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HEAT – INDUCED EXPLOSION IN HIGH STRENGTH CONCRETE

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Heat-Induced Explosion in High Strength Concrete

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PREFACE

This report has been prepared as one part of the thesis required to obtain the degree of "teknisk licentiat", equivalent to the Ph.D. degree.

The thesis consists of this report and the following three reports:

- Uniaxial Stress-Strain Curves of High Strength Concrete.
- Design Proposal for High Strength Concrete Sections Subjected to Flexural and Axial Loads.
- The Strength of Overlapped Deformed Tensile Reinforcement Splices in High Strength Concrete.

The thesis has been carried out at the Department of Structural Engineering, Technical University of Denmark under the supervision of Lecturer, M.Sc. Erik Skettrup, Lecturer, Dr. Herbert Krenchel and Professor Emeritus, Dr. Troels Brøndum-Nielsen.

The typing was carried out by Mrs. Inge Sørensen and the drawing of the diagrams and the figures by Mrs. Esther Martens.

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ABSTRACT

The thesis deals with the following four investigations:

- Heat-Induced Explosion in High Strength Concrete.
- Uniaxial Stress-Strain Curves of High Strength Concrete.
- Design Proposal for High Strength Concrete Sections Subjected to Flexural and Axial Loads.
- The Strength of Overlapped Deformed Tensile Reinforcement Splices in High Strength Concrete.

The thesis consist of four seperate reports. A short summary of these is given below.

Heat-Induced Explosions in High Strength Concrete.

This report contains the result and description of a series of tests which have been carried out in order to evaluate the explosion risk of heat induced high strength concrete as compared to normal strength concrete.

The tests were carried out with concrete test specimens shaped as ø100 x 200 mm cylinders with a compressive strength in the range from 30 MPa to 90 MPa. The cylinders were cured in two different ways:

a: 7 days in water followed by 21 days in laboratory atmosphere (20^{o} C and 60 % RH).

b: 7 days in water followed by 21 days sealed with plastic aluminum foil.

A total of 36 concrete cylinders were heated in an electrical oven at a heating rate of 2.5^{o} C per min. until reaching a temperature of 600^{o} C. After 2 hours at this temperature the cylinders were cooled at a rate of up to 1^{o} C per min.

The tests show that the explosion risk depends on the curing conditions and that the explosion risk in the case of high strength concrete is not higher than for normal strength concrete especially for concrete cured under condition a.

Uniaxial Stress-Strain Curves of High Strength Concrete.

This report describes a special test-rig developed in order to obtain the ascending as well as the descending part of uniaxial stress-strain curves. Test results is reported from test series where the complete stress-strain curve is determined for concrete with compressive strength in the range from 40 MPa to 92 MPa.

The test results show that the ascending part of the uniaxial stress-strain curves are more linear and steeper for high strength concrete when compared to normal strength concrete and that the descending branch becomes steeper the higher the strength level.

The inclination of the ascending part of the obtained uniaxial stress-strain curves for high strength concrete is steeper and the strain at peak stress is less when compared to results from USA and Norway. The declination of the descending part seems less when compared to the results from Norway and only slightly steeper when compared to results from USA.

Design Proposal for High Strength Concrete Sections Subjected to Flexural and Axial Loads.

In this report an investigation is carried out of the consequences when predicting the ultimate capacity of reinforced high strength concrete sections subjected to pure bending or combined bending and axial load by extrapolating DS 411 to the compressive strength level of 90 MPa. The investigation is based on calculated results using obtained knowledge of the complete uniaxial stress-strain curves for concrete and applying nonlinear computerized methods.

The investigation show that extrapolation of DS 411 overestimates the ultimate capacity of reinforced high strength concrete sections when subjected to pure bending with as much as 33 %, while DS 411 in the case of sections subjected to combined bending and axial load overestimates the ultimate capasity with as much as 39 %.

A design proposal is suggested for calculating the ultimate capacity of high strength concrete sections subjected to pure bending or combined bending and axial load. The design proposal is based on the same principles as DS 411 and the results from the nonlinear calculations using the knowledge of the complete uniaxial stress-strain curves as mentioned above.

The curvature ductility of single reinforced high strength concrete sections compared to normal strength concrete sections is also investigated on the basis of results from the nonlinear calculations. The investigation show that the ductility of high strength concrete sections is less than the ductility of normal strength concrete sections regardless of the reinforcement degree and that it can be reduced to as much as 78 %.

The Strength of Overlapped Deformed Tensile Reinforcement Splices in High Strength Concrete.

This report decribes a test series carried out in order to evaluate the strength of overlapped tensile splices in high strength concrete and the anchorage strength of deformed bars in pull-out test specimens similar to that of DS 2082.

The influence of concrete compressive strength, splitting strength and fracture energy, G_F, on the strength of overlapped tensile splices is evaluated on the basis of 22 tests. The test indicate that the fracture energy of concrete appears to be a more governing property to the strength of splices than the compressive strength and splitting strength.

The results from the tests with overlapped splices is compared to the Danish Code of Practice for the use of Concrete, DS 411. The comparison show that extrapolating DS 411 for the design of overlapped splices in high strength concrete will yield more conservative results than in the case of normal strength concrete.

The results from the tests with overlapped splices have also been compared to estimated values from a theoretical model developed at the Department of Structural Engineering by B. S. Andreasen. The model is based on the theory of plasticity and tests with concrete in the normal strength range. The comparison show that the model developed by Andreasen overestimates the strength of overlapped splices for high strength concrete. A modification to the ν-expression used in the model is suggested, yielding more acceptable deviations from the test results.

Estimated values from an empirical formula developed by Orangun et al. is compared to the results from the tests with overlapped splices. The comparison show that the empirical formula overestimates the strength of overlapped splices in high strength concrete.

The influence of concrete compressive strength, splitting strength and fracture energy, G_F, on the anchorage strength of deformed bars in pull-out test specimens is evaluated on the basis of 84 tests. No clear conclusion could be made from the tests regarding which proporty were the most governing on the anchorage strength.

A model is suggested for calculating the anchorage strength of deformed bars in pull-out test specimens similar to that of DS 2082. The model is based on the theory of plasticity as well as the experimental results and the principles used by Andreasen in his model for estimating the strength of overlapped splices.

The results from the tests with overlapped splices and pull-out tests are compared. The comparison indicates that the anchorage strength from the pull-out tests are considerably larger than the strength from overlapped splices regardless of the concrete compressive strength level. The reason for this is partly the surrounding spiral reinforcement in the pull-out test specimen which confine the concrete around the anchored bar and that the failure mechanism is completely different from that of overlapped splices.

RESUME

Afhandlingen omhandler følgende undersøgelser af højstyrkebeton:

- Heat-Induced Explosion in High Strength Concrete.
- Uniaxial Stress-Strain Curves of High Strength Concrete.
- Design Proposal for High Strength Concrete Sections Subjected to Flexural and Axial Loads.
- The Strength of Overlapped Deformed Tensile Reinforcement Splices in High Strength Concrete.

Afhandlingen foreligger som fire seperate rapporter over undersøgelserne og er kort resumeret nedenfor.

Heat-Induced Explosion in High Strength Concrete.

Denne rapport indeholder resultater og beskrivelse af en forsøgsrække udført med det formål, at undersøge explosionsrisikoen af varmepåvirket højstyrkebeton i forhold til normalstyrkebeton.

Undersøgelsen omfatter betonprøvelegemer formet som ø100 x 200 mm cylindre med en trykstyrke i intervallet 30 - 90 MPa, som er hærdnet på to forskellige måder :

a: 7 dage i vand efterfulgt af 21 dage i laboratoriet ved 20^{o} C og 60 % RH.

b: 7 dage i vand efterfulgt af 21 dage forseglet med plastik og aluminiums folie.

Ialt 36 betoncylindre blev opvarmet i en elektrisk ovn med en opvarmningshastighed på 2.5^{o} C pr. min. op til 600^{o} C. Efter 2 timer ved 600^{o} C blev cylindrene nedkølet med en hastighed på maksimalt 1^{o} C pr. min.

Forsøgene viste, at explosionsrisikoen afhænger af hærdningsforholdene, samt at risikoen for højstyrkebeton ikke er væsentligt højere end for normalstyrkebeton, specielt når disse hærdes som under a.

Uniaxial Stress-Strain Curves of High Strength Concrete.

Rapporten beskriver en specielt udviklet forsøgsopstilling, som muliggør bestemmelse af den stigende og faldende del af enaksede betonarbejdskurver.

Rapporten indeholder derudover resultater fra forsøgsrækker, hvor hele den enaksede arbejdskurve er bestemt for beton med trykstyrker i intervallet 40 - 92 MPa. De bestemte enaksede arbejdskurver af højstyrkebeton udviser i forhold til normalstyrkebeton et mere lineært og stejlere forløb af den nedadgående del.

De opnåede arbejdskurver for højstyrkebeton udviser sammenlignet med tilsvarende arbejdskurver fra USA og Norge et stejlere forløb af den stigende del af arbejdskurven, og en mindre tøjning ved maksimal spænding, mens den nedadgående del er mindre stejl sammenlingnet med de norske resultater og stejlere sammenlignet med de amerikanske resultater.

Design Proposal for High Strength Concrete Sections Subjected to Flexural and Axial Loads.

I denne rapport vurderes om beregningsmetoden i DS 411 til bestemmelse af betontværsnits bæreevne, påvirket til ren bøjning eller kombineret bøjning og normalkraft, kan ekstrapoleres til betonstyrker i intervallet 50 -90 MPa. Vurderingen er baseret på resultaterne fra en ulineær beregningsmodel, hvor der indgår både den stigende og den faldende del af eksperimentelt bestemte enaksede betonarbejdskurver fra en tidligere undersøgelse.

Bestemmes højstyrkebetontværsnits bæreevne ved ekstrapolering af DS 411 kan bæreevnen af tværsnit med balanceret armeringsgrad påvirket til ren bøjning overvuderes med op til 33 % i forhold til resultaterne fra den ulineære beregning, mens bæreevnen af tværsnit påvirket til kombineret bøjning og normalkraft kan overvuderes med op til 39 %.

Et beregningsforslag er derfor udarbejdet til bestemmelse af højstyrkebetontværsnits bæreevne påvirket til ren bøjning eller kombineret bøjning med normalkraft. Forslaget er baseret på de samme principper som DS 411 og resultater fra den ulineære beregningsmodel.

Endvidere er duktiliteten af højstyrkebetontværsnit vurderet i forhold til normalstyrkebetontværsnit på baggrund af resultaterne fra den ulineære beregningsmodel.

Resultaterne indikerer, at duktiliteten af højstyrkebetontværsnit er mindre uanset armeringsgraden af tværsnittet og kan forminskes ned til 78 % af tilsvarende normalbetontværsnit.

The Strength of Overlapped Deformed Tensile Reinforcement Splices in High Strength Concrete.

I denne rapport beskrives for både højstyrkebeton og normalstyrkebeton en eksperimentel behandling af overlapningsstøds bæreevne samt bæreevnen af forkammet armering forankret i prøvelegemer meget lig prøvelegemet efter Dansk Standard DS 2082.

Inflydelsen af betons trykstyrke, spaltetrækstyrke og brudenergi, G_F, på bæreevnen of overlapningsstød er undersøgt på basis af 22 forsøg. Undersøgelsen viser, at betons brudenergi G_F har større inflydelse på bæreevnen af overlapningsstød end betons trykstyrke og spaltetrækstyrke.

Der er foretaget en undersøgelse af muligheden for, at ekstrapolere beregningsmodellen i DS 411 til beregning af nødvendig overlapningslængde af stød til betonstyrker i intervallet 50 - 90 MPa. Denne undersøgelse viser, at DS 411 ved ekstrapolering giver mere konservative resultater af nødvendig overlapningslængde for højstyrkebeton end for normalstyrkebeton.

Resultaterne af forsøgene med overlapningsstød er sammenlignet med resultater fra en beregningsmodel udviklet på Afdelingen for Bærende Konstruktioner af B. S. Andreasen. Modellen der baseres på plasticitetsteorien og forsøg primært med betontrykstyrker i intervallet 6 - 50 MPa, overvurderer bæreevnen af overlapningsstød i højstyrkebeton. Et forslag til et andet ν-udtryk til beregningsmodellen er derfor udarbejdet.

Derudover er forssøgsresultaterne med overlapningsstød sammenlignet med resultater fra en empirisk formel udviklet af Orangun et al, der viser at den empiriske formel overvurderer bæreevnen af overlapningsstød i højstyrkebeton.

Inflydelsen af betons trykstyrke, spaltetrækstyrke og brudenergi G_F på bæreevnen af forankret armering i prøvelegemer meget lig prøvelegemer efter DS 2082 er undersøgt på basis af 84 forsøg. Det har ikke på baggrund af disse forsøg været muligt at fastslå hvilken af ovennævnte parametre, der har størst inflydelse på bæreevnen.

Et forslag til en beregningsmodel er udviklet til beregning af forkammet armerings bæreevne i prøvelegemer meget lig prøvelegemet i DS 2082. Beregningsmodellen er baseret på plasticitsteorien og de gennemførte forsøg samt principperne anvendt af Andreasen i beregningsmodellen for bæreevnen af overlapningsstød.

En sammenligning mellem de eksperimentelt fundne bæreevner af overlapningsstød og forankring af forkammet armering viser, at sidstnævnte generelt har højere bæreevne. Dette kan skyldes, at spiralarmeringen omslutter betonen hvori armeringsjernet er forankret samt, at brudmekanismen er forskellig fra brudmekanismen i overlapningsstød.

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NOTATIONS

The most commonly used symbols are listed below:

f_c	Uniaxial compressive strength of concrete.
ω	Physically bound water.
β	Ratio of compressive strength after heating and f_c .

1. INTRODUCTION

1.1 Purpose of the Investigation.

When producing high strength concrete by the use of superplasticizers and silica fume, the result will normally be a concrete with a very low permeability. Due to the dense microstructure, high strength concrete is far more resistant to many physical and chemical actions than normal strength concrete. Damage may, however, occur from internal steam pressure building up when the high strength concrete is subjected to excessive heating as during a fire.

Experimental results concerning the heat resistance of high strength concrete has been somewhat contradictory.

Hertz [1] investigated the lack of fire resistance by heating concrete cylinders in an electrical oven. The concrete cylinders had a compressive strength level of 150-170 MPa and contained silica fume amounting to 20 % of the cement weight. Hertz concluded that high strength concrete cylinders containing silica fume have a high explosion risk due to internal steam pressure combined with the low permeability. It must be noted that the cylinders were cured 20 days in water and 60 days at 20^{o}C, 60 % RH.

Rasmussen [6] heat tested concrete produced both with and without silica fume and two compressive strength levels, 40 MPa and 70 MPa. The silica content was 10 % of the cement by weight, and the cylinders were cured 28 days in water and approximately 1 year at 70 % RH and 20^{o}C. Rasmussen concluded, that there seems to be no high risk for explosions in concrete produced with silica fume when being exposed to excessive heating.

Both the above mentioned experimental results were obtained on concrete quite old and to some extent dry.

The purpose of this investigation is therefore to study the fire resistance of high strength concrete with compressive strength at the level of 50-100 MPa, not older than 28 days and with a high moisture content.

2. EXPERIMENTAL PROGRAM

2.1 Introduction

In order to study if high strength concrete with a compressive strength level of 50-100 MPa involve a high risk of explosion due to internal steam pressure combined with low permeability, 2 series of concrete cylinders were cast.

In the first series, the intended compressive strength of the cylinders were 90, 70 and 50 MPa, and in the second series 90, 70 and 30 MPa. The second series were cast after experimental results from the first series were obtained.

The cylinders in each series and for each intended compressive strength were cured under two different conditions in order to study, if the moisture content has any influence on the risk for explosion.

The ratio between compressive strength after and before heating was established in order to study if there were differences between high strength concrete and normal strength concrete in this respect.

A total of 108 cylinders were cast out of which 36 cylinders were heat tested.

2.2 Concrete

2.2.2 Materials.

Cement: Rapid hardening portland cement, ASTM Type III supplied by Ålborg Portland.
Specific gravity was assumed to be $3.3 \cdot 10^3$ kg/m^3.

Fly Ash: Fly ash supplied by Amagerværket, Copenhagen was used in the mix. when producing concrete cylinders with intended compressive strength at the 50 MPa and 30 MPa level.
Specific gravity was assumed to be $2.2 \cdot 10^3$ kg/m^3

Silica Fume: Silica fume supplied by Ålborg Portland, Ålborg, was used in the mix. when producing concrete cylinders with intended compressive strength at the 90 MPa and 70 MPa level. Specific gravity was assumed to be $2.2 \cdot 10^3$ kg/m^3.

Fine Aggregate: Sand (0-4 mm) from Danish marine deposits, supplied by Carl Nielsen A/S, Copenhagen.
Specific gravity was assumed to be $2.62 \cdot 10^3$ kg/m^3

Coarse Aggregate: Gravel (4-16) from Danish marine deposits, supplied by Carl Nielsen A/S, Copenhagen.
Specific gravity was assumed to be $2.62 \cdot 10^3$ kg/m^3.

Admixtures: Superplasticizer Mighty 100, supplied under the name of Scan Cem SP62/SP63, by Cemton, Norway.

Water: Tap water from the city's network was used.

2.2.2 Mix Proportions

2.2.2.1 Series 1.

In the first series three different mixes were used to produce the three intended compressive strength levels:

1) High strength concrete with compressive strength at the 90 MPa level.
2) High strength concrete with compressive strength at the 70 MPa level.

3) Medium strength concrete with compressive strength at the 40 MPa to 50 MPa level.

Mix proportions are given in Table 2.1.

2.2.2.2 Series 2.

The mixes from the first series were adjusted in order to produce the three intended compressive strength levels:

1) High strength concrete with compressive strength at the 90 MPa level.
2) High strength concrete with compressive strength at the 70 MPa level.
3) Normal strength concrete with compressive strength at the 30 MPa level.

Mix proportions are given in Table 2.2.

2.2.3 Mixing, Casting and Curing.

Mixing: Sand and coarse aggregates were mixed dry with cement and either fly ash or silica fume in a paddle mixer. After 1 min. of mixing the water and superplasticizer were added. Thorough mixing was achieved in approximately 6 min.

Casting: 18 cylinders were cast in each series and for each intended compressive strength, using polyethylene moulds, Ø100 mm x 200 mm.
To consolidate the concrete a vibrator table was used.

Curing: The moulds of all the cylinders from one batch was removed 24 hours after casting. The cylinders were then kept for 7 days in a water basin. The continuous curing of the cylinders took place under 2 different conditions.
Condition a: 21 days at 20°C and 60 % RH.
Condition b: 21 days sealed with plastic-aluminum foil.

2.3 Tests.

2.3.1 Compressive Strength.

From each series, intended strength and curing condition 3 cylinders were tested to determine the compressive strength. The cylinders were tested in a 200 Mp MFL (Prüf and Mess MFL System) compression test machine. The machine was servo-controlled by a Walter & Bai SRG 5000. The stress rates at which the cylinders were tested to failure are given in table 2.3.

2.3.2 Physically Bound Water

Physically bound water will be defined as, the amount of water released from concrete when heated to 105^{o}C.

For each series, intended compressive strength and curing condition the water content was determined from 3 cylinders.
The formular used was

$$\omega = \frac{\text{cylinder weight - cylinder dry weight}}{\text{cylinder dry weight}} \times 100$$

where ω is the physically bound water in %.

2.3.3 Heat Testing of Concrete.

For each series, intended compressive strength and curing condition, 3 cylinders were heated in an electrical oven.

The electrical oven itself was made by the Institute of Building Design, Techincal University of Denmark. The oven was servo controlled by a Gear Setting Type Trapezoid programmer, made by Chino Works LTD.

The heating rate is illustrated in fig. 2.1. Testing of compressive strength after heating was carried out on cylinders which were intact (see chapter 2.3.4).

2.3.4 Compressive Strength after Heating.

Intact cylinders (not exploded) from the heat test were tested in order to determine the compressive strength. The cylinders were tested in the same test machine as mentioned in chapter 2.3.1.

The stress rates at which the cylinders were tested are given in table 2.4.

3. EXPERIMENTAL RESULTS AND DISCUSSION

3.1 Introduction.

This chapter gives the results of the tests and compare these to other investigations which have been described in previous chapters. Due to the small amount of test-specimens no statistical analysis can be made.

3.2 Compressive Strength.

Results of the compressive strength tests after 28 days of curing are given in table 3.1 and 3.2.

Considering table 2.1 and 2.2 the water-cement ratio of the high strength concrete with an intended compressive strength of 70 MPa was reduced from 0.410 in serie 1 to 0.346 in serie 2. As a consequence an increase of the compressive strength of 16% and 3% for cylinders cured under condition a respectively b was observed. As for the high strength concrete with an intended compressive strength of 90 MPa the water cement ratio was reduced from 0.303 in serie 1 to 0.298 in serie 2. An increase of the compressive strength of 7% and 1% for cylinders cured under condition a respectively b was observed.

Considering the compressive strength obtained in series 1 and comparing the results from cylinders cured under condition a and b, the latter shows in generally higher values, while the opposite is the case when considering series 2. The results obtained in series 1 seems to be in contradiction to results obtained by Neville [7], but the results discussed here could be a chance deviation from a mean value, which has not been recognized due to the small amount of tests carried out.

3.3 Physically Bound Water.

3.3.1 Physically Bound Water.

Results of the tests for physically bound water, ω is given in table 3.3 and 3.4.

The ratio of ω of cylinders cured under condition b and a, was taken as an average, 1.29 for normal strength concrete and 1.11 for high strength concrete.

3.3.2 Physically Bound Water versus Compressive Strength.

Results of compression strength versus ω are shown on Fig. 3.1 and Fig. 3.2, from series 1 and series 2 respectively. The increasing content of cement and decreasing amount of water used in the mixes for high strength concrete of increasing strength level, explains why ω decreases with increasing compressive strength. ω of the high strength concrete observed here is on the same level as in the high strength concrete reported by Hertz [1].

3.4 Heat Testing of Concrete.

3.4.1 Heat Tests.

The results of the heat-induced explosion tests are given in table 3.5. The damage ratio expresses in % the number of test cylinders which exploded during heating out of a total of 3 cylinders for each intended strength and each curing condition.

It must be emphasized that the total number of cylinders tested was only 36, and that the results can only at the best give a rough indication of the trend.

3.4.2 Heat Test Results versus Compressive Strength.

On Figs. 3.3 and 3.4 is shown the damage ratio versus compressive strength, for the two curing conditions used.

It is well known from many investigations that high strength concrete gets a very low permeability, and therefore is more resistant to many physical and chemical actions than normal strength concrete, as for example reported by ACI [2].

For ordinary concrete it has been shown, that a lowering of the permeability causes an increase of the risk of spalling, Hertz [3], Shorter and Harmathy [4] and Hermathy [5]. In accordance with this the test results of ordinary concrete presented in this report seems to indicate, that the risk of explosion spalling increases as the compressive strength increases.

Judging from tabel 3.6 concerning high strength concrete with intended compressive strength of 90 MPa and 70 MPa from series 1 and 2, the risk of explosion spalling seems to decrease, when cylinders are cured under condition a , as the compressive strength increases from intended 50 MPa to intended 90 MPa. The same effect seems only to materialize to a lesser extent when cylinders are cured under condition b .

3.4.3 Heat Tests versus Physically Bound Water.

Figs 3.5 and 3.6 show the damage ratio versus ω . When concrete is heated, it develops steam partly originating from physically bound water but also and especially from dehydration of the hydrated calcium silicates and the calcium hydroxide. The steam flows to the surface of the body and the denity of the concrete determines the resistance to the flow.

It is clear from figs. 3.5 and 3.6 that the amount of physically bound water itself is not the major cause behind the risk for explosion spalling of the cylinders.

3.5 Compressive Strength after Heating.

3.5.1 Compressive Strength.

The compressive strength of cylinders who did not explode during the heat test was measured. The results are given in table 3.7 and 3.8.

Compared to Hertz's [1] experimental investigation the results presented here show lesser values of compressive strength after heating, probably due to the higher heating rate used in the tests for this report.

3.5.2 Compressive Strength after Heating versus Compressive strength before Heating.

Figures 3.7 and 3.8 show the ratio β for each intended compressive strength and each curing condition. β expresses the ratio of the compressive strength after heating compared to the compressive strength before heating.

The ratio β seems to be nearly constant as the compressive strength increases whether the cylinders were cured under condition a or under condition b.

4. CONCLUSION

It must be emphasized that the total number of cylinders tested was only 108, out of which 36 were heat tested.

From the investigation described above it can be concluded that high strength concrete produced with silica fume seems to involve only a moderate risk for steam explosion compared to normal strength concrete with compressive strength at the level of 50 MPa, especially when the concrete is 28 days old and cured 7 days in water and 21 days at 60% RH and 20^{o}C.

An increase in physically bound water itself seems not to cause a higher risk for steam explosion.

The ratio of compressive strength after and before heating seems nearly constant as the compressive strength before heating increases, whether the cylinders were cured under condition a or b .

The test series presented in this report must be considered as pilot test series. It is recommended that a larger test serie should be carried out in order to study effects of mix proportions, curing conditions, age of the concrete, heat rate and specimen size.

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6. TABLES

Intended Compressive Strength	90	70	50
Portland Rapid Cement	350	300	250
Silica Fume	35.0	30.0	-
Fly Ash	-	-	100
Superplasticizers	11.6	9.9	10.5
Sand (0-4 mm)	928	965	878
Gravel (4-8 mm)	395	422	376
Gravel (8-16 mm)	651	623	698
Water	106	123	120
Units	kg/m^3	kg/m^3	kg/m^3

Table 2.1 Mixing proportions for concrete in series 1.

Intended Compressive Strength	90	70	30
Portland Rapid Cement	366	306	260
Silica Fume	36.6	30.6	-
Fly Ash	-	-	105
Superplasticizers	12.1	10.1	11
Sand (0-4 mm)	886	915	820
Gravel (4-8 mm)	377	400	351
Gravel (8-16 mm)	622	591	652
Water	109	106	139
Units	kg/m^3	kg/m^3	kg/m^3

Table 2.2 Mixing proportions for concrete in series 2.

Intended Compressive Strength	90	70	50	30
Series 1	19.1	19.1	7.6	-
Series 2	19.1	19.1	-	7.6

Table 2.3 Load rates, in MPa/min., used to determine uniaxial compression strength.

Intended Compressive Strength	90	70	50	30
Series 1	3.0	3.0	2.0	-
Series 2	3.0	3.0	-	1.0

Table 2.4 Load rates, in MPa/min., used to determine uniaxial compressive strength on concrete after the heat test.

Series	1			2		
Intended Compressive Strength	90	70	50	90	70	30
1 2 3	77.1 78.4 84.7	61.2 61.5 63.7	48.1 46.6 45.7	84.7 83.6 87.9	72.5 69.3 74.3	32.9 33.4 36.0
Mean Value	80.1	62.1	46.8	85.4	72.0	34.1
Standard Deviation	4.06	1.37	1.21	2.23	2.53	1.66

Table 3.1 Uniaxial compressive strength of concrete in MPa measured on 100 x 200 mm cylinders cured under condition a.

Series	1			2		
Intended Compressive Strength	90	70	50	90	70	30
1 2 3	82.5 76.8 87.0	68.9 66.0 64.5	48.9 47.5 47.1	85.8 76.3 85.3	73.1 66.1 66.1	30.2 33.6 32.4
Mean Value	82.1	66.5	47.8	82.5	68.4	32.1
Standard Deviation	5.11	2.24	0.95	5.35	4.04	1.72

Table 3.2 Uniaxial compressive strength of concrete in MPa measured on 100 x 200 mm cylinders cured under condition b.

Series	1			2		
Intended Compressive Strength	90	70	50	90	70	30
1	1.85	2.58	2.66	1.83	1.87	3.13
2	1.80	2.17	2.70	1.82	1.87	3.17
3	1.82	2.55	2.60	1.79	1.85	3.08
Mean Value	1.82	2.43	2.65	1.81	1.86	3.13
Standard Deviation	0.03	0.23	0.05	0.02	0.01	0.04

Table 3.3 Water content in %, measured on 100 x 200 mm cylinders, cured under condition a.

Series	1			2		
Intended Compressive Strength	90	70	50	90	70	30
1	1.88	2.91	3.24	1.96	2.02	3.90
2	1.99	3.07	2.91	1.97	2.15	4.14
3	1.93	2.91	3.03	1.88	1.99	4.23
Mean Value	1.93	2.96	3.06	1.94	2.05	4.09
Standard Deviation	0.06	0.09	0.16	0.05	0.08	0.17

Table 3.4 Water content in %, measured on 100 x 200 mm cylinders, cured under condition b.

Series	1			2		
Intended Compressive Strength	90	70	50	90	70	30
Curing condition a	33.3	0	66.7	0	66.7	0
Curing condition b	33.3	33.3	66.7	66.7	66.7	0

Table 3.5 Damage ratio in %.

	Intended Compressive Strength			
	90	70	50	30
Curing condition a	16.7	33.3	66.7	0
Curing condition b	50.0	50.0	66.7	0

Table 3.6 Average damage ratio in % from series 1 and 2.

Series	1			2		
Intended Compressive Strength	90	70	50	90	70	30
1	10.40	8.92	7.23	10.06	9.17	3.18
2	8.86	9.13	-	10.75	-	3.71
3	-	9.54	-	9.33	-	3.75
Mean Value	9.63	9.20	7.23	10.05	9.17	3.55
Standard Deviation	1.09	0.32	-	0.71	-	0.32

Table 3.7 Compressive strength of cylinders after heating, in MPa. Cylinders cured under condition a.

Series	1			2		
Intended Compressive Strength	90	70	50	90	70	30
1	9.41	9.20	7.19	10.20	8.23	3.93
2	11.77	8.79	-	-	-	4.08
3	-	-	-	-	-	3.53
Mean Value	10.59	8.99	7.19	10.20	8.23	3.85
Standard Deviation	1.69	0.29	-	-	-	0.28

Table 3.8 Compressive strength of cylinders after heating, in MPa. Cylinders cured under condition b.

7. FIGURES

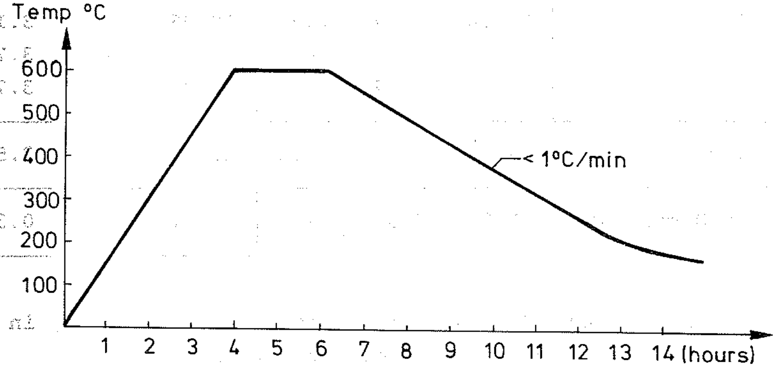

Fig. 2.1 Heating rate applied throughout the testing.

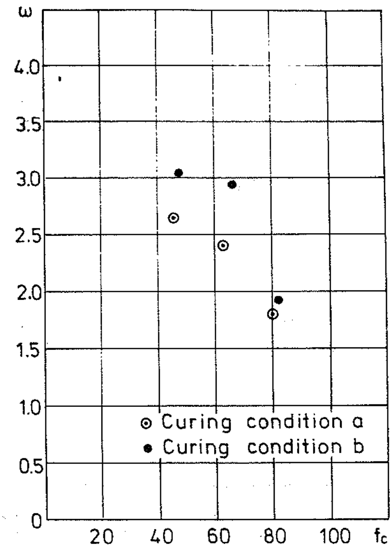

Fig. 3.1 Water content, ω , in % versus compressive strength, f_c, in MPa from series 1.

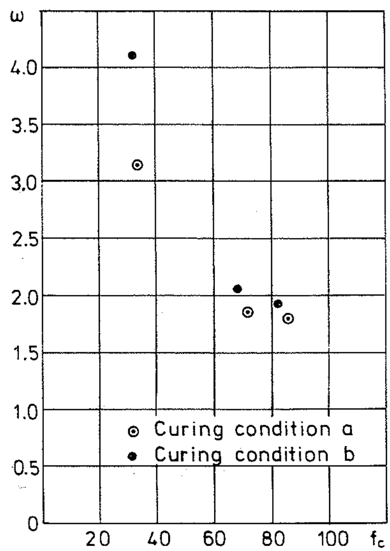

Fig. 3.2 Water content, ω , in % versus compressive strength, f_c, in MPa from series 2.

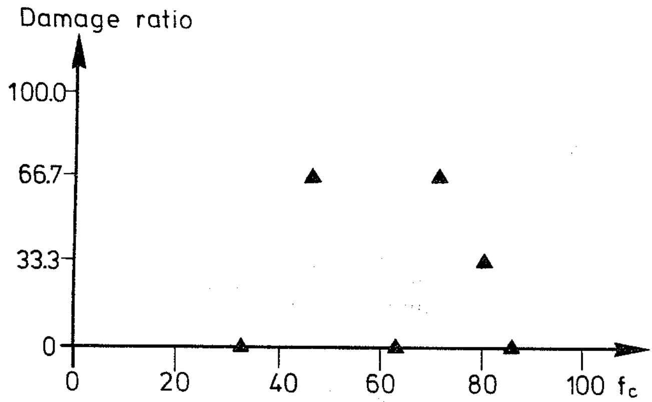

Fig. 3.3 Damage ratio, in %, versus compressive strength, f_c, in MPa, for cylinders cured under condition a.

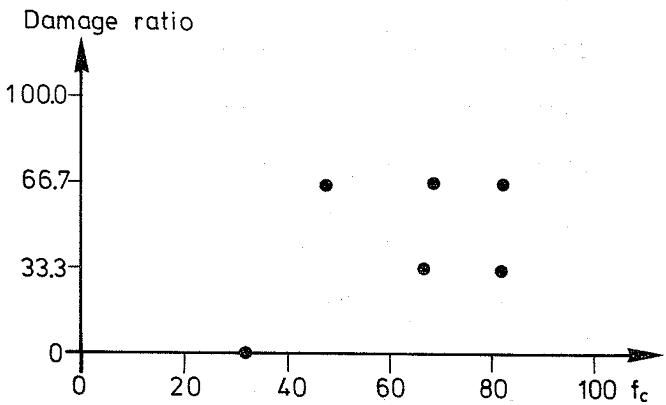

Fig. 3.4 Damage ratio, in %, versus compressive strength, f_c, in MPa, for cylinders cured under condition b.

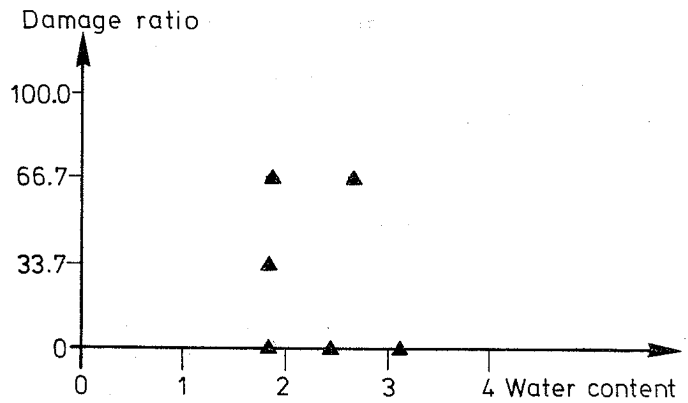

Fig. 3.5 Damage ratio, in %, versus water content, in %, for cylinders cured under condition a.

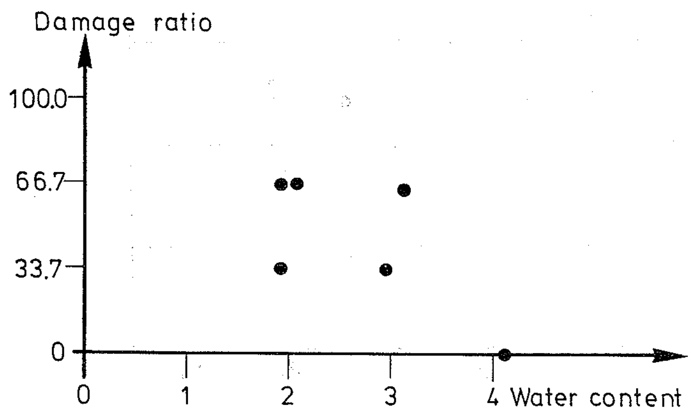

Fig. 3.6 Damage ratio, in %, versus water content, in %, for cylinders cured under condition b.

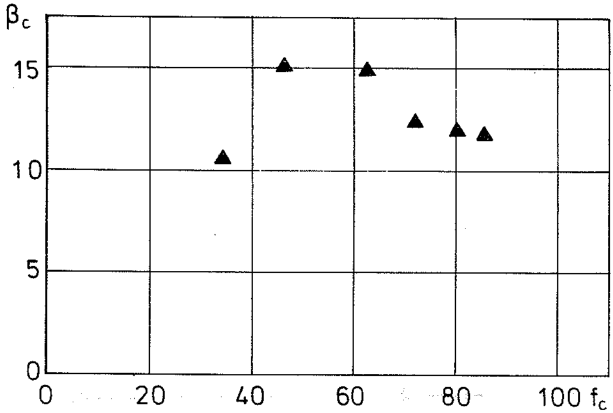

Fig. 3.7 Compressive strength, f_c, in MPa, versus β , in %. Cylinders cured under condition a.

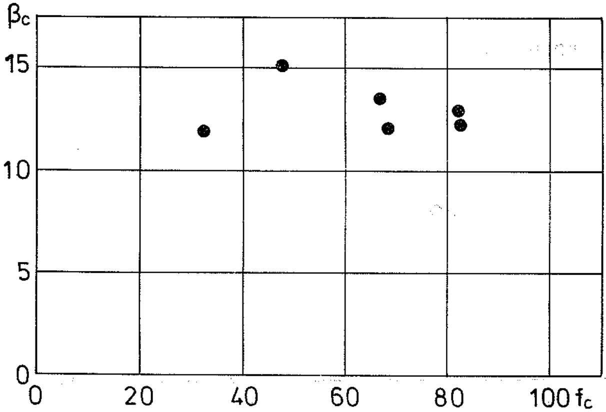

Fig. 3.8 Compressive strength, f_c, in MPa, versus β , in %. Cylinders cured under condition b.

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