The Behaviour of Concrete Under Attack of Liquid Steel

U. Schneider
Fachbereich Bauingenieurwesen, Gesamthochschule Kassel, Postfach 10 13 80, D-3500 Kassel, Germany
C. Ehm, U. Diederichs
Institut für Baustoff, Massivbau u. Brandschutz, Technische Universität Braunschweig,
Beethovenstr. 52, D-3300 Braunschweig, Germany

Summary

Within the scope of studies on the behaviour of concrete at extreme high thermal loadings investigations were carried out concerning the consequences of a hypothetical core-meltdown. As one result of such a core-meltdown liquid metals with temperatures up to 3.000 °C will attack concrete. So the problem had to be solved how concrete behaves under these extreme loadings and whether liquid metals can penetrate and destroy thick-walled concrete structures.

Therefore investigations were carried out to study the interaction between concrete and liquid steel. Different types and different forms of concrete were investigated at temperatures of liquid steel between 1.600 and 2.600 °C. The liquid steel of 1.600 °C was produced in an induction furnace, the liquid steel of 2.600 °C was produced in concrete crucibles by metallothermic reactions.

The reactions occuring during the interaction of concrete and liquid steel may be summarized as follows:

- Concrete reacts violently upon sudden loading with high temperatures and high heat fluxes. Great quantities of steam and gases are generated. The mechanical strength decreases rapidly with increasing temperature.
- At about 1.200 °C concrete begins to melt. First the cement matrix melts, then the aggregates melt. The melts of different concretes consist of different constituents and their reactions with liquid steel vary. The temperature of the liquid steel significantly influences the intensity of the reactions and the erosion rates.
- The erosion rates amounted to 30 mm/min, when liquid steel was produced in concrete crucibles. When cylindrical concrete specimens were immersed in molten steel the rate of melting off amounted up to 66 mm/min.
- The dissipation of heat during the interactions brings about that the reactions between concrete and liquid steel vanish gradually, if no additional energy is fed into the system.

1. INTRODUCTION

Investigations concerning the behaviour of concrete under attack of liquid metals were carried out since - within the scope of risk studies - experimental and theoretical work about the course of hypothetical core-meltdown accidents was done.

A hypothetical core-meltdown accident can be divided into four phases:
- core heat up (phase 1),
- residual water evaporation (phase 2),
- reactor pressure vessel heat up (phase 3) and
- penetration of containment concrete (phase 4) /1/.

The barrier material concrete is matched by the consequences of this accident especially in the third and the fourth phase. But also in the second phase locally high thermal loadings of the reactor pressure vessel are possible so that the unity may fail. In the third phase, the reactor pressure vessel will be heated up and fail in a relative short time. Thereafter in the fourth phase an interaction of core melt and concrete will occur.

On the basis of this accident pathes it is necessary to give answers on the following questions:

- how does concrete behave in different ranges of temperatures (from ambient temperature up to 2.500 °C);
- what kind of reactions occur when core melt and concrete surfaces interact;
- what are the consequences of these reactions and the high loading of temperature on the concrete barriers;
- are concrete structures able to offer resistance against molten corium and which parameters do influence this resistance.

To answer the questions concerning the behaviour of concrete at high temperatures results of investigations within the scope of fire protection are very helpful. Within the scope of reactor design research the mechanical properties of concrete are studied for temperatures up to 250 °C. A state of art report on this themes has been published recently /2/.

Physical properties of concrete are well known for temperatures up to 1.000 °C, but only a few works, for instance /3/, provide informations about the melting of concrete. Concerning the behaviour of concrete at temperatures beyond 1.200 °C and under attack of liquid core melt only few investigations and experiences exist.

To examine this problems complete new test techniques are necessary. Nevertheless it is with limitations possible to simulate the events more or less well compared to the real accidents. To investigate the melting off of concrete, for example, the concrete was exposed either to high densities of thermal radiation or to the influence of plasma jets /1, 4/. At the same time the behaviour of concrete at sudden thermal loadings was studied.

In the course of these investigations great problems with testing and measuring techniques had to be solved. The problems increased when the behaviour of concrete under attack of hot and liquid core melt was investigated. Therefore liquid steel was taken to simulate the core melt for these experiments.

During the first phase of investigations steel melts and other corium like materials were produced by metallothermic reactions with temperatures up to 2.600 °C. So the thermal loading of the concrete was simulated very close to a hypothetical core meltdown accident.

On account of the experimental problems, computer codes were developed by different workers as to make extensive studies with various parameters. More and more the practical researches were carried out to verify these codes /5/. By this way first results were found on melt front propagation and on phenomenology of interaction of concrete and steel melts.

Our investigations were carried out as to make a small contribution in solving the above mentioned problems.

2. TEST PROGRAM

Our test program on the interactions of concrete with molten steel was divided into two parts:

In the first part (part A) cylindrical concrete test specimens were immersed in a steel melt. In the second part (part B) molten steel was produced in concrete crucibles by metallothermic reactions. A general view of the test and measuring program is given in figure 1.

The cylindrical test specimens of part A had a diameter of 8 cm and a length of 30 cm. They were reinforced with steel fabrices to prevent explosive spallations. Some of the test specimens were stored until testing according to DIN 1048 (20 °C, 65 % rel. humidity), the others were dried at 105 °C.

The concrete crucibles of part B measured 60 x 60 x 60 m^3 and had cylindrical cavities with diameters of 40 cm and depths of 50 cm. In the cylinders and crucibles thermocouples were embedded which indicated the development of temperatures inside the concrete.
The failure of the thermocouples at 1.370 °C indicated the melting of concrete and the penetration of molten steel. The crucibles were furnished with marks for measuring extensions and receivers for measuring sound emission impulses. The test specimens were produced by three kinds of concretes: one concrete with quartzitic aggregates, one concrete with mainly limestone aggregates and one concrete with mainly basaltic aggregates. The concrete specifications are listed in table 1.

The molten steel of the test part A was produced in an induction furnace and had a temperature up to about 1.600 °C. In part B the molten steel was made by metallothermic reactions directly in the concrete crucibles and reached temperatures up to 2.600 °C. The quantities of thermite amounted from 50 kg to 130 kg.

3. TEST PROCEDURES, OBSERVATIONS AND RESULTS

Before investigating the interactions between concrete and molten steel tests were performed where concrete was exposed only to high thermal loadings. Therefore the cylindrical test specimens were exposed to the flames of an oxyacetylene blowpipe with temperatures up to 3.100 °C. In some other tests the cylinders were approached to the 1.600 °C hot molten steel. When the concrete began to melt the cylinders were moved down via the surface of the metal liquid as to provide a more or less constant thermal loading.

The qualitative results of these tests are:

- there are no explosive spallations likely to occur, when concrete is exposed to high heatflux densities of these types,
- at about 1.200 °C concrete begins to melt and starts dripping off,
- the quantity of liquid melt of quartzitic and basaltic concrete is greater than that of limestone concrete,
- the dripped pieces freezed with a vitreous coating. White crystals (cristobalites) are coated with a glaze. The freezed melt of quartzitic concrete is glassy-green, that of limestone concrete is olive and not glassy,
- concrete melt dripping on the steel melt reacts only a little with the molten steel.

After these pilot tests with thermic loadings the test speciemens were according to part A of the test program in a defined manner immersed in molten steel. For that purpose at first the test specimens were put above the middle of the induction furnace and then they were immersed in the steel melt with the aid of a gallows type lowering device. After a fixed time the immersed specimens were pulled out of the steel melt. The reaction products which swam on the steel melt were collected for making chemical analyses.

Because of the high rate of thermal loading (about 1.600 K/s) it was not possible to observe variations of colours in the concrete which is normally observed, when concrete is heated slowly. The reactions which occur during immersion can described as follows:

- When the concrete specimens are immersed, physically bounded water of the concrete evaporates immediately. The steam bubbles burst partly and the steel melt begins to sizzle and to bubble. Glowing particles are expulsed from the liquid. The lowering device shaked up violently. The concrete begins to melt immediately and the concrete melt spreads over the steel melt.
- Gas and steam - in the main carbondioxide and water vapour - escape from the concrete. A part of it is reduced in the steel melt and the reaction products carbonmonoxide and hydrogen ignite. The flames above the specimens became greater and greater. Especially limestone concrete seemed to burn intensively in this stage. The reactions decreased with increasing time of immersion.

In figure 2 the development of temperatures in two thermal loaded limestone concrete specimens is shown. One specimen was stored at 20 °C/65 % r.h. (according to DIN), the other specimen was dried at 105 °C. In the more wet concrete temperatures up to 100 °C increased quicker than in the dried concrete, due to the better thermal conductivity. The holding points at 100 °C which can be seen in the diagrams results from the evaporation of physically bounded water. Behind the 100 °C-points temperatures in the wet concrete increase quicker than in the dried concrete.

In figure 3 the development of temperatures in two quartzitic concrete specimens is shown. One specimen was stored at 20 °C/65 % r.h., the other was dried at 105 °C. Both specimens were immersed in the steel metl too. It is to be seen that the increase of temperatures is faster than in the experiments with concrete specimens only being thermally loaded. This results from the better heat transfer between concrete and steel and the two-dimensional heat flow into the concrete.

The loss of weigth resulting from meltung off of the concrete specimens was measured continiously by an electric load cell built on the lowering device. After the tests the lengths of the specimens were measured. With these data rates of melting off could be calculated. They are listed in table 2. The rates of the DIN-stored specimens are greater than these of the dried specimens. This is a result of the greater heat conductivity of the wet specimens. The rates the limestone concretes reach the highest erosion rates, a result of the decomposition of the limestone into lime and gaseous carbon dioxide.

The reaction product due to the interaction between concrete and molten steel is a slag which was chemically analysed. The slags mainly consist of silicium dioxide and calcium oxide, which comes from concrete, and oxides of iron which originate from the steel melt. It can be seen that the slag from the limestone-concrete interaction with steel had more calcium oxide and less silicium and iron oxides. This explains the lower constistency of this slag in the hot stage.

In part B of the test program mainly the melt front propagation of molten steel in concrete with various aggregates was investigated. For this purpose the concrete crucibles were filled with fixed quantities of thermite and then the thermite was ignited. About 8 s after ignition the thermite reaction starts and it lasts for around 20 s. During its course great quantities of smoke and steam are expelled, accompanied by a shower of sparks. Then flames grew higher and burned for about 50 s. Thereafter the height of the flames decreased rapidly and only a few of them burned for 200 s like blow-pipes.

The intensity of the reactions depend on the quantity of thermite and the type of concrete. The reactions are more violent when lager quantities are being used. The tests with the limestone concrete showed an enormous amount of flames, a few of them were several meters high.

The measuring technique for determining the crack development intensity was the Acoustic Emission Analyses (SEA). The SEA acoustic waves produced in the concrete were picked up and analysed. These measurements showed that the optical observations of high reaction intensities are being accompained by intensive crack development processes.

A few minutes after ignition it was possible to inspect the crucibles from close up. Liquid water poored out of 4 broad and some small cracks. Later water vapour came out of these cracks and out of further smaller cracks.

In figure 4 the development of temperatures in the bottom of a quartzitic concrete crucible is shown. The temperatures near the thermite powder increase in a few seconds up to 1370 °C the failure temperature of the thermocouples. Only at the farest ones a holding point at 100 °C can be observed. Later these temperatures increased up to 800 °C. It took about 25 h until the specimens cooled down to room temperature.

The failure of the thermocouples indicated the penetration of the steel melt into the concrete. Together with the data from later measurements of the geometry of the cold specimens a rate of erosion for each concrete was calculated. On table 2 these data and for comparison reasons data of other investigators are presented.

After cooling down the weights of the specimens were determined. The limestone crucible with the largest quantity of thermite had suffered the greatest loss of weight, because of the release of great quantities of gaseous carbon dioxide. Losses due to spallations were not found or observed.

Thereafter the specimens were cut into pieces. It was possible to make the following inspections

- depth of penetration of the steel melts, horizontally and vertically,
- zone of reaction in the concrete,
- alterations in concrete structure,
- cross-section of solidified steel and its permeability,
- distribution of cracks,
- geometry of the tested crucibles.

Figure 5 shows a schematic cross-section of the concrete crucibles. Most of the cavities were filled with aluminum oxide (corundum). Underneath there was the solidified steel which had a disk like form with curved sides. The inferior surface turned towards the concrete had uniformly distributed bulgings (knubs) and holes (pores). The steel regulus was permeable for air, which could stream through canal-like openings. Underneath the steel regulus was an air cleft followed by an intermediate layer of dicalciumferrite being attached to the concrete. The concrete at this contact surface was completely dehydrated. The following concrete layers were less dehydrated according to the lower temperatures which they were exposed to.

4. CONCLUSIONS

The investigations have shown that concrete can resist extreme thermal loadings especially the attack of liquid steel. But its resistance must be paid by a loss of matter and therefore it is limited. This means for practical applications that sufficient quantities of high quality concrete, and very thick foundations are necessary if a hypothetical core meltdown is to be considered.

REFERENCES

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/5/ Perinić, D. et al.: "Betontiegelversuche mit Thermitschmelzen", Research Paper KfK 2572, Kernforschungszentrum Karlsruhe, July 1979.

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Table 1: Concrete specifications

			concrete		
			quartz-	basalt-	limestone-
Cement PZ 35 F		[kg/m^3]	360	350	358
Water		[kg/m^3]	220	175	215
aggregates:					
quarzitic	0/2	[kg/m^3]	642	731	-
"	2/8	"	500	405	-
"	8/16	"	768	-	-
basaltic	8/11	"	-	635	-
"	11/16	"	-	173	-
limestone	0/2	"	-	-	562
	2/8	"	-	-	938
	8/16	"	-	-	375
density after 28 days		[kg/dm^3]	2,39	2,53	2,47
compressive strength after 28 days		[N/mm^2]	54,0	61,0	45,0

Table 2: Erosion rates of different concretes

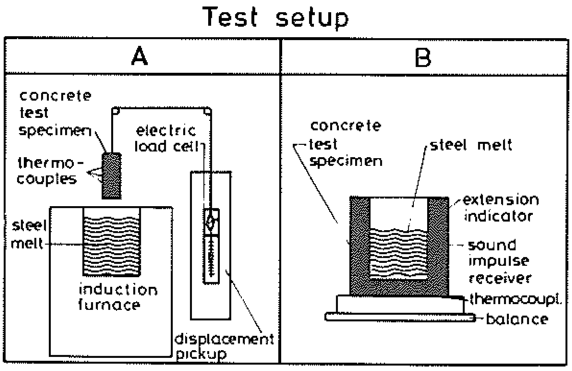
Type of concrete	Mean erosion rate [mm/min]	Test procedure	Author
basaltic limestone	20	metallothermic reaction	Sutherland [6]
silicous	40	metallothermic reaction	Perinic et al. [5]
basaltic	22	molten pool arc-heating	Hildenbrand [1]
limestone	35		
basaltic limestone	12	plasma jet	Muir [4]
limestone	66	immersed in molten steel	Ehm et al.
silicous	44		
basaltic	10	metallothermic reaction	
limestone	20		
silicous	30		

Test program

A	B
immersion of cylindrical test specimens in a steel melt	producing of steel melts in concrete crucibles

Measuring program

A		B	
temperatures	T_i	temperatures	T_i
weight of specimen	G	weight of specimen	G
depth of immersion	x	quantity of steel	M
time of immersion	t	time of reaction	t
length of specimen	l	sound impulses	N
		extensions	s



Test evaluation

A	B
kinetics of reactions, reaction masses, development of temperatures in the concrete, rate of erosion	

Fig. 1: Plan of tests

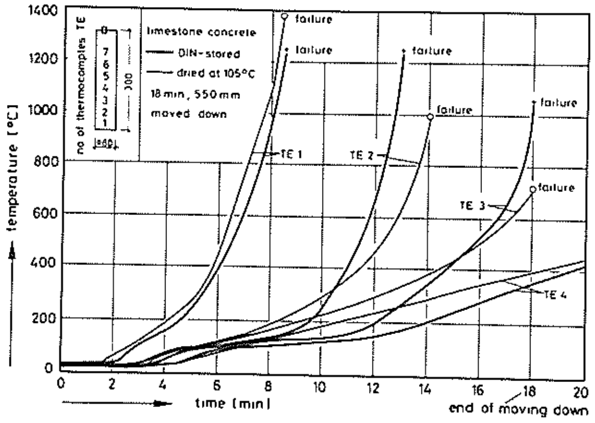


Fig. 2: Development of temperatures

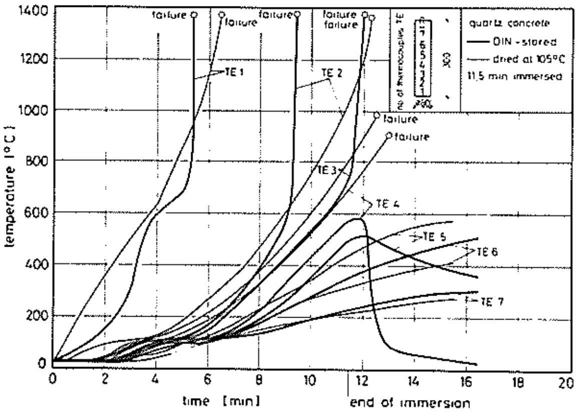


Fig. 3: Development of temperatures

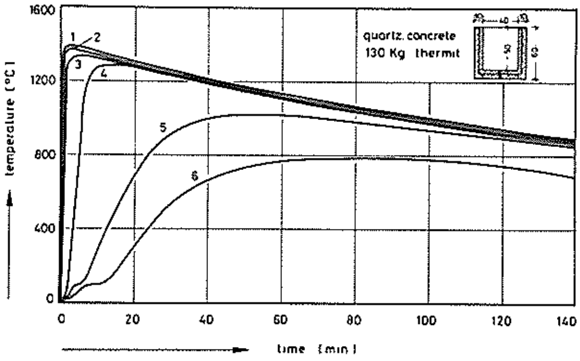


Fig. 4: Development of temperatures

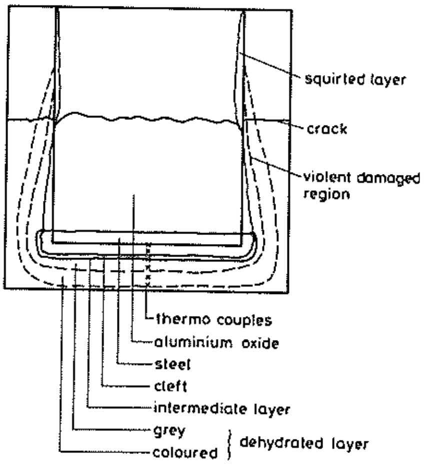


Fig. 5: Cross-section of concrete crucibles