: Measuring device block diagram

The changes in strain and temperature to be expected in this study were purely static. A circadian plot through the day and nighttime temperature changes was superimposed on these gradual changes; this can be clearly seen in **Figure 7** (see page 5). Measurement technique failure for a short while could be disregarded, as only one or at least, only a few data records would be missing. Long-term failures, on the other hand, could not be allowed, as it only took a week for the crucial changes in the reinforced concrete wall to be completed and the actual measurement run terminated. This is why, after concreting, the measurement system was checked every day at the site, even Saturdays and Sundays. The stored measured values were looked at with a conventional editor. The measured values at the dummys were also checked; these measured values had to be the same for each measurement; any tolerances had to be within the device measuring accuracy; slight variation caused by the temperature coefficient of the dummys in relation to the outside temperature, was permissible.

The measurement period at the construction site was dependent on numerous imponderables, of which the weather was just one. Approximately three weeks were allowed for each reinforced concrete wall, including setting up the measurement system and installing the measurement transducers in the reinforcing core. In such a major construction site, deadlines are always being moved; the onset of winter in 1993/1994 was also a factor. Altogether it took approximately five to six months to measure five walls.

Equipment:

a) UGR 60, later converted to UPM 60,
with the following accessories, all HBM:
2 modules for Pt 100 measurements: UMH 3204A
4 modules for S. G. measurements: UMH 3209
6 distribution boards type: VT 10A
6 connecting cables type: Kab 0231-3

b) IBM-compatible computer, 286 processor.

c) reset counter of in-house design.

d) 6 precision resistors, 120 ohms, type 1142,
from Burster Meßtechnik.

e) thermostat, type RC6, from Lauda.

3 Transducer construction

The following transducers were used:

a) Pt 100: type PCE 1.4328.1,
made by Jumo, M.K. Juchheim GmbH
dimensions: 4.3 mm × 2.5 mm × 2.8 mm (W × H × L)

b) S.G.: type 120 LC11, from HBM
S.G. adhesive: EP 310, from HBM
first covering: SG 250 from HBM
second covering: ABM 75 from HBM

A four-pole shielded cable conforming to the specifications in the measuring instrument description for the HBM UGR 60 was selected as the measuring cable. The length of measuring cable between the measurement transducers and the distribution boards was always 33 m.

Physical construction of the measurement transducers:

a) The temperature sensors for Ruhleben:
Precision resistor and cable were cast with synthetic resin in a 8 mm × 0.5 mm steel pipe the length of which was l = 70 mm; this made the transducer watertight.

b) Strain and temperature sensors for Waßmannsdorf:
The S.G.s, the associated soldering terminals and the Pt 100 were attached to a square steel bar 12 mm × 12 mm × 500 mm.

After soldering the measuring cable, the first covering was made with the SG 250 (HBM), a transparent one-component silicon rubber. This covering on its own makes the S.G.s, the Pt 100 and the soldering points watertight. A second covering, of the ABM 75 which is like plasticine, was applied purely as a safety measure. This was justifiable because of the high measurement transducer costs, the long manufacturing time for measurement transducers and need for the measurement transducer to be absolutely reliable.

Finally, the measurement transducers were given a concrete sleeve to protect them, during concreting, from the shock of fresh concrete falling on them from approx. 3 - 8 metres away. As the concrete layer covering the transducer was very thin, it was reinforced by a wire grid cage, designed to prevent the concrete covering breaking up and flaking off (see **Figure 10,** stage before last).

Fig. 10: The measurement transducer used with two S.G.s and a Pt 100 in the individual production phases

Figure 10 shows the installed measurement transducer in the individual production phases and also with the various coverings.

For reasons of cost, it was decided in Ruhleben not to buy distribution boards for the measurement; 2 in-house design distributors were used. For later measurements, in Waßmannsdorf, we changed our minds again, as the HBM distribution boards with their screw terminals were very practical for use on a construction site and with good preparation, let you quickly connect the measuring cables on-site (for 60 channels, 240 cables and 60 shielded cables had to be connected perfectly).

Inside the future reinforced concrete wall, the measurement transducers were installed on the reinforcing core at previously specified points. **Figure 11** shows a measurement transducer introduced into the reinforcing core.

Fig. 11: Measurement transducer integrated into the reinforcement

4 Measurement sequence

Before the measurement run, the UGR 60 measuring instrument and the computer were fully re-initialised by the reset counter. It had to be totally re-programmed again, just as if it were a cold start. To prevent measurement errors, each channel was measured seven times. During the first days of measurement in Ruhleben, we were still using a routine which also ascertained whether the measured values were within a preset allowed tolerance. If necessary, the program automatically took an additional series of measurements for a channel, if this tolerance limit were exceeded. Then in Waßmannsdorf, we changed our minds about this measurement signal monitoring, as the measured values could be reproduced with great precision. In the spring of 1996, in-house studies on the reproducibility of the UGR 60/UPM 60 measured values indicated that it is better to let the measurement program itself monitor the measured signals during the measurement run, as occasionally, despite the excellent accuracy class of the measuring instrument, there are freak values among the measured values, the cause of which cannot be ascertained, either during measurement or afterwards. As the permissible tolerance in the measurement program, you could allow the tolerance permitted under the accuracy class specified by HBM. For strain measurements, for example, at 225 Hz carrier frequency and 5V bridge voltage, this tolerance would be, ± 4 µm/m, i.e. the maximum difference for the two measured values furthest apart is 8 µm/m. This can be easily monitored by the software; if the difference is greater, the software carries out additional measurements and discards the faulty measured values.

After each measurement run, the data was written to the computer's hard disk. The file name was worked out from the date and the time of the computer's internal clock. This type of file name formation is tried and tested and was chosen because it could generate a unique file name, totally independently of all the read operations on the hard disk, which, on a construction site, might quite possibly develop a fault.

Example: file name 1104-03.30
The data in this file was measured
on November 4 at 3:30.

With this type of file name assignment, site monitoring can also immediately detect whether any measurement series are missing, e.g. because of power failure or any other interruptions. If there is a power failure in between, there is always a time shift, which changes the file extension, e.g. in the above example, to 41 for 41 minutes, i.e. the measurement was taken at 3:41, instead of 3:30.

5 Concluding remarks

These measurement runs have taught and confirmed the following:

- On construction sites, you always have to assume there will be power failures. Once the power is switched back on, it must always be possible for measurement to continue automatically.

- If a measurement cannot be repeated at a different site, you have to make sure that replacement devices can be borrowed from the device manufacturer (here HBM) extremely quickly – in less than 24 hours, for example.

- Despite the considerable cost involved, distribution boards have proved to be well worth the money, as measurement transducers can be quickly and flexibly installed for a new measurement.

- It is constantly being demonstrated that once you have bought a measuring instrument, you will find on the next occasion that it has insufficient channels to cope with the number of measurements required. Compromises have to be found regarding the desire for a large number of measurement points and the technical possibilities of an existing device.

6 Aim achieved

- Extensive measurement verified the computational model established at the Institute for determining the temperature and stress fields in the hydration phase. It can be used to assess by computation measures designed to prevent cracks.

- The method developed (base heating and wall cooling) was implemented at a major construction project on site and produced good results.

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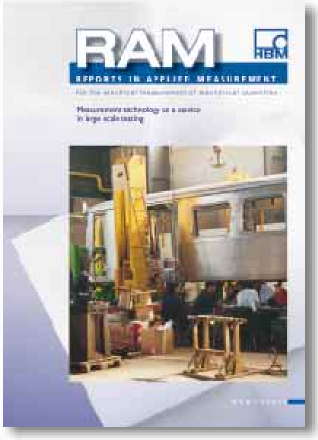

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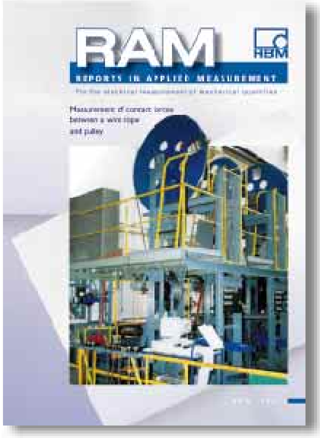

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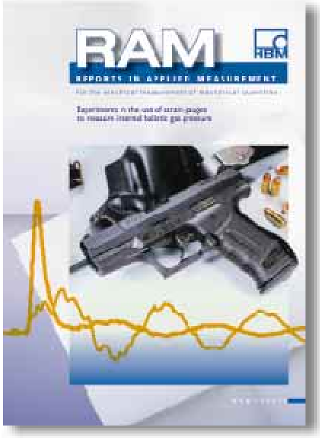

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