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HEAT - INDUCED EXPLOSION OF DENSE CONCRETES

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CONTENTS

Leonardo da Vinci

PREFACE

One of Leonardos Innumerable inventions was a steam cannon, which he called the Architronito.

Burning coals heated the copper barrel to high temperatures, and by means of a screw valve a small amount of water could suddenly be injected behind the iron ball.

Instantly a large steam pressure was developed driving the ball out accompanied by a great thunder.

In modern times the research on concretes of high strength has lead to the development of very dense materials known as DSP "Densified Systems containing homogeneously arranged ultra-fine Particles".

By heating specimens of such materials, even at small heating rates, violent explosions occur. So it may be said that the steam grenade is discovered five hundred years after the steam cannon of Leonardo.

This report deals with the steam explosions of DSP.

Copenhagen, February 1984
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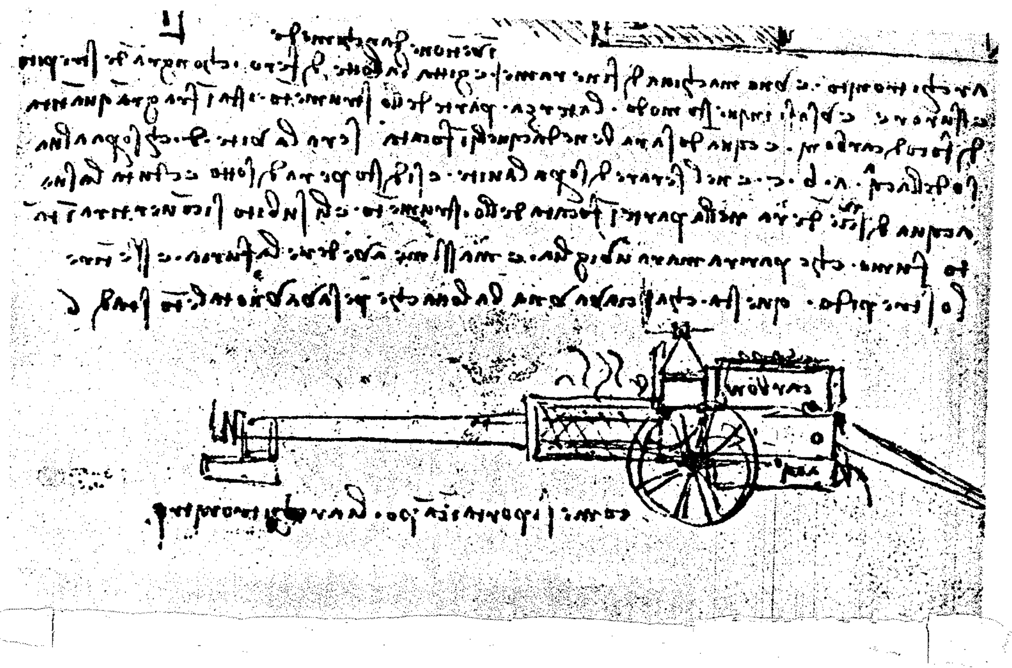

Leonardos steam cannon from Manuscript B [1].

ACKNOWLEDGEMENTS

I wish to express my greateful thanks to professor T. Brøndum-Nielsen for his encouragement in the preparation of this report and for many inspiring discussions.

I would also like to record my thanks to senior lecturer Aa. P. Jensen for his kind cooperation, to senior lecturer T. Jakobsen for reading the manuscript and to the Danish Technical Research Council for supporting the project financially.

Finally my best thanks should be given to the staff of Aalborg Portland and the Institute of Building Design for practical help during the period of work.

SUMMARY

The results of initial investigations concerning the mechanical properties of DSP exposed to high temperatures are reported.

Since the material exploded even at very low heating rates, this phenomenon was treated in particular.

In addition some values of the residual mechanical properties of the unexploded specimens are shown.

INTRODUCTION

The appearance of superplasticizing additives for concrete made it possible to develop materials composed by a dense packing of cement and ultra-fine particles of a size of about 1/100 of that of the cement particels. Bache [2].

The ultra-fine particles fill out the spaces between the cement particles and the paste becomes extremely dense leaving very little place for voids.

Silica fume is found to be suitable as ultra-fine particles.

This material is a waste product from the production of ferro-silicium, and consists of small spherical particles of silica.

Because of the dense microstructure of the silica fume cement paste it is far more resistant to many physical and chemical influences than ordinary plain cement paste, and the compressive strength is considerably increased.

Concrete made on silica-fume cement paste often has a compressive strength of more than 150 MPa (up to 280 MPa), and the fracture cut through the aggregates.

By now these concretes have many applications and still more are found utilizing their fine mechanical and chemical resistance and their workability which allows them even to be extruded.

But also the limitations of their use must be found.

One limitation seems to be caused by the risk of explosion, when the material is heated.

Fire Testings of DSP

At an early stage investigations on the mechanical properties of DSP at high temperatures were initiated at our laboratory.

Related to a graduation preject: Pedersen [4] a small series of 16 cylinders was produced of a silica-fume cement based concrete known as Densit by Aalborg Portland under supervision of H.H. Bache [2], who has developed the material.

The cylinders were 200 mm high with a diameter of 100 mm, and were intended to have a compressive strength level about 150 - 160 MPa.

They were stored 20 days under water and 60 days at 20°C, 60% RH, and heated in an electrical oven at the very low rate 1°C per minute to the maximum temperature selected, which was kept for 2 h, and the the oven was cooled down at a rate of no more than 1°C per minute.

The Densit was composed of:

			kg/m^3
Diabase	fraction	4-16 mm	1080
Quartz sand	-	1- 4 mm	404
Quartz sand	-	0.25- 1 mm	202
Quartz sand	-	0- 0.25 mm	101
Sand-lime cement			500
Elkem silica			100
Mighty (42% solution)			25
Water			80

The density became 2680 kg/m^3.

The cylinders were heated in series of 3 at maximum temperatures 350^{0}C, 450^{0}C and 650^{0}C, and the intention was to measure the residual compressive strength at 7 days after heating.

However, the most remarkable result of the testings was that several of the cylinders exploded while being heated.

The explosions occured with a loud boom, and the splinters scattered at such energy that they made considerable damage to the oven.

By all explosions no fragment left was larger than one tenth of the volume of the original cylinder, and the fractures crossed the aggregates as well as the matrix.

The explosion must be caused by the great denseness of the silica-fume cement matrix.

When heated, the concrete develops steam partly from the small amount of free water but especially from dehydration of the hydrated calcium silicates and the calcium hydroxide.

The steam flows to the surface of the body and the denseness of the concrete determines the resistance to the flow. For ordinary concrete it has been shown that a lowering of the permeability causes an increase of the risk of explosive spalling (Hertz [5], Shorter and Harmathy [6], Hamarthy [7]).

Meyer-Ottens [8] and Zhukov [10] indicate that the moisture content should be above 3-4 % by weight before explosive spalling can take place for ordinary concrete.

This limit is not valid of course to the extremely dense concretes based on silica-fume.

Bacause the silica-fume fills out all cavities, the space left for free water is small, and additional tests (Hertz [3]) show that the weight loss of cylinders heated at 150 °C for 7 days was only 1.2 %, while it was more than 3% for cylinders of the main series heated at more than 300 °C for 2 hours.

This means that the chemically bound water, which is released from the hydrated calcium silicates above 250 °C, must be an essential part of the moisture causing the explosions occuring at 300 °C.

It also means that it is doubtful that the risk of explosion of fire exposed Densit structures will decrease by age, and if it will, it will not be within a reasonable time, because the denseness of the material prevents evaporation of the free water.

The original "black" colour of the Densit caused by small amounts of carbon on the silica particles turned into grey when heated, and the sound made by knocking the specimens with a hammer became more soft, which indicates the formation of microcracks (Hertz [5]).

Out of three specimens heated to the maximum temperature 350 °C one exploded, at 450 °C two and at 650 °C two, and 7 days after heating the dynamic modulus of elasticity and the compressive strength was measured of the cylinders not exploded.

The test results are recorded in Appendix A.

Under supervision of senior lecturer Aa. P, Jensen from the Engineering Academy of Denmark further investigations were made (Jensen [9]).

A Densit concrete with an aggregate of burned bauxite and a compressive strength level about 170 MPa was cast in cylindrical specimens of three sizes: 200 × 100 mm, 100 × 57 mm and 52 × 28 mm.

The concrete was provided with a fibre reinforcement of 0.4 × 12 mm Wirex steel fibres of 0.0 -, 1.5 - and 3.0 per cent by volume in order to improve the resistance to thermal stresses and if possible to diminish the risk of explosion.

The cylinders were heated 1 °C per minute at the maximum temperatures 200 °C, 400 °C and 600 °C which were kept for 1 hour, and to protect the oven the specimens were placed in RHS-steel profiles with the openings secured by steel wire nettings.

Only the biggest size of cylinders (200 × 100 mm) with the largest fibre content (3 vol. pct.) exploded.

The explosions occured at 400 °C in stead of the temperature 300 °C of the first test series.

The smaller cylinders did not explode, presumably because the steam was able to escape before the critical steam pressure was developed.

This assumption is supported by the observation that the weight loss in per cent was greater for small cylinders at 200 °C while it was not greater at 600 °C.

The fractions of the exploded specimens were very small, almost as powder, which indicates that the fibre reinforcement resulted in a more uniform stress distrubution, though it obviously did not diminish the risk of explosion.

In a third series slabs of about 200 × 200 × 50 mm were cast and insulated by mineral wool so that only one large surface was exposed to the heat of the oven.

By this one dimensional heat conduction explosions were achieved, which in two cases gave a completely plane fracture about 10 - 20 mm from the exposed surface in accordance to the theory of explosive spalling.

CONCLUSION

From the investigations considered it must be concluded that "DSP" - concrete possesses a high risk of steam explosion due to the dense microstructure, even at an extremely low heating rate as 1 ^{0}C per minute.

Therefore, the material should not be used for structures, where heating rates of this magnetude or greater could be expected, before the problems involved have been solved.

This means that "DSP" - concrete so far may not be used for constructions for which any requirement whatever can be set up regarding the load-carrying capacity in case of fire.

Furthermore it must be dissuaded to use this concrete for any subject that should be able to withstand a heating rate of 1 ^{0}C per minute or more to a high temperature level.

The limit of this level depends on the rate.

By adding steel fibres the risk of explosion does not seem to be diminished, but the fractions become smaller and the explosions occure at a somewhat higher temperature level.

Concretes composed with a smaller content of silicafume than the tested material may still be more dense than ordinary concretes, and the risk of explosion will increase gradually by the denseness from the well known spalling phenomenon for ordinary concretes to the violent explosions dealt with in this report.

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APPENDIX A: Results of the first test series

SIZE: 200 × 100 mm cylinders

Max Temp ^0C	Compressive strength MPa	Weight Loss %	E-dyn after GPa	E-dyn before GPa	Relative E-dyn -
20	169.1	-	-	58.1	
20	119.2	-	-	64.0	
20	146.4	-	-	58.4	
150	113.1	1.2	44.6	61.3	0.73
150	207.5	1.2	42.9	60.2	0.71
150	167.8	1.2	43.6	60.8	0.72
350	171.9	3.1	21.3	59.5	0.36
350	179.0	3.2	20.7	58.3	0.36
350	EXPLODED			58.5	
450	120.2	3.5	31.7	60.7	0.52
450	EXPLODED			59.0	
450	EXPLODED			59.9	
650	64.7	3.1	0	62.6	0
650	EXPLODED			62.5	
650	EXPLODED			60.7	

APPENDIX B: Results of the second test series

SIZE 200 × 100 mm cylinders

Max Temp °C	Fibre content vol. %	Compressive strength MPa	Weight loss %	Relative E-dyn -
20	0.0	177	-	-
20	0.0	200	-	-
20	1.5	175	-	-
20	1.5	191	-	-
20	3.0	171	-	-
20	3.0	185	-	-
200	0.0	181	1.4	0.90
200	0.0	202	1.3	0.96
200	1.5	183	1.6	0.90
200	1.5	200	1.7	0.90
200	3.0	200	1.3	0.96
200	3.0	207	1.3	0.90
400	0.0	105		
400	0.0	124		
400	1.5	109		
400	1.5	127		
400	3.0	EXPLODED		
400	3.0	EXPLODED		
600	0.0	87	5.4	0.50
600	0.0	88	5.5	0.50
600	1.5	82	5.7	0.46
600	1.5	83	5.6	0.46
600	3.0	99	6.3	0.42
600	3.0	EXPLODED		

SIZE: 100 × 57 mm cylinders

Max Temp °C	Fibre content vol. %	Compressive strength MPA	Weight loss %	Relative E-dyn -
20	0.0	130	-	-
20	0.0	173	-	-
20	1.5	165	-	-
20	1.5	167	-	-
20	3.0	151	-	-
20	3.0	154	-	-
200	0.0	158	2.3	0.83
200	0.0	159	1.0	0.85
200	1.5		2.8	0.85
200	1.5		2.7	0.99
200	3.0	168	2.3	0.76
200	3.0		2.3	0.86
400	0.0	105		
400	0.0	111		
400	1.5	107		
400	1.5	109		
400	3.0	116		
400	3.0	121		
600	0.0	84	4.9	0.59
600	0.0	84	5.1	0.56
600	1.5	76	5.1	0.53
600	1.5	84	5.4	0.46
600	3.0	80	5.1	0.46
600	3.0	83	5.0	0.44

SIZE: 52 × 28 mm cylinders

Max Temp °C	Fibre content vol. %	Compressive strength MPa	Weight loss %	Relative E-dyn -
20	0.0	175	-	-
20	0.0	188	-	-
20	1.5	166	-	-
20	1.5	174	-	-
20	3.0	156	-	-
20	3.0	158	-	-
200	0.0	163	2.9	0.71
200	0.0	178	3.1	0.66
200	1.5	164	2.5	0.92
200	1.5	175	3.3	0.77
200	3.0	162	3.1	0.72
200	3.0	192	2.4	0.77
400	0.0	114		
400	0.0	134		
400	1.5	111		
400	1.5	115		
400	3.0	128		
400	3.0	-		
600	0.0	91	9.0	0.48
600	0.0	98	11.7	0.49
600	1.5	77	5.1	0.48
600	1.5	79	4.8	0.50
600	3.0	87	-0.5	0.45
600	3.0	89	-3.2	0.50