DEVELOPMENT OF A METHOD FOR MEASURING DESTRUCTION ENERGY AND GENERATED HEAT AT FATIGUE OF CONCRETE

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ABSTRACT

In fatigue of concrete, if the loads are not uniformly repeated and the dynamic load levels change, every particular load will contribute with certain portion to the fatigue deterioration of the concrete. For estimation of this destruction of concrete the Palmgren-Miner partial damage hypothesis has been used, but has turned out to give contradictory results. As the Palmgren-Miner hypothesis is not generally applicable to fatigue of concrete attempts have been made with volumetric, ultrasonic and acoustic emission measurements to interpret the damage accumulation in concrete. However, no acceptable relation between the measured values and the fatigue deterioration of concrete caused by different loads has been found. The present paper investigates a method for another parameter, which might be important for the deterioration process to be understood, when concrete is loaded by varying dynamic loads. The parameter is the energy absorbed by the concrete and is represented by the work in a form of load times of the deformation for each cycle of load. At each un-loading certain energy is regained, but not all. The load deformation relationship shows a hysteresis and the area within the hysteresis loop represents the absorbed energy used up in the material causing micro cracks, crushing material, redistributing stress and rising temperature due to internal friction. This research investigates methods to determine the energy for the fatigue destruction of concrete and for the rise of temperature within the concrete specimen. Different types of plates and Teflon layers are tested to avoid friction between cylinder ends and loading platens. An insulating material layer with thermocouples around the concrete cylinder is used for heat loss measurements. The paper presents the tests done and discusses problems with the measuring methods. A result is obtained which does not exclude the hypothesis that the destruction energy for concrete in compression is the same whether it is a static or dynamic fatigue failure.

Key words: Concrete, fatigue, absorbed energy, destruction energy, heat energy, measuring methods

INTRODUCTION

During 1970-ies the first concrete oil production platforms in North Sea were planned and erected. It was concluded that the platforms were loaded by different waves up to 30m in height. These varying waves caused fatigue to the structure. The influence of changing repeated loads on concrete was not investigated at that time.

In fatigue of concrete, if the loads are not uniformly repeated and the dynamic load levels change, every particular load will contribute with certain portion to the fatigue deterioration of the concrete. For estimation of this destruction of concrete the Palmgren-Miner, Palmgren (1924), Miner (1945), partial damage hypothesis has been used for steel, but for concrete has turned out to give contradictory results.

The Palmgren–Miner rule states that failure occurs when

$$\sum_{i=1}^{I} n_i / N_i = 1 \quad \ldots \quad (1)$$

where n_i is the number of applied load cycles of type i, ;
N_i is the pertinent fatigue life.

In codes the Palmgren-Miner sum for concrete has been altered down to 0.2 for reason of safety.

As the Palmgren-Miner hypothesis is not generally applicable to fatigue of concrete attempts have been made with volumetric, ultrasonic and acoustic emission measurements to interpret the damage accumulation in concrete. However, no acceptable relation between the measured values and the fatigue deterioration of concrete caused by different loads has been found.

The present paper investigates a method for another parameter, which might be important for the deterioration process to be understood, when concrete is loaded by varying dynamic loads. The parameter is the energy absorbed by the concrete and is represented by the work in a form of load times of the deformation for each cycle of load. At each un-loading certain energy is regained, but not all. The load deformation relationship shows a hysteresis and the area within the hysteresis loop represents the absorbed energy by the concrete used up in the material causing micro cracks, crushing material, redistributing stresses and rising temperature due to internal friction.

This research investigates the methods to determine the energy for the fatigue destruction of concrete and for the rise of temperature within the concrete

specimen. It is necessary to avoid friction between the loading platens and the concrete cylinders end surfaces to enable representative measurements of concrete deformations during loading cycles. Further the amount of energy used for temperature rise in the specimen and heat exchange with the loading machine plus losses to the surroundings have to be determined. Different types of plates and Teflon layers are tested to avoid friction between the cylinder ends and loading platens. An insulating mineral wool layer with thermocouples around the concrete cylinder is used for heat loss measurements from the concrete cylinder side surfaces. A wood fiber layer with thermocouples is used for heat exchange measurements between the cylinder end surfaces with two Teflon layers and the loading steel platens of the machine.
These types of measurements are difficult to perform especially at a fast load pulsating frequency of 2 Hz measuring at several levels of strain. The paper presents the tests done and discusses problems with the measuring methods, which unfortunately did not work satisfactory and have to be improved further. A result is obtained which does not exclude the hypothesis that the destruction energy for concrete in compression is the same whether it is a static or dynamic fatigue failure.

METHODS

Hypothesis

It can be assumed that for concrete static failure as well as fatigue failure the same amount of destruction energy is required. At static failure all supplied energy is used to destroy the concrete (a very slight rise of temperature is possible). At fatigue failure of the concrete specimen the supplied and absorbed energy generates internal friction heat and destruction of concrete. The idea with the tests is to measure the heat energy and to separate it from the destruction energy. The performed tests have a pilot character, because the necessary measuring methods have to be developed.
The supplied energy is represented by the areas A1, A2 etc. under the load-deformation curve as it is shown in Fig. 1.

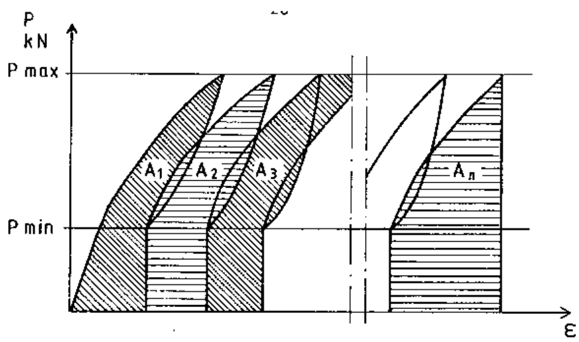

Figure 1. By the pulsating load machine supplied energy shown in load P – strain ε diagram.

The hysteresis loops represent the absorbed energy, which consist of destruction and the heat energy.

Energy balance

Energy balance of the in fatigue tested concrete specimen

$$\Delta W = \Delta E + \Delta Q; \quad \ldots(2)$$

Where
ΔW is absorbed energy from loading machine
ΔE is generated heat from internal friction
ΔQ is destruction energy

Energy absorption measuring method

The energy supplied to and absorbed by the concrete cylinder is measured according to Fig. 2 and Fig. 3.

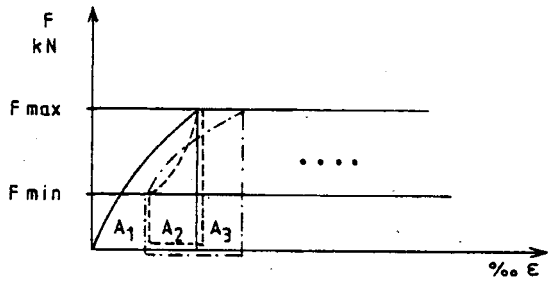

Figure 2. Load F – strain ε diagram showing absorbed energy measurement sequence. W = A1 – A2 + A3 – ….;

The longitudinal strain gauges on opposite sides of the concrete cylinder were used for the registration of strain ε. The energy driven into the cylinder by the loading machine is calculated from the measurements according to formula (3).

$$W = F \cdot \Sigma \Delta\, \varepsilon_{//} \cdot H; \quad \ldots(3)$$

Where W = energy, *Nm or J*
F = load *N*
$\Delta\varepsilon_{//}$ = incremented compressive strain ‰
H = height of cylinder *m*

The strain measurements were incremented in $\Delta\varepsilon_{//}$ according to Fig. 3 and the existing increments between the maximum and minimum load levels were used to register the measured load-deformation surfaces.
The strain gauge dummy is placed close to the cylinder surface under the insulating layer to have the same temperature as the strain gauges registering the vertical strain Fig. 4. It compensates for temperature changes.
The cylinders are loaded by sinusoidal load pulses with the frequency of 2 Hz. The recovery of concrete after each load cycle is connected with the applied rate of loading.

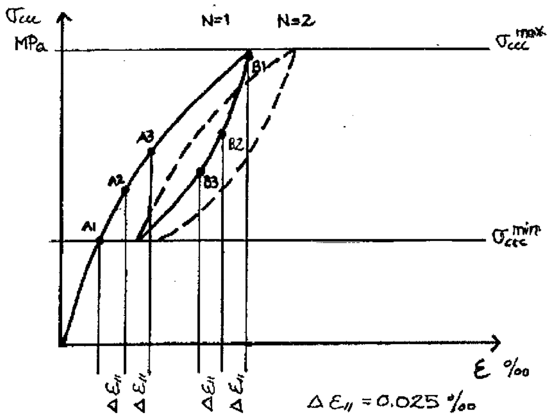

Figure 3. The principle for registration of $\Delta\varepsilon_{//}$ values from stress-strain relation. Frequency is constant.

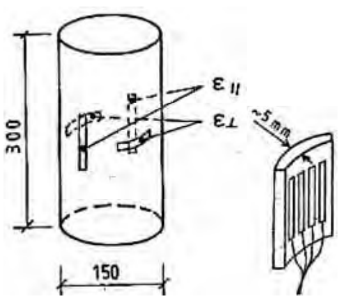

Figure 4. Strain gauges $\varepsilon_{\parallel}$ in longitudinal direction and $\varepsilon_{\perp}$ in transverse direction on concrete cylinders and dummy for strain gauges.

A part of the absorbed energy, which is measured, is that which gives micro cracking and blocked deformations within the concrete. The blocked deformations have a time dependent recovery. This means that when taking the measurements with a constant rate of loading the measured absorbed energy will belong to just this certain rate of loading.

The measured absorbed energy is defined by the areas under the stress-strain relationship according to Fig. 1 and 2. In the measurements the strain is incremented according to Fig. 3

The strain increments were chosen to be 0.025‰ at on- and un-loading and this instead of load increments which due to a slight vibration in the machine caused a contact between the incremented load levels to make the system to believe that the top load level was reached and caused the system to change the registration direction. The absorbed energy was registered continuously and at specimen failure the complete absorbed energy was in the computer.

At the static tests obtained cylinder strength f_{ccc} was used to determine the minimum σ_{ccc}^{min} and maximum σ_{ccc}^{max} load levels at pulsation tests. The relation $R = \sigma_{ccc}^{min}/\sigma_{ccc}^{max}$; was chosen to be 0.20.

Friction reduction between concrete cylinder ends and loading platens

To be able to measure the absorbed energy it is necessary that the concrete cylinder is not restricted in transverse expansion by the loading platens, Fig. 5, because otherwise it is not possible to determine correctly the absorbed energy by the concrete cylinder.

The layers between the concrete cylinder end surfaces and loading platens should be without friction hindering concrete expansion. Tests were performed for this reason. Uneven changing shear stresses at the end surfaces will generate uncontrolled heat and have to be avoided.

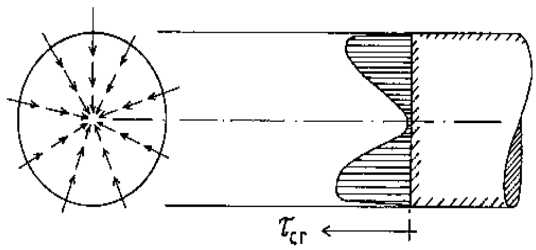

Figure 5. Fluctuating shear stresses τ_{cr} caused by friction, which also generate heat under load cycles.

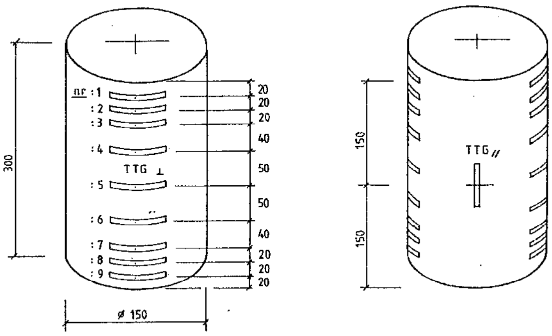

Figure 6. Arrangement of strain gauges $TTG_{\parallel}$ in longitudinal direction and $TTG_{\perp}$ in transverse direction on concrete cylinders.

The arrangement of strain gauges for measuring transverse expansion and longitudinal compressive strain is shown in Fig. 6.

Different layers consisting of wood fiber plates also cut in a form of a grid were tested. Long laboratory experience showed that wood fiber plates could be used instead of making a smooth layer on tested concrete objects surface exposed to compression. The best result was obtained with 2 layers of Teflon sheet between concrete and wood fiber plate giving uniform transverse deformation along the cylinder. The measured transverse expansion for 2 layers of Teflon sheet between concrete cylinder and wood fiber plate against loading platens of the machine are shown in Fig. 7. Two layers of Teflon sheet give uniform expansion of the cylinder under load and should enable the determination of the supplied energy in absolute value.

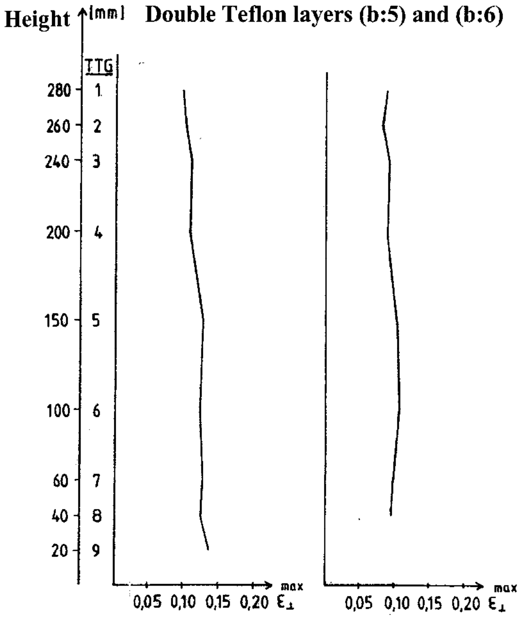

Figure 7. Along the height measured transverse cylinder expansion strain under load with two Teflon layers between cylinder and wood fiber plates against steel platens. TTG are strain gauges in transverse direction.
Tests (b:5) and (b:6).

Figure 8. With two Teflon layers to reduce friction, the concrete cylinder completely disintegrates at compressive failure. Vertical cracks show up.

The concrete cylinders with two Teflon layers for friction reduction disintegrated completely at failure, Fig. 8. They did not form the usual friction caused conical concrete peaces at the ends of the failed concrete cylinder. The tensile cracks, due to exceeding ultimate tensile strain in transverse direction of the cylinder, were vertical along the whole height of the cylinder. Double Teflon layers were chosen for tests.

Heat exchange of the concrete cylinder with surroundings

It is necessary to separate from the absorbed energy, the heat developed by internal concrete friction during the load cycles. This requires measurements of heat exchange with the surroundings and with the loading machine and also the heat stored by concrete. An insulating material layer (mineral wool) with thermocouples around the concrete cylinder is used for the heat loss measurements from the concrete cylinder side surfaces and a wood fiber plate with thermocouples is used for the heat exchange measurements from cylinder ends. The cylinder ends have 2 layers of Teflon, then wood fiber plate and then loading steel platens of the machine, Fig. 9 and 10.

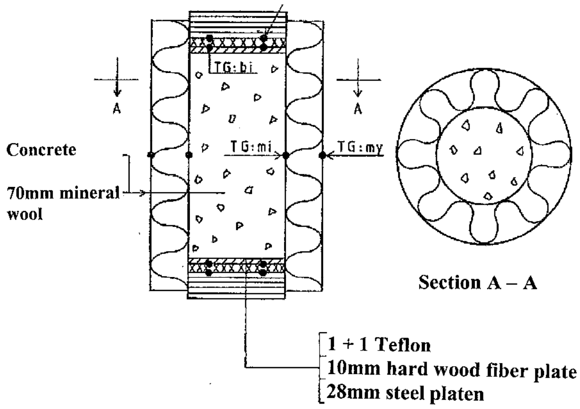

Figure 9. Thermocouples, TG:(location), attached on insulating layers.

A computer calculation program was prepared to register the heat exchange through the insulating jacket layer and the end insulating layers. During the test continuous heat flow from concrete cylinder was accumulated in the computer memory.

TEST PROGRAM

The test program is shown in Table 1. The used load frequency was 2Hz and $R = \sigma^{min}{}_{ccc} / \sigma^{max}{}_{ccc} = 0.20$. The number of load cycles N_c at failure in Table 1 has been calculated with equation (4) Aas-Jacobsen (1970) and Tepfers-Kutti (1979), Tepfers (1980 a, b).

$$\log 10\ N_c = (1 - \sigma^{max}{}_{ccc} / f_{ccc}) / \{(0.685\ (1 - R)\} \quad ...(4)$$

where:

N_c calculated number of load cycles at failure.
$\sigma^{max}{}_{ccc} / f_{ccc}$ maximum pulsating stress related to static concrete compressive strength.
$R = \sigma^{min}{}_{ccc} / \sigma^{max}{}_{ccc} = 0.20$.
$\sigma^{min}{}_{ccc}$ minimum pulsating stress.

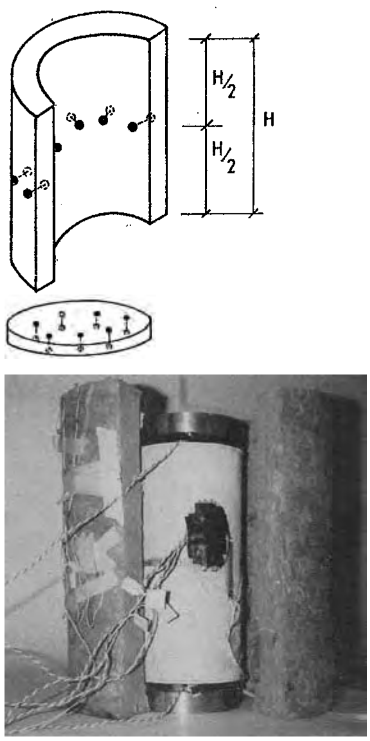

Figure 10. Concrete cylinder with insulating layers and wood fiber plates at cylinder ends with thermocouples.

Table 1

Test program of concrete cylinder fatigue tests with number of load cycles at failure N_c calculated with eq. (4)

Test No	$\sigma_{ccc}^{max}/f_{ccc}$	N_c	log N_c
C: 6, 7	0.90	67	1.8248
C: 8, 9	0.85	546	2.7372
C: 10, 11	0.80	4463	3.6496
C: 12, 13	0.75	36475	4.5620
C:14, 15	0.70	298194	5.4745

From the same batch of concrete 21 cylinders (height 300mm and diameter 150mm) and 12 cubes (side 150mm) were produced. 10 cylinders were tested in fatigue and three to determine static compressive strength. The rest was used for friction influence measurements and also in reserve.

CONCRETE

Composition of concrete was: cement 245 kg/m^3, water 196 kg/m^3, sand 1175 kg/m^3 and crushed granite stone 694 kg/m^3. For fresh concrete slump was 40mm, air content 1.0% and density 2365 kg/m^3. The specimens were after remolding stored under water for 5 days followed by 3 days under wet feltings and then in laboratory at temperature 20^o centigrade and RH 50% until the tests after 7 months, when the concrete strength was stable.

The mean compressive cube strength determined on 6 cubes was 40.1 MPa and cylinder strength on 3 cylinders was 30.1 MPa at time of fatigue testing.

The fatigue testing machine was Losenhausen 1000 kN servo pulsating machine with all sinus formed load pulses controlled.

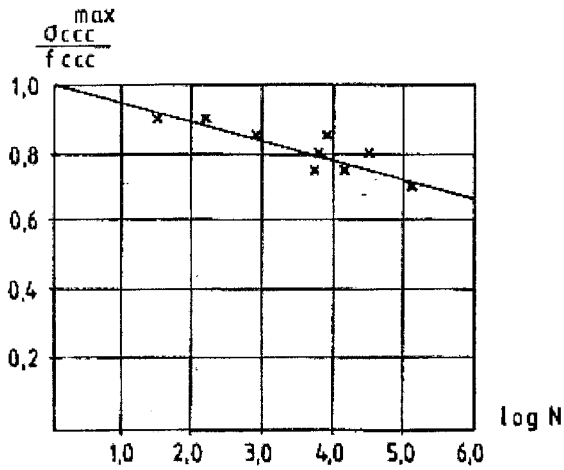

Figure 11. Wöhler or SN-relation of the performed fatigue tests. Line according to equation (4), Aas-Jacobsen (1970) and Tepfers-Kutti (1979).

The number of load cycles N at fatigue failures loads of the specimens in the test program, Table 1, are shown in Wöhler diagram Fig. 11 and put in relation to the fatigue line represented by eq. (4). The test results situated relative to this line shows normal agreement.

RESULTS AND DISCUSSION

Determination of static failure energy

The measured static failure energies determined according to eq. (3) on 3 cylinders was Test C:3 240 J; Test C:4 280 J and Test C:5 240 J with mean value 253 J are shown in Fig. 12.

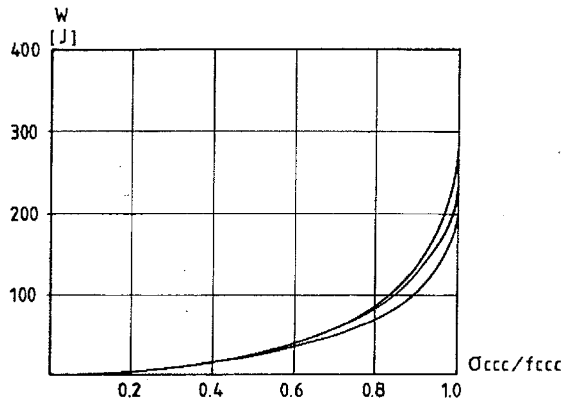

Figure 12. Absorbed static failure energy W at different related stress levels of concrete cylinders.

As the curve of the measured absorbed energy W close to the failure load is asymptotic, the values obtained are uncertain.

Measured absorbed energy

The measuring system for supplied and absorbed energy unfortunately did not work as expected. The absorbed energy measurements based on strain increments were registered unsatisfactory due to overflow in the computer system. Therefore, the results based on load increments of Bergquist (1984) are used in the evaluation instead, where this did not happen. The absorbed energy follows a straight line after a staring zone and is shown in Fig. 13. Bergquist did not measure the heat energy, so a separation of destruction energy and heat energy from his results is not possible.

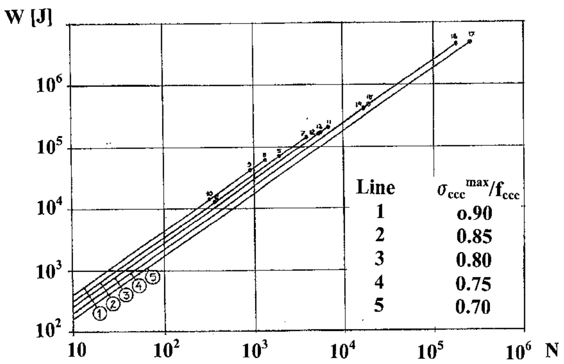

Figure 13. Absorbed energy W up to fatigue failure related to numbers of load cycles N. Bergquist (1984).

Average absorbed energy per load cycle at different stress levels is shown in Fig. 14, according to Bergquist (1984). It increases slightly with increasing the maximum pulsating stress level as it can be expected. The concrete cube strength of the present tests was 40.1 MPa and cylinder strength 30.1 MPa, while those of Bergquist (1984) 47.3 MPa respective 35.9 MPa.

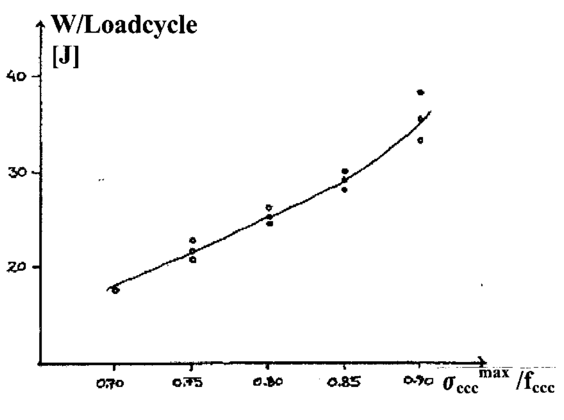

Figure 14. Average absorbed energy per load cycle at different related stress levels including destruction and heat energy, Bergquist (1984).

Measured heat energy

The development of heat energy in principle is shown in Fig. 15.

At the beginning of the measurements the temperature differences over the insulating layer are very small which makes the results very uncertain causing curves not starting at 0;0 point. The stored energy in the concrete cylinder and heat exchange with the loading machine platens dominates in the beginning phase, but the through insulating mineral wool measurement layer transmitted energy rose when temperature difference between the cylinder and air in the room increased.

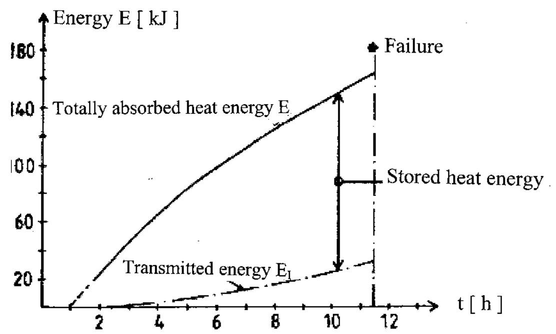

Figure 15. Relation in principle between stored heat energy and transmitted energy as function of time t is shown.

The thermocouples arranged in the wood fiber plate at cylinder ends however became destroyed by load pulses. The Teflon polymer layers experienced internal temperature increase due to pulsating load, and most likely did not function satisfactory.

Therefore energy exchange between the cylinder and loading platens went unfortunately out of control.

COMPARISON BETWEEN SUPPLIED AND ABSORBED ENERGY

Taking into considerations the shortcomings of the measurements a try to compare the absorbed energy and the energy in the form of heat and deterioration of concrete is done in the following.

It can be stated that temperature increase of the concrete cylinders was more for higher stress levels and could reach up to 10^o centigrade and resulted in stored energy.

The transmitted energy was low due to the thickness of the cylinder side surface insulating layer for transmission energy measurements and due to this fact became uncertain, especially in the beginning phase of loadings, when the temperature difference over the insulating layer was small.

Improvements have to be done in placing thermocouples to avoid air slots between concrete and the insulating layer and also to better control surface heat resistance. Room temperature

development has also to be followed in detail.
The energy transmission trough the concrete cylinder ends to machine loading platens could not be determined, due to destruction of the measuring equipment by load pulses. It was therefore assumed to be the same as through side surfaces. The measuring technique has to be improved. Measurements for some specimens became however possible to use.
Fig. 16 shows heat energy measured for specimen C:14 compared with absorbed energy measured by Bergquist (1984). At the beginning the measurements, when registering smaller quantities, suffer from un-precision. In later phase an approach is observed between the absorbed energy and the measured heat energy consisting of the in the concrete cylinder stored and from concrete surfaces transmitted energy. The distance between these energies is the destruction energy. However the concrete in Bergquists tests was 19% stronger than in the present tests and makes this distance wider.

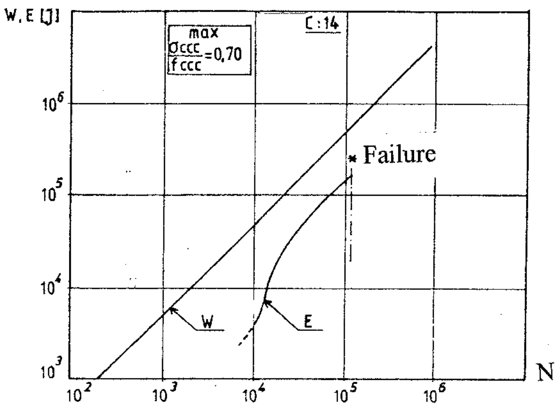

Figure16. Comparison between absorbed energy W (J) Bergquist (1984) and developed heat energy E (J) until fatigue failure of cylinder C:14.

In Fig. 17 a try is done to adapt the absorbed energy measurements performed by Bergquist (1984) to the concrete strength in present tests. The concrete compressive static cylinder strength f_{ccc} in Bergquists tests was 19% higher and therefore comparison is done for Bergquists tests with his $\sigma_{ccc}^{max}/f_{ccc} = 0.70$ adapted for present test C:12 with $\sigma_{ccc}^{max}/f_{ccc} = 0.75$ approaching somewhat the relative stress levels. It can be seen in Fig. 17 that the heat energy curve approaches the from machine load absorbed energy line according to Berquist (1984) to a distance, which is of the size of the static destruction energy level 0.30 kJ.
It can be stated that measured absorbed energy and the measured developed heat energy are in region 100 kJ, while the destruction energy being the difference of absorbed and heat energies, is only about 0.3 kJ, as it was determined in static tests Fig. 12. The destruction energy is a small number obtained as the difference of two very big numbers. As these are not very precise the destruction energy could not be determined with the necessary precision to confirm the hypothesis that the destruction energy is the same for static and fatigue types of concrete failures. But the hypothesis cannot be excluded either.

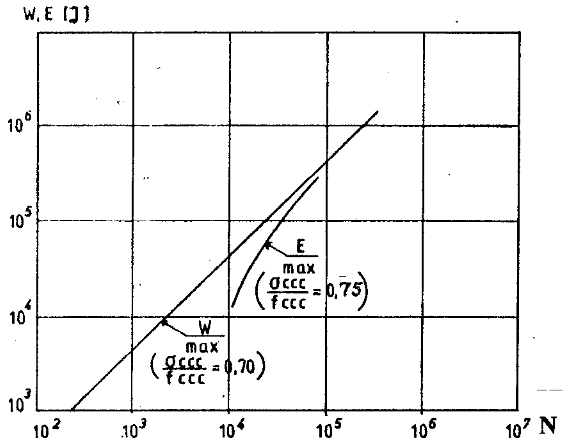

Figure17. Comparison between absorbed energy W (J), Bergquist (1984), with to these tests somewhat adapted concrete strength level, and developed heat energy E (J), test C:12, as function of load cycles N until fatigue failure.

As these tests, with these methods were performed for the first time a lot of complications turned up. To obtain better results repetition of the tests should be done with the necessary improvements in the measuring technique. However, the improvements could not be done due to certain reasons and in present paper are presented what the results became to be.

CONCLUSIONS

1. About friction between concrete cylinder and steel loading platens
Under static tests it is possible to avoid friction between concrete cylinder ends and steel loading platens with two Teflon layers.
Under pulsating load with frequency 2 Hz however the Teflon layers are deteriorated due to internal heat development in the polymer.
2. Temperature increase
Temperature increase was more for higher stress levels and could reach up to 10^o centigrade in the concrete cylinder.
The transmitted energy was low due to thickness of the insulating layer for measurements and relatively small temperature gradient especially at the beginning of the tests, which made the results uncertain for transmission energy measurements.
Improvements have to be done in placing thermocouples to avoid air slots between concrete and the insulating layer and also to determine surface heat resistances.

Thermocouples placements possible to sustain the pressure between the concrete cylinder end surfaces and loading steel platens of the machine have to be developed.

Room temperature development has to be followed.

3. Developed heat energy and destruction energy

Both from the loading machine transmitted and by the concrete cylinder absorbed energy and developed heat energy, which is stored in concrete cylinder or transmitted to surroundings, is in region 100 kJ, while the destruction energy, being the difference between absorbed and heat energies, might equal to that in the static tests 0.3 kJ.

The destruction energy in fatigue obviously is a small number obtained as the difference of two very big numbers. As these were not very precise, the destruction energy could not be determined with the necessary precision to confirm the hypothesis that the destruction energy is the same for static and fatigue types of concrete failures.

ACKNOWLEDGEMENT

The tests were done as students master thesis work with the aim to elaborate the systems for measuring of the absorbed and developed heat and destruction energies at fatigue of concrete, Sjöström G. O., Svensson J. I. (1985). A master thesis has a certain extent in work and the required limit was achieved. The measuring methods were developed, but new problems discovered. Here the results are documented of what was achieved and in further research the systems have to be improved. Unfortunately, a follow up of this investigation could not be performed due to unexpected passing away of responsible laboratory technician Gerald Herrmann.

The work was a follow up of earlier investigations in reference list, especially Tepfers et. al. (1977a), Tepfers et. al. (1977b), Tepfers et. al. (1984).

REFERENCES

Aas-Jakobsen K. (1970) *Fatigue of concrete beams and columns.* Bulletin No.70-1, Institutt for betonkonstruksjoner, NTH Trondheim, September 1970, p. 148.

Bergquist J. (1984) *Energiabsorption hos betong vid utmattande last (Energy absorption of concrete in fatigue).* Department of Building Materials, Chalmers University of Technology, Work No. 396. Examination work 84:2. Göteborg, June 1984. p.48.

Miner M. A. (1945) Cumulative damage in fatigue. *Trans. ASME,* Vol. 67.

Palmgren A. (1924) Die lebensdauer von Kugellagern (The fatigue life of ball bearings). *Zeitschrift Verein Deutscher Ingenieure,* Vol 68, No. 1924, p. 339-341.

Sjöström G. O., Svensson J. I. (1985) *Utveckling av metod för mätning av värme- och destruktions energi vid utmattning av betong (Development of method for measuring heat- and destruction energy at fatigue of concrete).* Department of Building Materials, Chalmers University of Technology, Work No. 410. Examination work 85:3. Göteborg, June 1985. p. 60.

Tepfers, R., Görlin, J., Samuelsson, T. (1977a) Concrete subjected to pulsating load and pulsating deformation of different wave forms. *Nordisk Betong* 4:1973. p. 27-36.

Tepfers, R., Fridén, C., Georgsson, L. (1977b) A study of the applicability to the Palmgren-Miner partial damage hypothesis. *Magazine of Concrete Research,* Vol. 29, No 100, p. 123-130.

Tepfers, R., Kutti, T.(1979) Fatigue Strength of Plain, Ordinary and Lightweight Concrete. *ACI Journal, Proceedings* Vol 76, No. 5, p. 635-652.

Tepfers, R. (1980 a) Tensile Fatigue Strength of Plain Concrete. *ACI, Journal, Proceedings,* Vol 76, No. 8, p. 919-933.

Tepfers, R. (1980 b) Fatigue of plain concrete subjected to stress reversals. *ACI Symposium at 1980 Fall Convention 23-26/9 1980, San Juan Puerto Rico*. American Concrete Institute Publication SP 75-9. p.195-215.

Tepfers R., Hedberg B., Szczekocki G. (1984) Absorption of energy in fatigue loading of plain concrete. *Matériaux et Constructions,* Vol. 17, No 97. p. 59-64.