

Fire Spalling of Concrete

Theoretical and Experimental Studies

ROBERT JANSSON



**KTH Architecture and
the Built Environment**



Doctoral Thesis in Concrete Structures
Stockholm, Sweden 2013

Preface

The research presented in this thesis has been conducted mainly with the support from the Swedish Research Council (FORMAS), the Swedish Transport Administration, the Swedish Fire Research Board (Brandforsk) and SP Technical Research Institute of Sweden, department of Fire Technology. This work is a continuation of the work presented in the author's Licentiate thesis published in 2008.

While conducting this work I have been enrolled at KTH Royal Institute of Technology in Stockholm, Sweden, with Professor Johan Silfwerbrand as supervisor. He is greatly acknowledged for his sharp and detailed input on everything I have presented for him. I also want to acknowledge Professor Anders Ansell for his input during the latter stages of writing this thesis.

The in-situ supervisor at SP Fire Technology in Borås Sweden has been Dr Lars Boström, who has been exposed to many theories both those presented here and others that have not yet been (and some perhaps never will) be published. Thanks for letting something through!

I also want to acknowledge my colleagues and friends at SP Fire Technology and the Swedish Cement and Concrete Research Institute who are too numerous to mention by name. Further on I acknowledge the RILEM TC HPB group, in particular my dear friend Dr Pierre Pimienta.

Unfortunately Professor Ulrich Schneider can only be recognized posthumously as a source of knowledge from discussions on the tricky but inspiring subject of the behaviour of concrete at high temperature. Thanks Ulrich.

Regarding everything, strictly meaning everything including a great deal of patience, I want to thank my partner and Head of Research at SP Fire Technology Dr Margaret McNamee.

At last (and by far the least) I want to acknowledge my mother's mother's, mother's mother's, mother's father's, father's father Andreas Hesselius (1677-1733) who showed a good fighting spirit and managed to survive a very controversial disputation event in 1698 in Uppsala,

Sweden. In advance the disputation met heavy opposition from the famous Swedish researcher Olaus Rudbeck and his son, the Rector of the University of Uppsala Olaus Rudbeck the younger, as they did not want to have any opposition to Rudbeck's geographical placement of the pagan Æsir cult temple in Uppsala. To be allowed to conduct the dissertation the thesis should be re-written according to Rudbeck, but Hesselius and his supervisor Jacob Arrhenius managed to obtain permission from the vice-chancellor of the University (the archbishop) to proceed. On the day of the event Gustavianum, where the dissertation was to be held, was locked and no one seemed to remember where the keys were (Grimberg, 1922). Fortunately, after some hours of waiting outside in the cold, some students managed to find their way into the building through a window, at which point a blacksmith could enter and open up the heavy gates from the inside so the dissertation could be completed¹. I will make sure that there is a copy of the keys to my lecture theatre on hand if needed!

Borås, August 2013

Robert Jansson

¹ Hesselius A. (1698) "Dissertatio historica de Vandalis", Uppsala, Sweden, 42 pp., (in Latin).

Summary

Fire spalling of concrete is not a new phenomenon. To some degree there has always been a risk during rapid heating of concrete. Therefore, to a certain degree the effect of fire spalling is included in the bank of data from fire tests and fires on which our understanding of the fire resistance of concrete is based. However, the development and modern use of more dense concrete mixes have produced cases of very severe fire spalling which have increased the urgency to understand this phenomenon. In this context, the use of an addition of polypropylene (PP) fibres to the mix to limit the amount of spalling has been one topic of interest for this thesis.

During fire tests on a post-tensioned concrete structure made of spalling sensitive concrete, it has been shown that substantially lower amounts of PP fibres than 2 kg/m^3 , which is recommended in the Eurocode (1992-1-2:2004), can be used with successful results.

As part of this study, another important aspect has emerged, i.e. the impact the test method used can have on the fire spalling depths observed in concrete specimens. This has been known for many years but is seldom discussed in the scientific literature. In this thesis it has been shown that results from tests on unloaded cubes do not necessarily correspond to results seen on larger loaded slabs. In the results presented, none of the tested cubes spalled whereas some of the large slabs spalled to the degree that the reinforcement became fire exposed. Further, the difference in spalling depths between small and large post-tensioned slabs was shown to be substantial; although in general the ranking in severity from least to greatest spalling correlated between these two specimen sizes. The correlation to larger specimens was much vaguer in the case when the small slabs were not loaded in compression as there sometimes was no spalling in the small slabs.

From time to time the randomness of the fire spalling of concrete has been mentioned. To investigate this further, an analysis of 110 fire tests performed on small slab type specimens was performed. This analysis showed that the spalling behaviour had a good repeatability between two identical tests, which proved that the so called “random factor” relating to spalling depth was low for the chosen data set. It was also possible to make a multiple least squares fit of test parameters that could be used to predict the spalling behaviour which also underlines that a substantial stochastic factor was not present.

Regarding the influence of different factors, the results compiled on the influence of ageing show that for three of the tested Self-Compacting Concrete (SCC) mixes, the amount of spalling was reduced with age whereas for the fourth mix (which included the highest amount of limestone filler, 140 kg/m^3) the spalling was not reduced with age. In this test series no systematic influence of the intensity of the fire, between standard fire exposure and the more severe hydrocarbon fire, on the spalling depth was detected for this type of specimen. The only major difference was that spalling started earlier during the more severe fire exposure.

Pressure measurements conducted as part of the work within this thesis, supported by results from the literature, indicate that there is no relationship between pressure rise due to moisture and fire spalling. Based on this and the fact that the spalling event in many cases happens at relatively low temperatures where the saturation vapour pressure is low two alternative factors to explain the function of PP fibres have been presented: (i) PP fibres reduce the moisture content in the critical zone close to the heated surface which affects the mechanical properties

advantageously, and (ii) PP fibres amplify moisture movement leading to larger drying creep and shrinkage which locally relax the thermal stresses.

To investigate the influence of the presence of moisture on the compressive strength, specimens were tested after being boiled for varying periods of time in a water bath. The study showed a remarkable reduction of strength due to boiling of the mortar specimens. After boiling mortar in a water bath for 3, 10 or 20 minutes, i.e. approximately the same time span as the initiation of fire spalling during fully developed fires, the strength was only 64% of the corresponding value for a dry specimen. As no strength change was detected between the specimens boiled 3, 10 or 20 minutes, and that the corresponding saturation pressure for steam at 100°C is negligible compared with the tensile strength of concrete, it was concluded that pore pressure is not a significant contributor to the measured reduction in strength. It appears that the presence of moisture itself rather than an increased pressure is the most important factor reducing strength. This is a clear indication that moisture plays a key role in the fire spalling of concrete but in a different way from previously assumed.

Sammanfattning

Brandspjälkning av betong är ett fenomen som är känt sedan mycket lång tid. Det har alltid förekommit fall då delar från tvärsnittet spjälkat av vid snabb upphettning av betong. Så till en viss del är effekterna från brandspjälkning inkluderade i den stora databas av brandprovningar och erfarenheter från bränder som vår kunskap kring brandmotstånd av betongkonstruktioner vilar på. Men i om utvecklingen och användningen av tätare betongkvalitéer, som i många fall visat sig vara mer spjälkningsbenägna i flera typer av konstruktioner, har det blivit mer angeläget att belysa fenomenet mer på djupet eftersom det, när det inträffar, har en direkt påverkan på brandmotståndet. Också användandet av polypropylenefibrer (PP fibrer) som brandspjälkningshämmare faller inom området för denna avhandling.

Vid ett antal brandprovningar på en efterspänd konstruktion byggd av spjälkningsbenägen betong har det visat sig att betydlig lägre doser än de $>2 \text{ kg/m}^3$ som rekommenderas i eurokoden (1992-1-2:2004) kan användas för att kraftigt reducera brandspjälkningen.

Som ett resultat av de genomförda studierna har det också visat sig att provkropparnas utformning har mycket stor inverkan på brandspjälkningsresultatet. Detta har man för visso vetat i många år, men faktumet och omfattningen av denna skillnad är sällan diskuterad i den vetenskapliga litteraturen. Som ett belysande exempel visas att spjälkningsresultat uppmätt på obelastade standardkuber, med sidmåttet 150 mm, inte stämmer överens med brandprovningar på större efterspända plattor, $1700 \times 1200 \times 200 \text{ mm}$. De större plattorna spjälkade i flera fall vilket kuberna inte gjorde. Det är också en stor skillnad i spjälkningsdjup när man provar olika storlekar av tryckbelastade plattor men det har också framkommit att rangordningen från minst till mest spjälkning mellan olika betongblandningar från de mindre plattorna, $600 \times 500 \times 200 \text{ mm}$, stämmer väl med rangordningen från de större plattorna. Korrelationen mellan små och större provkroppar med samma principiella utformning var mycket otydligare om de små plattorna var obelastade eftersom det ibland inte uppstod någon spjälkning i de små plattorna.

Spridningen i resultat vid brandprovning som inkluderar brandspjälkning har många gånger påtalats. För att undersöka detta mer i detalj har en analys av resultaten av 110 brandprov på små belastade och obelastade plattor genomförts. Analysen visar att repeterbarheten mellan två identiska brandprov var god. Det var också möjligt att göra en multipel minsta kvadratanpassning av resultaten som kan användas för spjälkningsprediktion inom spannet av de testade parametrarna vilket visar att ingen betydande slumpfaktor var närvarande när man provar med denna metod.

När det gäller inverkan av olika faktorer på brandspjälkningsresultaten har en studie gjorts av ålderns inverkan på brandspjälkning av självkompakterande betong. Det visade sig att spjälkningsbenägenheten reducerades vid högre ålder (upp till 5 år) för tre av de fyra undersökta betongblandningarna medan den fjärde blandningen, innehållande den största andelen kalkstensfyller, 140 kg/m^3 , inte minskade i spjälkningsbenägenhet vid högre ålder. I denna studie, utförd genom ensidig brandpåverkan av plattor av olika storlekar, kunde ingen systematisk skillnad i spjälkningsdjup upptäckas mellan standardbrandspåverkan och den mer kraftiga hydrokarbonbranden. Den enda signifikanta skillnaden var att spjälkningen startade tidigare vid den kraftigare branden.

Tryckmätningar i brandutsatt betong samt resultat insamlade från litteraturen visar inte något samband mellan den uppmätta tryckuppbyggnaden från innesluten fukt och brandspjälkning. Baserat på det faktum att brandspjälkning ofta sker innan temperaturen är så hög att förångningsångtrycket spelar någon viktig roll har två alternativa modeller för att förklara funktionen av en tillsats av PP-fibrer presenterats: (i) fibrerna reducerar mängden fukt i den kritiska zonen nära den upphettade ytan vilket påverkar de mekaniska egenskaperna i en gynnsam riktning, (ii) fibrerna förstärker fukttransporten under uppvärmning vilket leder till lokalt högre krypning och krympning som reducerar de termiska spänningarna i den kritiska zonen.

För att undersöka fuktens inverkan på tryckhållfastheten vid förhöjd temperatur provades provkroppar som kokats i olika lång tid i ett vattenbad. Studien visar en kraftig reduktion av tryckhållfastheten hos små kokta provkroppar, $20 \times 20 \times 40$ mm gjorda av cementbruk. Efter kokning i 3, 10 eller 20 minuter, ungefär den tid det tar fram till den första spjälkningen vid fullt utvecklade bränder, reducerades tryckhållfastheten med 64% jämfört med uttorkade provkroppar. Då ingen skillnad kunde ses mellan kokning under olika lång tid samt att förångningsångtrycket vid 100°C är försumbart jämfört med draghållfastheten, drogs slutsatsen att portrycket inte var en signifikant faktor som ledde till den kraftiga hållfasthetsreduktionen. Det verkar som om närvaron av fukt snarare än den rena ökningen av portrycket, framkallat av temperaturhöjningen, leder till denna kraftiga reduktion i hållfasthet. Närvaron av fukt är alltså en nyckelparameter i fenomenet men dess roll har visat sig vara en annan än vi tidigare trott.

List of publications

This thesis consists of an extensive summary and five appended papers.

- Paper I** Jansson R. and Boström L. (2007) *Experimental study of the influence of polypropylene fibres on material properties and fire spalling of concrete*. Proceedings from the fib Task Group 4.3 workshop “Fire Design of Concrete Structures – From Materials Modelling to Structural Performance” Coimbra, Portugal, November 8-9, 2007, pp 177-188.
- Paper II** Jansson R. and Boström L. (2010). *The influence of pressure in the pore system on fire spalling of concrete* Fire Technology, Vol 43, No 1, 2010, pp 217-230.
- Paper III** Jansson R. and Boström L. (2013). *Factors influencing fire spalling of self compacting concrete*. Accepted for publication in Materials and Structures, Published online: January 22, 2013. 12 pp.
- Paper IV** Jansson R., Sjöström J., Boström L. and Silfwerbrand J. (2013). *Reduction of fire spalling of concrete with small doses of polypropylene fibers*. Submitted to ACI Materials Journal, July 5, 2013. 24 pp.
- Paper V** Jansson R, Boström L. and Silfwerbrand J. (2013). *Fire spalling of concrete*. Submitted to Fire and Materials, July 5, 2013. 17 pp.

The papers were prepared in collaboration with co-authors. The author of this thesis was the main author of all the publications. The experimental studies performed were planned, conducted, and analyzed by mainly the first author.

Other publications by the author related to the subject

Licentiate thesis

Jansson R. *Material properties related to fire spalling of concrete*, Licentiate thesis, Report TVBM-3143, Lund Institute of Technology, Sweden, 2008, 120 pp.

Conference papers

- I. Lange D. Jansson R. *A comparison of an explicit and an implicit transient strain formulation for concrete in fire* Submitted to the 11th International Symposium on Fire Safety Science, February 10 – 14, 2014 at the University of Canterbury, New Zealand.
- II. Jansson R. *Fire spalling of concrete - A historical overview* Accepted for publication as a key note in the Proceedings of the 3rd International RILEM Workshop on Concrete Spalling due to Fire Exposure, Paris, France, Sept. 2013.
- III. Jansson R. Boström SP *Fire spalling in concrete The moisture effect part II* Accepted for publication in the Proceedings of the 3rd International RILEM Workshop on Concrete Spalling due to Fire Exposure, Paris, France, Sept. 2013.
- IV. Albrektsson J. and Jansson R. *Capillary suction and chloride migration in fire exposed concrete with PP-fibre* Proceedings of the 3rd International Conference on Concrete Repair, Rehabilitation and Retrofitting, Cape Town, South Africa, September 3-5, 2012.
- V. Lange D., Sjöström J., Jansson R. and Boström L. *Deflection of concrete floor slab during a fire test: Tests and modelling* Proceedings of the 15th International Conference on Experimental Mechanics, Porto, Portugal, July 22-27, 2012.

- VI. Jansson R. and Boström L. *Test methods for determination of fire spalling of concrete* Proceedings of the 15th International Conference on Experimental Mechanics, Porto, Portugal, July 22-27, 2012.
- VII. Sjöström J., Lange D., Jansson R. and Boström L. *Directional dependence of deflection and damages during fire tests of post-tensioned concrete slabs* Proceedings of the 7th International Conference on Structures in Fire, Zürich, June 6-8, 2012.
- VIII. Jansson R. and Boström L. *Determination of fire spalling of concrete-Relevance of different test methods* Proceedings of the 7th International Conference on Structures in Fire, Zürich, June 6-8, 2012.
- IX. Albrektsson J., Jansson R., Flansbjer M. and Lindqvist J-E. *Quantification of fire damage of concrete for tunnel applications* Proceedings of the Fifth International Symposium on Tunnel Fire Safety and Security, New York, USA, March 14-16, 2012.
- X. Jansson R. and Boström L. *Test methods for determining fire spalling of concrete* Proceedings of the Fifth International Symposium on Tunnel Fire Safety and Security, New York, USA, March 14-16, 2012.
- XI. Jansson R. and Boström L. *Fire test of loaded beams* Proceedings of the 2nd International RILEM Workshop on Concrete Spalling due to Fire Exposure, Delft, The Netherlands, Oct. 2011.
- XII. Jansson R and Ödeen K. *Fire in Storehouse 6 in the Free Port of Stockholm* Proceedings of the 2nd International RILEM Workshop on Concrete Spalling due to Fire Exposure, Delft, The Netherlands, Oct. 2011.
- XIII. Boström L. and Jansson R. *The age effect on fire spalling of concrete* Proceedings of the 2nd International RILEM Workshop on Concrete Spalling due to Fire Exposure, Delft, The Netherlands, Oct. 2011.
- XIV. Zhang P., Nordlund E., Mainali G., Sainag C. and Jansson R. *Experimental study of thermal spalling on rock blocks exposed to different fire/heating conditions* Bergmekanikdagen, Stockholm, Sweden, 2011.
- XV. Schneider U., Alonso M. C., Pimienta P. and Jansson R. *Physical Properties and Behaviour of High Performance Concrete at High Temperature* Proceedings of the 6th Conference on Structure in Fire, Michigan State University, USA, 2010.
- XVI. Zhang P., Nordlund E., Mainali G., Sainag C., Jansson R. and Adl-Zarrabi B. *Experimental study on thermal spalling on rock blocks exposed to fire* Proceedings of the Rock Mechanics in the Nordic countries, Kongberg, Norway, 2010.

- XVII. Boström L. and Jansson R. *The effect of fire curve on concrete spalling* Interflam, Nottingham, 2010.
- XVIII. Jansson R. and Boström L. *The role of moisture in fire spalling of concrete* Interflam, Nottingham, 2010.
- XIX. Jansson R. and Boström L. (2009) *Fire spalling – the moisture effect* Proceedings of the 1st International Workshop on Concrete Spalling due to Fire Exposure - From Real Life Experiences and Practical Applications to Lab-scale Investigations and Numerical Modelling, MFPA Institute Leipzig, Germany, September 3-5, 2009.
- XX. Boström L. and Jansson R. , (2009) *Effect of fire exposure on the spalling of concrete* Proceedings of the 1st International Workshop on Concrete Spalling due to Fire Exposure - From Real Life Experiences and Practical Applications to Lab-scale Investigations and Numerical Modelling, MFPA Institute Leipzig, Germany, September 3-5 2009.
- XXI. Jansson R. *Pressure measurement inside concrete during fire exposure* Proceedings of the Nordic Concrete Research, Bålsta, Sweden, 2008.
- XXII. Jansson R. and Boström L. *The influence of pressure in the pore system on fire spalling of concrete* Proceedings of 5th Conference on Structure in Fire, Singapore, May 28-30, 2008.
- XXIII. Boström L. and Jansson R. *Results from two research programs on spalling of concrete* Proceedings of 5th Conference on Structure in Fire, Singapore, May 28-30, 2008.
- XXIV. Boström L, Hjohlman M. and Jansson R. *Fire testing of concrete and concrete protection systems for tunnels in Sweden - An overview* Proceedings of the Third International Symposium on Tunnel Safety and Security, Stockholm, 2008.
- XXV. Jansson R. and Boström L. *Influence of polypropylene fibres on fire spalling and material properties of concrete* Proceedings of the Third International Symposium on Tunnel Safety and Security, Stockholm, 2008.
- XXVI. Jansson R. and Boström L. *Fire spalling: Theories and Experiments* Proceedings of the Fifth International RILEM Symposium PRO 54 Self-Compacting Concrete SCC, Ghent, Belgium, 2007.
- XXVII. Hjohlman M., Boström L. and Jansson R. *Overview of fire testing of concrete and concrete protection systems for tunnels in Sweden* Proceedings of fib Workshop on Fire Design of Concrete Structures - From Materials Modelling to Structural Performance, Coimbra, Portugal, November 8-9, 2007.

- XXVIII. Jansson R. and Boström L. *Experimental study of the influence of polypropylene fibres on material properties and fire spalling of concrete* Proceedings of fib Workshop on Fire Design of Concrete Structures - From Materials Modelling to Structural Performance, Coimbra, Portugal, November 8-9, 2007.
- XXIX. Jansson R. *Liquid/steam pressure measurement inside concrete exposed to fire* Proceeding of the 4th International Workshop Structures in Fire, Aveiro, Portugal, 2006.
- XXX. Boström L. and Jansson R. *Spalling of self compacting concrete* Proceeding of the 4th International Workshop Structures in Fire, Aveiro, Portugal, 2006.
- XXXI. Jansson R. *Measurement of concrete thermal properties at high temperature* Proceedings of the Workshop: Fire Design of Concrete Structures: What now? What next?, Milan, Italy, 2004.
- XXXII. Boström L. and Jansson R. *Experimental investigation of concrete spalling in fire* Proceedings of the Workshop: Fire Design of Concrete Structures: What now? What next?, Milan, Italy, 2004
- XXXIII. Boström L. and Jansson R. *Spalling of concrete for tunnels*, Interflam, Edinburgh, July 2, 2004.
- XXXIV. Jansson R. *Measurement of the thermal properties at high temperature*, Interflam, Edinburgh, July 2, 2004.

SP Reports

- I. Albrektsson J., Flansbjer M, Lindqvist J-E. and Jansson R. *Assessment of concrete structures after fire* SP Report 2011:19, SP Technical Research Institute of Sweden, Borås, Sweden, 2011.
- II. Boström L., Jansson R. *Self-Compacting Concrete Exposed to Fire* SP Report 2008:53, SP Technical Research Institute of Sweden, Borås, Sweden, 2011.
- III. Jansson R. and, Boström L. *Spalling of concrete exposed to fire* SP Report 2008:52, SP Technical Research Institute of Sweden, Borås, Sweden, 2011.
- IV. Jansson R. *Measurement of thermal properties at elevated temperatures* SP Report 2004:46, SP Technical Research Institute of Sweden, Borås, Sweden, 2011.

Other Reports

- I. Swedish Concrete Association: *Concrete and Fire – Recommendations to Prevent Spalling in Civil Engineering Structures* Concrete report No. 16, Swedish Concrete Association, Stockholm 2011, Interimistic Edition (R. Jansson technical secretary)
- II. Boström L. and Jansson R. *Fire Resistance* Chapter 4.6 in the report *Durability of Self-Compacting Concrete* RILEM TC 205-DSC: State-of-the-Art Report”, Rilem Report 38, Ghent, Belgium, 2007.

Table of Contents

1 Introduction	3
1.1. Objective and scope of research	3
1.2. Limitations	4
1.3. Outline of the thesis	4
2 Fire spalling of concrete	5
2.1. A historical overview	5
2.2. Observations of fire spalling of concrete	33
2.3. Analysis of results from 110 fire tests	51
3 Fire spalling theories	59
3.1. Thermal stress theories	59
3.2. The vapour pore pressure and moisture clog theory	60
3.4. The fully saturated pore pressure theory	61
3.4. The BLEVE theory	61
3.5. The frictional forces from vapour flow theory	61
3.6. Discussions from the literature on theories	62
4 The function of polypropylene fibres	63
4.1. Introduction	63
4.2. Enhancement of permeability due to formation of capillary pores	66
4.3. Enhancement of permeability due to development of transition zones around the fibres	68
4.4. Enhancement of permeability due to the development of additional micro-pores during mixing	68
4.5. Enhancement of permeability due to additional micro-cracks developed during heating and melting	69
4.6. Steam pressure release around fibres in the fibre bed	69

4.7. Reduction of moisture movement to colder areas.....	69
5 Test methods for spalling assessment	71
5.1. Traditional fire resistance testing and testing of real elements.....	71
5.2. Dedicated fire spalling tests	71
5.3. The moisture level in concrete during fires and fire testing	78
6 The influence of moisture	83
6.1. Determination of the pressure in the pore system.....	83
6.2. The influence of moisture and temperature on some mechanical properties.....	89
7 Discussion on fire spalling	93
7.1. Introduction.....	93
7.2. Summary of observations and fire spalling theories with additional comments	93
7.3. The influence of the presence and movement of moisture at temperatures below 250°C.....	95
7.4. The influence of specimen size.....	97
8 Conclusions and further research	99
8.1. Conclusions.....	99
8.2. Further research	100
9 Resume of appended papers	103
Paper I: Experimental Study of the Influence of Polypropylene Fibres on Material Properties and Fire Spalling of Concrete	103
Paper II: The Influence of Pressure in the Pore System on Fire Spalling of Concrete	103
Paper III: Factors Influencing Fire Spalling of Self Compacting Concrete.....	104
Paper IV: Reduction of Fire Spalling of Concrete with Small Doses of Polypropylene Fibers.....	104
Paper V: Fire Spalling of Concrete.....	105
Bibliography.....	107
Details of statistical test.....	123
APPENDED PAPERS	135
Paper A – Jansson R. Boström L. Experimental study of the influence of polypropylene fibres on material properties and fire spalling of concrete	
Paper B – Jansson R. & Boström L. The influence of pressure in the pore system on fire spalling of concrete	
Paper C – Jansson R. & Boström L. Factors influencing fire spalling of self compacting concrete	
Paper D – Jansson R., Sjöström J., Boström L. and Silfwerbrand J. Reduction of fire spalling of concrete with small doses of polypropylene fibers	
Paper E – Jansson R, Boström L. and Silfwerbrand J. Fire spalling of concrete	

Fire spalling of Concrete – Theoretical and Experimental Studies

Chapter 1

Introduction

1.1. Objective and scope of research

“Thus there are not two concrete pieces that are alike and there is not a single concrete piece that is the same all through. Even if two pieces are identical from the beginning, there are so many factors influencing their condition that they will not be identical in the end”

Helsing Atlassi (1993)

The ability of a structure or a member to carry load and/or maintain compartmentation during a fire is called its fire resistance. As concrete has a relatively high density and low heat conductivity the penetration of heat is slow in structures made of concrete. If a concrete member, which has been optimized for a certain fire resistance with the assumption that the whole cross-section will remain intact during the fire exposure, instead loses some of its cross-section during fire exposure, the fire resistance can be substantially reduced. Fire spalling of concrete is a phenomenon which has been recognised since the introduction of reinforced concrete; but the severity of this, at first glance random, phenomenon has become more intense since the introduction of high strength and self-compacting concrete. There are measures to combat or limit the fire spalling of concrete. One of these measures is to add thin polypropylene (PP) fibres to the concrete mix.

Despite a century of experience and a great deal of effort, the prediction of spalling is still in many cases a very difficult task as so many factors seem to be involved in the phenomenon. Further, the mechanism of polypropylene fibres to reduce the amount of spalling is not totally clear. The purpose of the work presented in this thesis has been to deepen our knowledge of

Chapter 1. Introduction

the fire spalling phenomenon and the function of PP fibres in combating it. In the long term it is hoped that this will lead to a safer and more economical use of concrete.

1.2. Limitations

The majority of the studies included in the thesis assume that fire spalling has occurred during unilateral heating. Therefore some of the factors considered might have a different significance in the case of bi- or multi-lateral heating.

1.3. Outline of the thesis

This thesis is based on five papers. These papers are reprinted in the last section of the thesis. To place the papers in their scientific context the following chapters have been written:

Chapter 2 “*Fire spalling of concrete*” provides a historical overview of the subject followed by a collection of observations of the phenomenon. This is supplemented by a more in-depth analysis of a series of fire tests, to investigate the seemingly random nature of the occurrence of this phenomenon. Details of the statistical analysis conducted on the large set of experiments presented in this chapter are given in an appendix after the bibliography.

Chapter 3 “*Fire spalling theories*” includes a compilation of the most common theories regarding the origin of the phenomenon.

Chapter 4 “*The function of polypropylene fibres*” is dedicated to the most common theories concerning the function of PP fibres to reduce fire spalling.

Chapter 5 “*Test methods for spalling assessment*” gives an overview of test methods and includes an extended discussion of moisture level in specimens during fires and fire testing.

Chapter 6 “*The influence of moisture*” deals with both the measurement of pressure caused by trapped moisture and the influence of this moisture on the mechanical properties of concrete.

Chapter 7 “*Discussion on fire spalling*” presents and discusses some aspects of fire spalling of concrete and includes the postulation of an alternative explanation for the fire spalling phenomenon and an argumentation for where the focus should be placed for further development of our understanding of the phenomenon.

Chapter 8 “*Conclusions and further research*” summarizes the findings of this thesis and makes some suggestions on how to proceed in this area.

Chapter 9 contains a short resume of the papers. Thereafter a list of references is given in the bibliography.

Reprints of the five full papers, on which this thesis is based, are appended after the bibliography.

Chapter 2

Fire spalling of concrete

2.1. A historical overview

The true nature of the fire spalling phenomena of concrete is still the subject of significant contention in the scientific community. It is, therefore, of interest when embarking on this thesis to begin by gazing into the past and consider different milestones in the origins and development of fire spalling research historically. It is important to remember, when reading about the different observations and theories presented, that the material “concrete” has changed dramatically during the past 150 years. Despite this, the following historical overview will set the stage for further discussions, thereby providing a proper perspective for the experimental and theoretical work presented in the ensuing chapters.

This chapter will present the most important research developments in this field (in my humble opinion) as well as related experience from real fires and fire tests. The presentation is chronological rather than in order of significance (although one cannot assume that the most important research findings are exclusively the most recent findings). The disposition at each point in time begins with a single sentence (bold) describing the pivotal development(s) related to the fire spalling of concrete for each selected year. This is followed by illustrative details and the author’s comments related to this work or its implications for subsequent progress.

Before 1850 **Spalling recognized as a phenomenon.** During the Stone Age tools were produced by mechanically knocking away, spalling away, smaller pieces from a larger block of flint. Also in mining, spalling by mechanical action was used, as illustrated in Figure 2.1. The first cases of human induced spalling by heat were probably from campfires located on or close to rocks. Rock material exposed to heat can in some cases spall violently by continuous flaking of layer after layer. An example of spalling of granite during fire exposure can be seen in Figure 2.2.



Figure 2.1 Women spalling ore according to Henderson (1858).

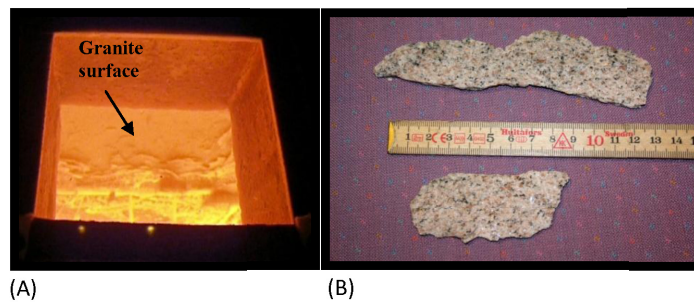


Figure 2.2 Spalling of granite due to fire exposure. A) Granite exposed to fire in a fire resistance testing furnace. B) Examples of pieces of granite that were spalled away during the fire exposure. Photo: Robert Jansson.

1854

First recorded observation of fire spalling of concrete. Probably the first description of the spalling behavior of concrete during fire was made in a publication by Barret (1854). He described a discussion where Mr. Tite states that if flint was used as aggregate in the concrete it would “split, and yield under the action of fire”. Pure flint aggregate has been shown to be unstable under the influence of heating, see Figure 2.3.



Figure 2.3 Flint before and after heating. The aggregate splits violently as observed by Mindeguia (2009).

1866

Recognition that rapid cooling of heated concrete building elements could precipitate spalling. According to Ingle (1866), some of the numerous instances of destruction by fire of concrete buildings, which were supposed to be fire resistant, are probably due to the application of water during fire fighting.

This is almost certainly a rare scenario but there is at least one documented example of this. During a fire event, described by the Swedish Tariff Association (1959), pre-stressed beams were used as targets for distributing water in the fire enclosure with the consequence that a large part of the webs of the beams spalled away as shown in Figure 2.4. In contrast with this experience it was summarized by Kordina (1965) during a workshop in Braunschweig on the subject of fire resistance of pre-stressed concrete that the hose steam test did not appear to result in dangerous spalling. This fast cooling effect by water addition is sometimes considered during fire testing. When conducting fire tests on walls and partitions according to ASTM E119 (2011), a hose stream is applied directly after the fire exposure if the fire exposure is not less than one hour. In the corresponding European standard test procedure, EN 1363 (1999), no hose stream test is added after the fire exposure.



Figure 2.4 Spalling of pre-stressed beams due to fast cooling by adding water described by the Swedish Tariff Association (1959).

1877

Pioneering research into the impact of wrought iron reinforcement on the fire performance of concrete and the use of large scale fire tests to demonstrate performance. One of the pioneers in the development of the use of reinforcement in concrete, Thaddeus Hyatt (1877), performed a large number of fire tests on concrete beams with different types of reinforcement. Hyatt also compared the thermal expansion of wrought iron and concrete and concluded that it was almost the same. Concrete in combination with iron was shown to be an excellent material in a fire situation. The insulating properties of concrete were good and the function of the elements was maintained during prolonged fire exposure. Some of the tested concrete samples included something as modern as different types of fibres and he concluded that not even asbestos fibres improved the fire resistance. The only factor that was important for the protection of the reinforcement was the compressive strength of the concrete. Based on this information Hyatt concluded that higher strength concrete gave a better protection. One experiment illustrated that if concrete made of Portland cement was put into water when “heated to redness” it disintegrated instantaneously, see Figure 2.5. This experiment was repeated without damage on a concrete mix which included a new type of cement invented by Hyatt (1877) called the “New Portland Cement”. At the time of his publication New Portland Cement was not on the market and Hyatt was looking for a company

willing to produce it. The experiments performed also showed that the moisture content in concrete contributed to keeping the temperature down during fire exposure. This effect was later investigated in more detail by Harmathy (1965) who proposed a method for correcting fire resistance results from tests performed with specimens of high moisture content. This is significant as high moisture content not in equilibrium with the surroundings leads to an overestimation of the fire resistance time if not corrected. This method of correcting fire resistance data is now included in the ASTM E119 (2011) standard for fire resistance testing. For a more detailed discussion on this method see chapter 5.3.

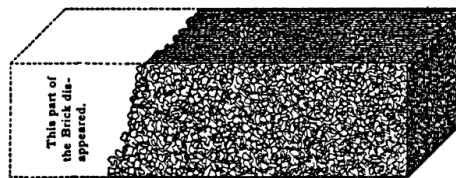


Figure 2.5 Illustration made by Hyatt (1877) showing the remains of a concrete brick after it had been "heated to redness" and the left end had been put under water.

1903

The first fire resistance test standard was declared. As fire spalling of concrete is closely connected with fire resistance, the way of maintaining a load or preserving a compartmentation during a fire, the development of evaluation methods for fire resistance is of interest as we later in the thesis will see that the test method used gives a huge impact on the spalling behavior. As described in the "Red Books" of the fire prevention committee No 80 (1904), the International Fire Prevention Congress in London 1903 adopted the first fire resistance standard issued. The prominent members supporting the standard can be seen in Figure 2.6. This was not the start of fire resistance testing, as experiments were conducted more than 120 years earlier by Lord Viscount Mahone (1778) and much furnace testing was performed in the late 1800s, but this was the first attempt to unify the test methodology.



Figure 2.6 The noble gentlemen at the International Fire Prevention Congress who adopted the first standard for fire resistance testing 1903.

The principle of the test was to evaluate the construction in the three classes: full protection, partial protection and temporary protection each with a sub-class A and B. The different classes were then associated to different durations of the test and minimum temperature in the furnace. Loading of some types of specimens was prescribed and at the end of all fire exposures a hose stream test was performed.

Since then the principles for standardized fire resistance testing have now and then with more or less relevance been questioned. In particular the mechanical boundary conditions and the equal area concept of severity of fires that Ingberg proposed, that are one of the fundamental ideas behind using one (or mainly one) fire exposure curve, have been questioned². In contrast the use of mainly one fire exposure time temperature curve should, in theory, make the task of determining details of the fire spalling of concrete phenomenon easier, as the thermal boundary for fire resistance testing should be the same in the majority of tests. Unfortunately this is only partly true as the lack of precision in the principles of temperature measurement in older fire resistance furnaces gave very different thermal exposure in different furnace configurations, i.e. different geometries, furnace material and fuels gave different combinations of heating, by convection and radiation, of the specimen. The small thermocouples that were used for measuring temperature in fire resistance furnaces did not register the same differences in thermal boundary conditions that larger objects tested for fire resistance did. As an example Van Acker (2004) experienced a test laboratory where the measured temperatures inside concrete specimens were 20-40% lower than similar tests at other laboratories despite the fact that the furnaces were fired with the same fire curve. A lot of effort was put into the art of calibration of test furnaces and discussing solutions to this problem in the 70's; but the errors were not minimized until the use of plate thermometers³, introduced by Wickström (1986), was included in the European and ISO fire resistance standards. Thus, when evaluating fire tests on concrete that are older than 10 years or that do not include plate thermometers in the furnace, great care must be taken when comparing results between different laboratories. Although the majority of furnaces seem to have given the same thermal inertia great deviation also existed. Some hint when trying to estimate these differences between old furnace tests controlled with ordinary thermocouples to follow the standard time temperature curve can be found in a report by Van Keulen (1974). In this study a comparison of accumulated heat in ceramic plates in six different furnaces around the world was made. The largest deviation from the average value after 20 minutes fire exposure was as much as $\pm 25\%$ (reduced to around $\pm 10\%$ difference after an hour).

² For more information on this issue see Ödeen (1963), Magnusson and Thelandersson (1970), Pettersson (1971), Malhotra (1974), Babrauskas (1976) and Pettersson and Magnusson (1977).

³ Plate thermometers, as defined in EN 1363 (2012) and ISO 834 (1999), can be viewed as a standardized small object with low thermal diffusivity where the surface temperature is accurately measured in the middle of a $10 \times 10 \text{ cm}^2$ flat area. This together with the fact that it is direction dependent in the same way as a flat surface and that a thermal boundary layer more representative for larger surfaces is created is the reason why plate thermometers are superior to small thermocouples when regulating thermal exposure of objects larger than the plate in fire resistance furnaces.

The factor of different heat exposure in different furnaces, including electrical ovens, when only measuring the temperature with ordinary thermocouples introduces unquantifiable differences in heat exposure between tests made by different research groups. To make comparison easier between test programs it is therefore recommended to use plate thermometers or/and measure the surface temperature of the test specimens, despite the fact that surface temperature measurements is also associated with errors.

1905

Observations of liquid water coming out of the unexposed side of concrete during fire testing. Woolson (1905) first recorded the flow of liquid water from the cold side of a concrete sample during fire tests on floor slabs. This is a very common phenomenon during fire testing of concrete, see Figure 2.7. After as little as 40 minutes of single-sided fire exposure to a 30 cm thick concrete slab, water can pour out of the cold surface of the specimen. This illustrates the fact that during fire exposure a continuous crack system is present through the cross-section of the specimen. This crack system is probably a mixture of cracks already present before the fire test and new cracks developed during the fire exposure. Experience from fire testing shows that only a couple of minutes after the start of fire exposure from below, a curvature can be measured on the top of a 300 mm thick slab. Modeling the flow of water in the cold area of a fire exposed concrete sample in the continuous crack system is one of the major challenges that needs to be overcome if a detailed thermo-hydro-mechanical model of fire spalling is to be successful. Indeed, this is a prerequisite if such a model is to be used to predict the fire spalling phenomenon.

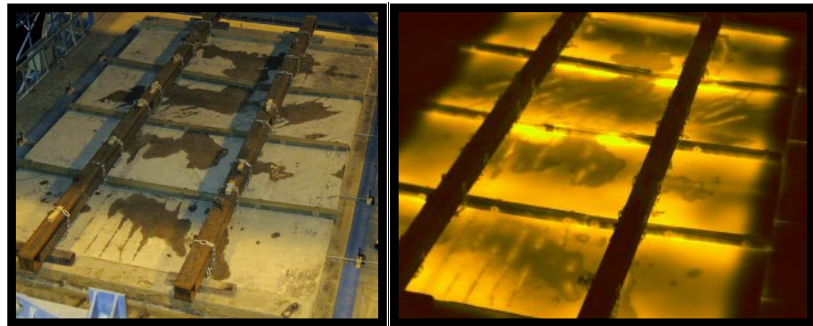


Figure 2.7 a) Water is pouring out on the non fire exposed side during a fire test of 8 cm thick concrete specimens. b) Thermal image showing the cracks where water reaches the surface. Photo: Robert Jansson.

1905

Recognition of the significance of age prior to fire testing for the fire spalling behavior of concrete samples. It was discovered by Miller (1905) that if fire testing of concrete is performed too soon after manufacture huge quantities of water must be driven off leading to disintegration due to the expulsion of the water from the specimen and its conversion into steam. Out of fourteen tests performed on loaded slabs only eight were “successful”. Even in successful tests, the concrete flaked off to a depth of about one inch on the fire

exposed surface. Despite this potential problem, the time allowed for setting before performing fire tests deserves some attention according to Miller (1905). Indeed, he stated that “[A] maximum limit should be fixed dependent on the interval between construction of a building and its occupancy in ordinary cases.” One interpretation of this must be that a concrete structure shall have the required fire resistance from day one when it is taken into service. This is not the approach used later when a test specimen is “required” to be in moisture balance with the surroundings before testing. See a more detailed discussion on this issue in the chapter 5.3.

1906

An example of surface spalling caused by fire during the San Francisco earthquake. During an investigation of the damage to the Academy of Science building during the San Francisco earthquake, shown in Figure 2.8, the following observations were made by Himmelwright (1906): *“The falling away of the concrete protection under the reinforcing bars of the concrete beams and floor slab in the basement, from the effects of a very moderate fire, has considerable significance. The entire strength of a reinforced concrete beam depends upon the tensile members that are imbedded near its under side. When the protection falls away, and the reinforcing metal is exposed to fire, it is only a matter of a very short time until such small sections of metal become heated to temperatures at which they lose all their strength and failures result.”*



Figure 2.8 Spalling of the concrete cover during a moderate fire after the San Francisco earthquake.

1911-18

Early categorization of the fire spalling of concrete. During several fire test series performed by Gary (1911)(1916)(1918) in concrete buildings, different fire spalling phenomena were observed, see Figure 2.9. Mayer-Ottens (1972) summarizes the phenomena that Gary identified during these test in the following way⁴:

- Crater-shaped spalling of single aggregate grains – “aggregate spalling” – but not of concrete with basalt aggregates. The spalling was attributed to the mineralogical character of the aggregates, especially to weathered feldspars.

⁴ Translation from German to English by Klaus Pistol, BAM, Germany.

- Shell-shaped explosive spalling on the surfaces of the structural elements – “surface-spalling” – at levels of the order of 100 cm² up to several square meters, especially at compression loaded walls and columns, whereby the reinforcement was partially exposed. The spalling was explained by water vapor stresses in relatively wet concrete.
- Explosive spalling at the corners of joists, columns and steps – “corner-spalling” – whereby the corner reinforcement was partially exposed. Simultaneously tested sandstone steps have also shown corner spalling. Also this spalling was explained by water vapor stresses and temperature stresses⁵ due to bilateral rapid heating.
- Explosive spalling at the walls, whereby up to 1 m² big wall sections were fully blasted and the integrity was lost, but the bearing capacity was preserved. Wall pieces were thrown away more than 12 m from the experimental house.

Only slight changes have been introduced to Gary’s terminology postulated approximately 100 years ago. As an example, in this thesis *explosive spalling* is discussed further in subsequent chapters where it is defined as the occasion where a substantial part of or the whole cross-section is lost in one event. Further, the term *progressive surface spalling* is used to describe the case when *surface spalling* is continuous.

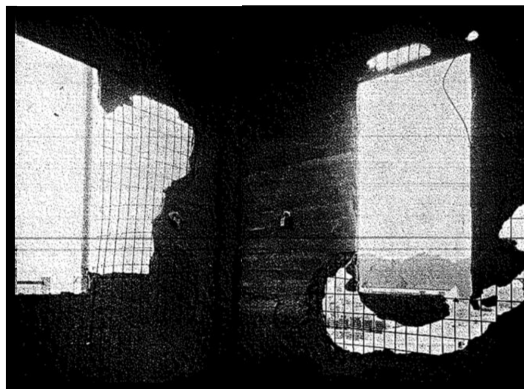


Figure 2.9 A view from inside one of the specially built concrete houses that Gary (1916) fire tested.

1916

Fire spalling as a trigger for building collapse. In the Far Rockaway Fire in the U.S. five of the eight levels of the concrete building were exposed to fire. The 4th floor collapsed during the fire and extensive spalling was found in the building despite the fact that the building built in 1909 was supposed to be a first class fire proof building and the fire exposure was not particularly severe. The reason for the severe spalling behavior, shown in Figure 2.10, was according to Woolson (1918), the use of quartz gravel from the New York vicinity. A special committee was appointed by the American Concrete Institute to investigate the

⁵ According to Thelandersson (1974b) these stresses leads to tensile failure.

fire further and some noteworthy findings by the committee included the following:

- In the case of no sprinklers when a very rapid rising fire or a slow fire with long duration is suspected, special care must be taken regarding the protection of concrete.
- Round columns are preferred compared to square columns⁶.
- If the reinforcement is placed near the surface, serious damage will likely occur and the concrete will be stripped off by the rapid expansion of the reinforcement.
- When using gravel concrete, protective coatings of concrete or other materials can be used to enhance the fire resistance during rapid fires of considerable intensity or slow fires with long duration.
- The thermal expansion of the aggregate is a very important factor influencing the fire resistance during rapidly developing fires. Quartz undergoes a critical transformation at 575°C, which is the main cause of the intense spalling during the Far Rockaway fire.

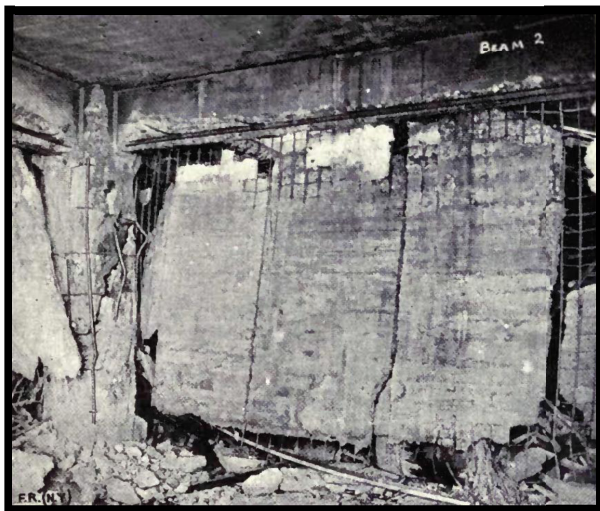


Figure 2.10 Extensive spalling after the Far Rockaway fire observed by Woolson (1918).

1918 **Definition of the standard fire curve for fire testing.** According the NFPA Handbook (1954) the standard fire curve for fire exposure was defined by a committee in U.S. 1918. Before the final decision was made a dozen different rates of rise were considered. A significant feature of the standard fire curve is the rapid rise of temperature during the first ten minutes of exposure which was chosen to represent the behavior in real fires in occupancies, but at the time for

⁶ Although round cross-sections are preferable compared with square cross-sections the cover of round columns made of ordinary concrete can also spall during certain restraint cases as shown by Korzen, Rodrigues and Laim (2013).

defining the curve there was no knowledge in the U.S. concerning the actual temperatures evolved in real fires, according to Babrauskas (1976). Although some experiments with real fires had at that time already been conducted in Europe the committee members defining the standard fire curve were not aware of them. Since then the standard fire curve has become the totally dominating fire exposure chosen for fire resistance testing worldwide.

- 1920 **Additional reinforcement close to the surface of concrete suggested to compensate for the expansion of thermally unstable aggregate.** Hull (1920) had the same opinion as many others that the expansion of quartz in the aggregate was the main reason for fire spalling. To limit the spalling behavior the author recommended adding a thin extra reinforcement layer close to the surface. More recent research has, however, indicated that the addition of an extra reinforcement layer (which is also an option defined in the national choice in the Eurocode 1992-1-2) does not work properly for high strength concrete according to Diederichs, Jumppanen & Schneider (1995) and Diederichs & Schneider (2007).
- 1920 **Development of high temperature material testing of concrete as a counterbalance to large scale testing.** During the early 20th century a large amount of effort was put into the fire testing of large non-reinforced and reinforced concrete test specimens. As a reaction to this, Lea (1920) performed a series of small scale material tests to understand the fundamentals of the material behaviour of steel and concrete at high temperatures. According to Lea, it was unwise to spend money on large scale tests before the fundamentals were understood. He investigated the thermal behaviour of different concrete mixes and also the residual compressive and tensile strength of unloaded specimens after heat treatment up to 700°C. A conclusion from his work was that the internal temperature in a fire exposed concrete cross-section can vary considerably between concretes made with different aggregates. The main factors influencing the thermal conductivity of concrete at room temperature are the aggregate type, aggregate content and the moisture content of the concrete. In the Eurocode 1992-1-2 (2004) the thermal conductivity is defined as a span as shown in Figure 2.11.

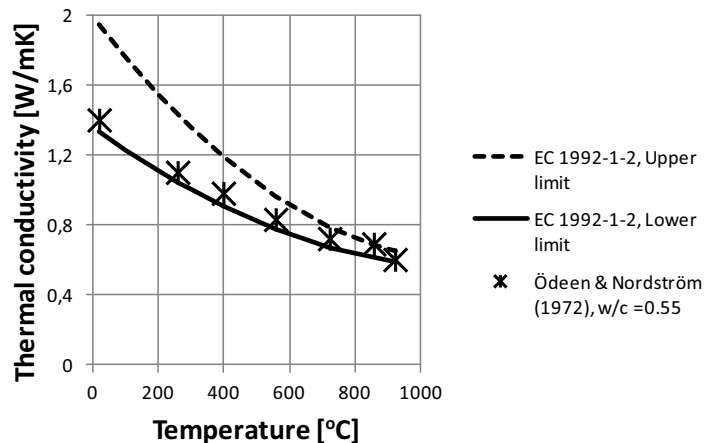


Figure 2.11 Thermal conductivity according to Eurocode EN 1992-1-2 (2004) and Ödeen & Nordström (1972).

Which curve should be used when determining the thermal conductivity is then defined in the implementation of the Eurocode 1992-1-2 into national regulations but it is important to know that the calculated temperature profiles shown in Annex A of the Eurocode are based on the lower limit. When seeing the two limiting curves it is natural to think that the curves represent concrete with two different aggregates as this is the main influence on thermal conductivity. But according to “Background Documents to EN 1992-1-2” (2004) and Anderberg (2005) the lower curve is fitted to temperatures measured in concrete structures exposed to fire and the upper curve is fitted to temperatures measured in steel concrete-composite structures during fire exposure. The lower limiting curve is by coincidence very close to the curve measured with the Stålhane/Pyk method by Ödeen and Nordström (1972) on a w/c=0.55 concrete with granite aggregate, see Figure 2.11.

1925

Further evidence of the impact of high silica content aggregate on the fire performance of concrete. In a test series by Ingberg et al. (1925) which included a large number of fire tests on columns it was concluded that concrete made with sand and pebbles high in silica (chert and quartz) disintegrated during fire exposure. The reason for the behaviour was according to Ingberg et al. (1925):

- Points of abrupt volume change, for chert as low as 210°C and for quartz 573°C.
- Disintegration of the pebbles from evaporation of the chemically combined water in the chert, and water occluded in tiny cavities in the quartz when it crystallized.

According to Lin et al. (1992) this fire test program performed 1925 was the basis for fire design of concrete columns until the 1987 revision of the ACI 216 “Guideline for Determining the Fire Endurance of Concrete Elements”.

1931 **Discussion of the significance of crack growth in concrete for the occurrence of spalling.** Based on a microscopy study of concrete from a fire in a storage building in Sweden, Sundius (1931) drew the conclusion that physical changes such as crack growth in the cement paste were induced by the expulsion of water. He also found large cracks parallel to the heated surface which he concluded could lead to flaking.

1934 **A mechanism for fire spalling postulated.** Preston and White (1934) made the following definition of spalling *"A spall is properly a flake-shaped piece; it is thin one way, namely, in a direction perpendicular to the original face. Equi-axed fragments are not properly spalls. When a bricklayer trims half an inch from the length of the brick with his hammer, the fragments are spalls."* They also proposed a mechanism for the fire spalling after observing delamination during the heating of clay. As shown in Figure 2.12, the starting point of thermal spalling in clay is hypothesised to be an initial flaw, lamination or weakness in the material. This is quite similar to Bazant's (2005) description of fire spalling of concrete as a "brittle fracture and delamination buckling caused by compressive biaxial thermal stresses parallel to the heated surface".

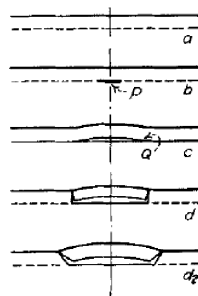


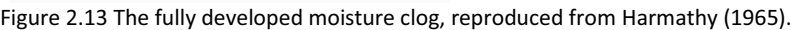
Figure 2.12 Mechanism of thermal spalling during sudden heating of clay according to Preston and White (1934). The dotted line is the heat wave and point P is an initial flaw, lamination or weakness in the material. The behaviour in d_2 seems to be more probable than d.

1935 **New description of the main factors leading to fire spalling.** In his PhD thesis produced at the University of Braunschweig, Hasenjäger (1935) summarised the factors leading to fire spalling as being:

- Rapid heating of concrete
- Exceeding the tensile strength by unilateral strain
- Rapid structure and volume change in the aggregate
- Pressure from liberation of water vapour and gases from the aggregate and the cement paste

Clearly Hasenjäger mainly identified two types of stresses leading to the spalling phenomena: thermal stresses and pressure from moisture. The relative importance of these two factors has since been the subject of intense discussion by the scientific community.

- 1952 **Initial concerns about the implications of mechanical vibration of modern concrete on its fire spalling performance.** Concerns were voiced by Sönnnerberg (1952) that concrete moulded using modern methods (mechanical vibration) have been seen to spall leading to a reduced fire resistance when exposed to fire. The modern concrete was found to be denser compared to traditionally “tampered” concrete. When concrete is exposed to heat during a fire the water, which is always present in free or bound form in concrete, will evaporate and strive towards the surface through cavities. If the concrete is dense this moisture transport is somewhat hindered, so high gas pressures can result leading to explosions of the surface layers of the structural member (i.e. spalling). This can happen even due to rather weak fire exposures. According to Sönnnerberg (1952) more research and testing were needed to solve this problem.
- 1961 **Emergence of the Moisture Clog Theory.** A classical approach to the role of moisture was formulated by Shorter & Harmathy (1961), i.e. the Moisture Clog Theory. According to this theory, when a concrete specimen is heated water desorbs in a thin layer close to the surface. The pressure gradient then drives moisture not only out of the specimen but also towards the inner (colder) parts of the concrete specimen. When the steam meets a neighbouring colder layer it will condense. This process will continue, moving further into the cross-section, until a fully saturated region of “considerable thickness”, Harmathy (1965), is created. This region is the so called “moisture clog”. When the moisture clog is created, further movement of steam inwards towards the colder regions is restricted which will lead to the situation shown in Figure 2.13. The figure is obviously a simplification because in a real situation the temperature and pressure fields will not be linear, but the main point is that the highest pressure will be developed at the boundary of the moisture clog and when (or if) this pressure exceeds the tensile strength of the concrete, a piece will spall away. According to Shorter & Harmathy (1961) it is not necessary to assume that the explosive release of energy, or spalling, comes from expanding water alone as the dry layer closer to the surface is already highly stressed by thermal expansion. The presence of moisture leads to two effects that can contribute to the spalling behaviour, i.e.; a sharp temperature gradient and vapour pressure force.



Notch for splitting

Saturated zone

Zone over 100°C, dry or instantaneous evaporated during splitting

Spalling front

1963

18

exposure. Wierig (1963) noted a propensity towards spalling in slender I-beams and on the underside of cross slabs of T-beams.

1965

F.I.P. meeting in Braunschweig on the “Fire resistance of pre-stressed concrete” including a new theory on the cause of fire spalling. The local host of the meeting, professor Kordina, summarized the discussion held on the cause of spalling as follows (F.I.P., 1965):

“We are not in a position to name a specific cause of spalling but a combination of the following factors could lead to dangerous spalling:

- a) Residual stress due to non-uniform heating in the cross-section or between flanges and stem of a beam*
- b) Excessive longitudinal restraint*
- c) High moisture content*
- d) Closely spaced reinforcement*
- e) Mineralogical character of aggregates”*

Other noteworthy additions to the discussion during the meeting were:

“Spalling which usually occurred within 15-30 minutes after fire attack and was most frequent when there was a quick rise in temperature could lead to substantial loss of material.”

“Application of a hose stream did not appear to be conducive to dangerous spalling”

“Mr. Gustaferrero reported that mesh wire was not always effective against spalling and experience in America indicated that stirrups, spaced not too far apart, were preferable.”

“Mr. Gustaferrero pointed out that spalling had not occurred with normal concrete specimens when using either lime, dolomite, or quartz aggregates.”

In the proceedings from the meeting Saito (1965) presented his theory of the cause of explosive spalling. According to his theory explosive spalling is initiated by thermal stresses leading to compressive failure. Especially in pre-stressed concrete members the tensile cracking in the central part is restricted. When no pre-stress or longitudinal restraint is present the compressive stress close to the surface is reduced by internal tensile cracking. The same is seen when pre-stressed concrete is subjected to bending moment where the compressive stresses on the heated side became lower leading to a delay in the spalling behaviour. Saito (1965) noted that this difference between loaded and unloaded pre-stressed members can be seen in the results from fire tests performed by England. The influence by the amount of free water in ordinary concrete that have been seen in fire tests is explained by changes in the thermal profile. With a large amount of water present in the porous system the temperature gradient will be larger and higher stresses and strains will be developed as shown in Figure 2.15.

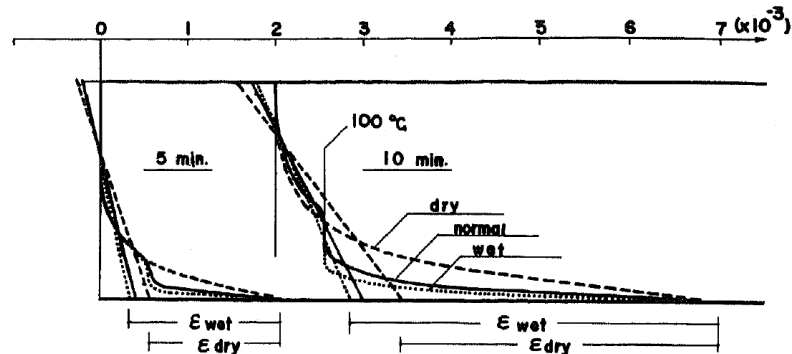


Figure 2.15 Thermal strain during fire exposure of concrete with various humidity, by Saito (1965).

Shortcomings in the theory by Saito, are according to Dougill (1972), that concrete is not a linear elastic material so failure does not necessarily occur in concrete when the compressive stresses at a point reach their maximum value. He also pointed out that Saitos theory could not explain the explosive nature of the failure. According to Dougill an important factor in the explosive nature is a type of spring effect caused by the internal tension region. He compares the phenomenon with a compressive test made with a testing machine that is not stiff enough, i.e. a violent failure caused by accumulated energy will occur. Another shortcoming in the theory is, according to Connolly (1995), that the large moisture effect on the thermal profile that is described by Saito (1965) is overestimated as the thermal conductivity is going up in the moist region, reducing the steepness of the temperature profile.

1972

Extensive study shows the effect of load and heating from more the one side on the spalling sensibility. In an extensive study by Meyer-Ottens (1972) the influence on spalling of the aggregate type, concrete quality, reinforcement, moisture content, shape of the member and compressive stresses, was investigated. One of the most important conclusions from the study was that a clear effect of compressive stress on the amount of spalling on elements heated from two sides could be seen. The results are based on tests performed on concrete with the compressive strength of 22.5, 45 and 60 MPa. The results from Meyer-Ottens were included in a previous version on the Eurocode 1992-1-2, see diagram in Figure 2.16. This diagram is according to Anderberg et al. (1978) valid for concrete with a low percentage of reinforcement whereas an increase of reinforcement gives an increased risk of spalling. Based on the data from Mayer-Ottens, Sertmehmetoglu (1977) made the refined diagram shown in Figure 2.17 showing the influence on spalling from compressive stress, moisture content and thickness of the concrete cross-section when heated from two sides.

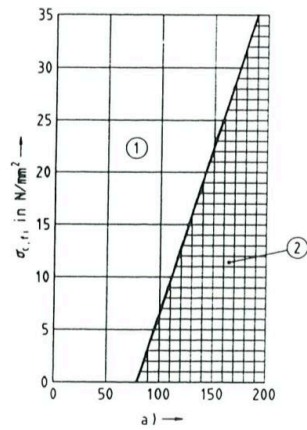


Figure 2.16 The risk of spalling in two side exposed cross-sections. The X-axis is the thickness in mm while the Y-axis, $\sigma_{c,fi}$ is the compressive stress in the fire situation. Area (1) denotes where there is a risk of explosive spalling, while area (2) shows where explosive spalling is unlikely to occur. (Eurocode 2: ENV 1992-1-2:1995).

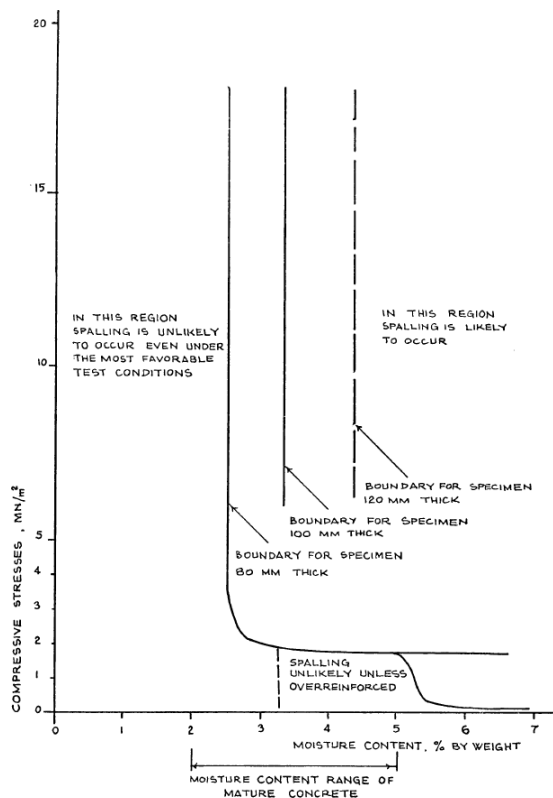


Figure 2.17 Spalling as a function of compressive stress, moisture content and thickness of the element heated from two sides, the test data from Meyer-Ottens (1972) compiled by Sertmehmetoglu (1977).

- 1974 **Similarities between flame cleaning of concrete and fire spalling.** In an experimental study by Johansson (1974) on flame cleaning of concrete some parallels to fire spalling can be drawn. Flame cleaning is a thermal shock method for taking away the outer surface layer of concrete with an oxygen-acetylene flame with the temperature of approximately 3100°C. During the process the flame is moved at an optimal speed over the surface layer so either the surface spalls away or melts and becomes fragile. Thereafter the melted parts are brushed away. During the experiments, the low strength concrete with aggregate made of blast furnace slag was harder to clean than the mixes with more other commonly used aggregates. A small influence of strength on spalling could also be seen as high strength concrete was slightly easier to clean than low strength concrete. Moreover a clear effect of moisture content could be seen as slabs that were watered one hour before the test flaked off much more evenly than dried concrete where large areas could not be induced to flake off. Later, in the first phase of a test program to investigate the behaviour of concrete under the influence of liquid steel Schneider, Ehm and Diederichs (1983) also used an oxygen-acetylene flame to produce a high thermal shock. Conclusions from those tests and exposure of concrete to liquid steel and up to 130 kg of burning thermite, were that no explosive spalling occurred; the process was more like constant erosion. Regarding cleaning of concrete surfaces through a heat induced spalling process Bažant and Goangseup (2003)⁷ proposed a method based on microwave heating and a similar method for thermal fracturing of rock with a convective heat source was purposed by Lauriello (1974).
- 1976 **A program for calculation of temperature moisture and pressure distributions in concrete exposed to fire with the goal to investigate fire spalling** Bennet, Claesson & Thelandersson (1976) made a computer program for calculating temperature moisture and pressure distributions in fire exposed concrete. The results from calculations based on a chosen set of properties for concrete show maximum pressures around 1 MPa and occasion stagnations of temperature rise close to 200°C when water evaporates.
- 1976 **Moisture influence on spalling.** Zhukov (1976) found that granite based concrete with a compressive strength of 40 MPa spalled when the moisture content was over 3%. When testing a similar concrete with the compressive strength 20 MPa the limit of moisture content was 4%. In the Eurocode 1992-1-2 (2004) a moisture limit of this type can be found where it says that under this limit spalling is unlikely to occur, see a more detailed discussion of this in chapter 5.3.
- 1977 **Measurements of pressure development in innovative pressure cell.** Sertmehmetoglu (1977) compares heating of a concrete surface with a biaxial loaded test specimen where cracks are created parallel to the unloaded surfaces corresponding to parallel to the heated surface in the fire case. When these cracks have been opened they are filled with expanding vapour and tensile stresses at a right angle to the compressive stresses arises which lead to spalling.

⁷ With a complementary article by Goangseup and Bažant (2003)

As this spalling mechanism includes both the increase in pore pressure and the experimentally confirmed influence from compressive stress, Sertmehmetoglu (1977) found it plausible.

In an attempt to reproduce the phenomenon during heating from two sides, Sertmehmetoglu (1977) developed the pressure cell shown in Figure 2.18. The idea is that the right side of the pressure cell is exposed to heating and the left side represents the centre line of symmetry in a typical cross-section. In the middle of this “symmetry side” the development of pressure from moisture is measured. During the tests the maximum pressure measured at the centre line (2.1 MPa) was registered in a specimen that did not spall with a $w/c = 0.45$ and compressive strength of 37 MPa. When the w/c ratio was lowered to 0.4 giving a higher strength of between 45 and 50 MPa, almost no pressure development could be recorded before the surface of the specimen spalled.

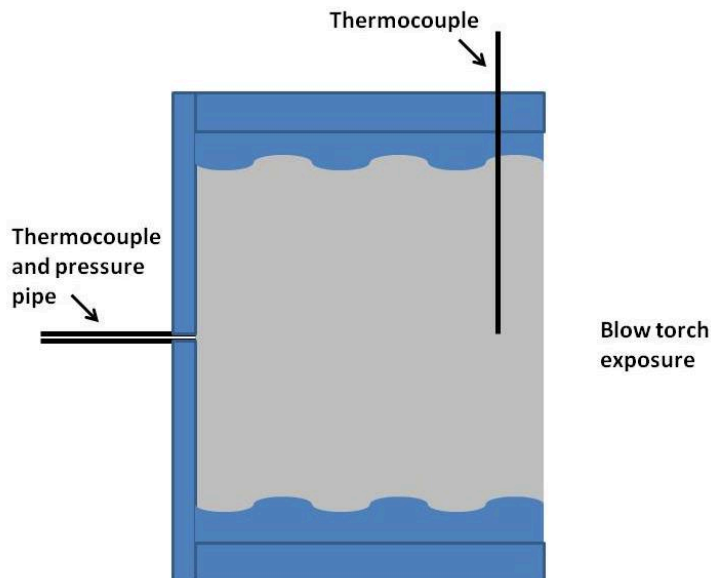


Figure 2.18 Pressure cell developed by Sertmehmetoglu (1977). The right side is exposed to heat and the left side represents the line of symmetry during two sided heating of a twice as thick element. Pressure and temperature is measure at the symmetry line as well as temperature close to the surface.

- 1977 **Awareness of the risk of explosive spalling.** RILEM Technical Committee 19-FRC (1977) with the scope fibre concrete materials states that “*Without special precautions the dense cement paste explodes in fire as the passage of steam through the bulk of the material is not free.*”
- 1978 **The impact of the addition of polypropylene fibres on the fire performance of concrete noted.** A concrete panel of 0.9 m square and 50 mm thickness containing 1.2% by volume polypropylene fibres was fire tested at the Fire Research Station in the UK. According to Hannant (1978), no difference regarding fire resistance was found between similar concrete specimens with

and without the fibre addition. This is an early fire test performed on concrete including polypropylene fibres. The fibre type tested is not described in detail but it was probably a thick type of fibre compared with the fibres commonly used today to reduce fire spalling behaviour. In a comment on the shortcomings of polypropylene fibres Hannant (1978) stated that after a fire an extra porosity, usually 0.3-1.5% by volume, should be present when the fibres have been combusted. There is a risk that the long term durability is reduced already after relatively small fires when the fibres melt away. This is a question that is included in the ongoing PhD work of Joakim Albrektsson at SP Technical research Institute of Sweden.

- 1979 **Study of fire spalling of concrete with focus on drying.** Based on an empirical research program and a literature survey, Copier (1979) drew conclusions on the importance of different factors on the fire spalling of concrete. The principal cause of spalling was stated to be the moisture content but this was combined with the following important influences:
- heating from one or two sides
 - reinforcement
 - compressive stress
 - thickness of the member
- Less important factors were found to be:
- the quality of the reinforcement (provided that the bars are not too closely spaced)
 - the magnitude of compressive stress applied
 - the quality of concrete (if suitable for structural purpose)
 - the distribution of moisture in the cross-section
 - for lightweight concrete: the type of lightweight aggregate used
- 1980 **Investigation of the addition of Cemos to avoid fire spalling.** In an experimental study including bilateral heating of thin plates with the thickness of 25 mm, explosive spalling was avoided in ordinary concrete by including a polymer addition called Cemos, an acrylate-styrene co-polymer dispersion modified with asphalt, usually used in light weight concrete. According to Chandra, Berntsson and Anderberg (1980) the 25 mm thick plates made of concrete without this addition exploded after 5 minutes of standard fire exposure.
- 1982 **Small cylinders of ultra high strength concrete were shown to spall at low heating rate.** Hertz (1982)(1984) found that some of the cylinders, diameter 100 mm and height 200 mm, made with the addition of silica fume and strength of 170 MPa, spalled explosively although the heating rate was as low as 1°C/min and no external load was applied during the heating. Spalling results are shown in Table 2.1. According to Hertz (1984) the reason for the explosion was the dense micro structure that hindered the steam to escape. He also added that there is reason to believe that the chemically bound water of the hydrated calcium silicates is enough to cause the explosion.

Table 2.1 Spalling results from Hertz (1982) on unloaded cylinders made of ultra high strength concrete exposed to the heating rate 1°C/min. Three cylinders per temperature were tested.

Max temperature [°C]	Cylinder A	Cylinder B	Cylinder C
150	No explosion	No explosion	No explosion
350	Exploded	No explosion	No explosion
450	Exploded	Exploded	No explosion
650	Exploded	Exploded	No explosion

1983 **Water transport around polypropylene fibres suggested as the mechanism to relieve fire spalling in refractory materials.** In a patent, Long & Moeller (1983) describe the use of polypropylene fibres with the diameter of 15 µm to solve the problem of explosive spalling of refractory materials. In an electron microscopy study, small annular passageways or channels with the thickness of approximately 1 µm around each polypropylene fibre were found in the refractory material. According to Long & Moeller water transport in these channels was caused primary by capillary forces but also pressure differences.

1984 **Survey on fire spalling theories.** To illustrate the whole palette of spalling theories, a survey performed by Malhotra (1984) provides an overview of which theories various researchers consider to be the primary and secondary causes of spalling during the 60's and 70's. The different causes are summarised in Table 2.2.

Table 2.2 Main spalling theories with sub groups according to Malhotra (1984).

1) Moisture	1a) Vapour pressure
	1b) Moisture clogging
	1c) Vapour pressure enhanced by frictional resistance
2) Stress	2a) Initial compression
	2b) Initial compression + thermal stress
	2c) Initial compression + thermal stress + stress caused by frictional resistance
3) Cracking	3a) Aggregate expansion
	3b) Internal cracks
	3c) Reinforcement expansion

In Table 2.3, the different theories are graded by different researchers.

Table 2.3 Highlighted theories by different researchers, compilation by Malhotra (1984).

Researcher	Main factors	Secondary factors
Saito (1965)	2a, 2b, 2c	1a
Harmathy (1965)	1b	-
Meyer-Ottens (1972)	1c, 2b	2c, 3c
Dougill and Sertmehmetoglu (Sertmehmetoglu, 1977)	1b, 3b	2a
Akhtaruzzaman and Sullivan (1970)	1a	Dense surface layer
Gustaferro (Kordina, 1970)	1a	3a
Copier (1979)	2a, 1a	--

- 1992 **Study of the influence of steel fibres on the fire spalling of concrete.** During a continuation of the work on high strength silica concrete performed in the early eighties, Hertz (1992) conducted a study of the influence of adding steel fibres to the concrete with a compressive strength 170 MPa used in the previous tests. The results showed that the explosions were not hindered by adding steel fibres but delayed to higher temperatures. The cylinders with diameter 100 mm and height 200 mm were pulverized by the explosion. This should be compared to the behaviour during tests on cylinders without steel fibres that exploded into larger pieces. Tests on smaller cylinders with the diameters 100 and 52 mm were also included in the study. Cylinders with these smaller diameters did not spall at all. This shows a clear size effect on the occurrence of spalling see further discussion in chapter 2.2 and in Paper IV.
- 1993 **Pivotal study on the difference between high strength concrete and normal strength concrete.** In an often cited⁸ experimental study, Sanjayan & Stocks (1993) conducted a fire test on two full sized T-beams, one made of high strength silica fume concrete and one made of ordinary concrete. During this test the high strength concrete spalled whereas the ordinary concrete did not spall. According to Sanjayan⁹, the aggregate used in the mixes during these tests was basalt¹⁰. Details about the mixes are shown in Table 2.4. The high strength concrete contained more free moisture than the normal strength concrete. The moisture content was determined by drying cross-sections identical to those included in the fire test. Therefore, an average value was defined dependant on the cross-section and time. For a more detailed general discussion about determination of moisture content and the use of a moisture limit for spalling see chapter 5.3. The results of the test indicated that the region that spalled during the fire test was the fire exposed area of the flange which was 200 mm thick

⁸ 91 citations according to Google Scholar December 7, 2011

⁹ Personal communication, 2011

¹⁰ According to a literature study performed by Khoury and Aderberg (2000) concrete with basalt aggregate, with low thermal expansion coefficient, is less prone to spalling compared with concrete including aggregate of limestone, siliceous or River Thames gravel.

with a concrete cover made of high strength concrete. No spalling was seen in the normal strength concrete.

Table 2.4 Description of material in the T-beams tested by Sanjayan & Stoks (1993).

	Normal strength concrete	High strength concrete
Cement [kg/m ³]	220	452
Water [kg/m ³]	170	143
Silica fume [kg/m ³]	-	39
Compressive strength 28-day [MPa]	25	92
Moisture content [%]	4.0	4.6

1994

Significant fire incident identifies progressive fire spalling in real fires. On the morning of June 11, 1994, a fire started in the tunnel boring machine (TBM) in the Great Belt Tunnel. As described by Tait & Høj (1996) and Høj & Tait (1998), the primary fuel in the fire was the hydraulic oil from the TBM. The fire developed rapidly and could not be extinguished so it had to burn itself out. Based on observations of the smoke from the fire it was estimated that the fire continued for between 4 to 8 hours. The concrete mix included micro silica, fly ash, and granite aggregate and had an equivalent w/c ratio of 0.32 leading to a 28-day strength of 76 MPa. According to the state-of-the-art knowledge at that time, spalling should have been confined to the cover of the concrete, 40 mm, and take place during the first 20 minutes of fire exposure. This estimated limitation in spalling severity was not reflected in the real fire incident. In the segment that was affected most severely by the fire only a third of the 400 mm thick cross-section remained, the rest had spalled away contrary to the predictions of that time.

As an emergency measure the spalled areas were covered by reinforced shotcrete to the original thickness; but, due to increasing inflow of groundwater through the badly cracked segments, evacuation of all personnel was mandated and no entry was allowed until a full investigation had been undertaken. Bulkheads including flood doors were installed to reduce the risk for a catastrophic event if the lining was to fail and flooding occur.

To refurbish the tunnel as rapidly as possible, available tunnel segments of the type RB2 SG1 from the Channel Tunnel were used. However, as the diameter of the standard elements from the Channel Tunnel was larger than that used in the Great Belt Tunnel, modifications were made to make them fit. The new elements were put onto top of the spalled elements and resulting cavities were filled with grout.

To further investigate the unexpected amount of fire spalling and to broaden our understanding of the behaviour of the concrete elements, fire tests were performed on two tunnel segments from the production. The fire tests were performed at SP Technical Research Institute of Sweden and are described in more detail in an official report from Trafikministeriet (1995). When the fire test

was performed the moisture content in the concrete was approximately 4% which was assumed to be the same as in the segments in the tunnel during the real fire event. The outcome of the experiments was that the degree of spalling was less during the fire test compared to the real fire despite the fact that the fire exposure used in the furnace testing, the RABT fire curve, was estimated to be more severe than the real fire. Although the fire spalling during the experiment was less than during the real fire, 140 mm compared with 227 mm, the original assessment that the spalling would only take place in the cover, 40 mm, was confirmed to be incorrect. The fire exposed surface of the concrete element after fire testing is shown in Figure 2.19. The actual fire event and the ensuing fire test show typical examples of progressive spalling.



Figure 2.19 Tunnel element from the Great Belt tunnel fire tested at SP Technical Research Institute of Sweden. Photo included in the official report from Trafikministeriet (1995).

- 1995 **Attempts to limit moisture by “self desiccation” as a means to preclude spalling in high strength concrete fail.** In a study of the high temperature properties and spalling behaviour of high strength concrete, Diederichs et al. (1995) designed concrete mixes with a “self desiccation” so strong that the amount of evaporable water would be low enough that spalling cannot occur. Tests on 20 extreme mixes showed that this was not possible. However, results from a variety of fire tests performed by Diederichs et al. on high performance concrete in the early 1990’s show the spalling behaviour can be controlled by adding polypropylene fibres to the mix.
- 1996 **Extensive damage from fire spalling in Chaneel tunnel made of high performance concrete shows what researchers have known for many years.** The compressive strength of the concrete used in the tunnel was, according to Ulm et al. (1999), between 80 to 100 MPa. This is probably the 28 day strength as Khoury (2000) gives a value of 110 MPa for the mature compressive strength. As shown in several cases above, high strength concrete like this had already been shown to exhibit an elevated risk of fire spalling. Further, the use of this mix and the lack of fire protective material was, according to Coates (1996), questioned by an expert in this area in a special letter to the Health and

Safety Executive of the tunnel three and a half years before the fire event. But the tunnel safety authority replied that the question of fire resistance had been dealt with satisfactorily several years before.

During the fire 500 meters of the tunnel had damages from the fire event, according to Khoury (2000), and extensive damage was found along 50 meters of the tunnel including some places where the whole 450 mm thick concrete elements was penetrated by spalling. Luckily there was no water pressure causing flooding in this part of the tunnel.

- 1997 **The hydraulic spalling theory based on fracture of fully saturated pores proposed.** According to Khoylou (1997) the probable cause of the fire spalling of concrete is the occurrence of fully saturated pores. If more than 32% of closed pores are initially filled with water, the water will expand during heating and force the trapped air into solution resulting in a fully saturated pore at elevated temperatures. The same phenomenon that Khoylou describes is used as the activation mechanism for sprinklers with bulb activation, where a glass container is filled with water and a bubble. When the temperature rises sufficiently the water expands and the air is forced into solution in the water until the whole bulb is filled and breaks due to the build up of hydraulic pressure.
- 1997 **Investigation of failure mechanisms in pre-stressed beams identifies that prediction of spalling performance is still poor.** In an experimental series performed by Bengtsson (1997) and also described by Jansson & Boström (2011) with the goal to determine the failure mechanism of beams with thin webs, violent spalling failure occurred. The goal of the project was to investigate whether shear failure is the failure mechanism of slender I-beams under fire exposure. A further aim was to provide input to Eurocode 2 concerning under which conditions it is important to consider shear failure. Before the tests were conducted at SP Technical Research Institute of Sweden the Reference Group of the project discussed the relative risk of spalling during the tests. This discussion is described in Brandforsk (1999). Prior to the tests, the prevailing opinion in the Reference Group was that if some spalling were to occur (which was doubtful) it would only be minor. Thus, the assessment prior to the tests was that the beams with thin webs would achieve a fire class of 90 minutes. In reality the loaded pre-stressed concrete beam collapsed after severe fire spalling just 30 minutes after the start of fire exposure clearly indicating that despite a century of fire spalling research, the possibility to predict fire spalling was still inadequate. The results of these tests and an additional test at higher age are described more in detail in chapter 2.2.
- 1999 **The HITECO project on behavior of high performance concrete at high temperature performed.** The aim and subtitle of the HITECO (1999) project was “Understanding and Industrial Applications of High Performance Concretes in High Temperature Environments”. In the context of fire spalling (which was not the main focus of the project) highlights from the project include an extensive fire resistance test program, measurement of properties needed for

modeling, development of software with the aim to model behavior at high temperature and measurements of moisture movement during heating with a gamma-ray spectrometer. Each of these parts is summarized below:

- *Fire resistance test program.* The fire resistance test program included tests of 36 short columns both loaded and unloaded. The age of the tested columns was between 7 and 88 weeks. During this time the specimens were kept in a constant climate of 23°C and RH 50%. As the initial tests showed unexpected spalling of the C70 and C 90 SF (silica fume addition) concretes new specimens were molded that were dried in a climate of 40°C and RH 40 % for five months. After this conditioning 2% moisture by weight was achieved and the specimens were thereafter kept in 23°C and RH 50 % for four months before the fire tests. This preconditioning made the C70 resistant to spalling whereas the dried C90 SF spalled severely despite the artificial drying. The influence of moisture content on the fire resistance (spalling included if occurring) of the C60 and C90 concretes exposed to the standard fire exposure can be seen in Figure 2.20. In an additional test of a C60 200 × 200 mm² column with a moisture content of 2.8% exposed to the more severe hydrocarbon curve, the fire resistance was reduced by spalling to only 15 minutes. In this diagram all results are included so different factors are changing between the tests but according to Diederichs, Alonso and Jumppanen (2007) the main conclusion from the test series was that the moisture content did not clearly influence the spalling behaviour instead the strength, geometry and load were important factors.

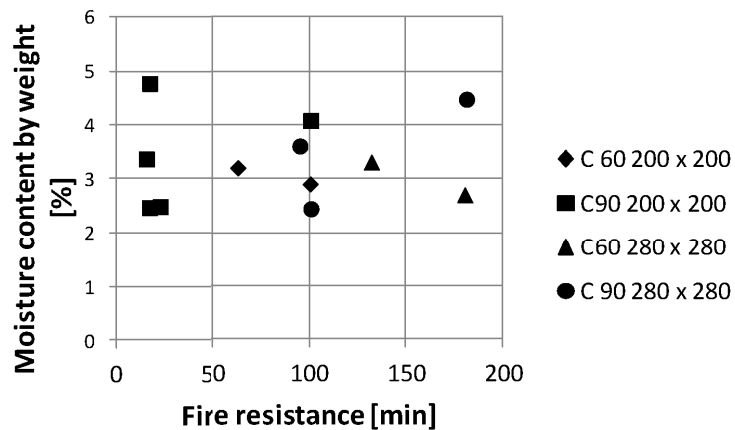


Figure 2.20 Influence from moisture content on fire resistance of short columns in the HITECO project, Diederichs, Alonso and Jumppanen (2007).

- *Software development.* The software called HITECOSP (High Temperature Concrete Spalling) for simultaneous simulation of hygro-thermo-mechanical processes in heated concrete was developed in the HITECO (1999) project. This software included a spalling indication

factor and has later been developed into the so called “Padua” model described more in detail by Gawin et al. (2006). As understanding and a full description of the spalling phenomenon has not yet been achieved and real material properties are rare, this type of software is still highly indicative.

- *Gamma-ray spectrometer measurements of moisture distribution.* The aim of the gamma ray spectrometer measurements performed by Kalifa and Sallee (1998) was to measure the temperature and moisture distribution in heated concrete. Measurements were conducted on cores with diameter 60 mm and length 100 mm. One of the flat sides of the cylinders was exposed to a heater and the outer round area was sealed to restrict water loss. By using the gamma-ray spectrometer measurements and internal thermocouples, the penetration of the heat- and drying/dehydration front could be monitored. The experimental results on a C60 concrete with silica fume addition and a C90 concrete do not show any evidence of the built-up of a moisture clog like the one shown in Figure 2.14 or monitored by splitting heated concrete by Jansson and Boström (2009). Two possible reasons for this might be the slow heating used, ramps of around 2 degrees per minute compared with the standard fire curve, and the geometrical shape of the specimen. When exposing concrete to a standard fire curve large thermal gradients lead to extensive cracking, both close to the hot surface and further into the cooler area, making the flow paths for moisture totally different than exposure to slow heating. Another important factor regarding how cracks develop during heating is the shape and restraint of the specimen, where a cylinder heated on one flat side is hardly representative for a real element. In a study initiated by the author of this thesis and described by Albrektsson et al. (2011)(2012) a clear indication of this dependence of the cracking behavior on boundary conditions and shape of cross-section could be seen. This experimental program included the analysis of the residual stiffness of a cross-section after fire exposure of restrained $600 \times 500 \times 200 \text{ mm}^3$ concrete slabs exposed to the standard fire curve and slower heating of $10^\circ/\text{minute}$. This analysis was performed by measuring the strain field on the surface of drilled cores from the fire exposed concrete with a digital image correlation measurement technique during a compression test. With this method the change of the strain field when going up in load could be recorded. When comparing the stiffness reduction caused by the fire with typical results from the literature a large deviation could be seen in the colder areas of the cross-section, see Figure 2.21. During material tests, results are often between the two straight lines in the figure. The goal during material testing is to achieve a uniform “property” in the whole cross-section, therefore cores are heated slowly to avoid high thermal gradients causing cracking or, when testing with the thermal gradient in the specimen, to avoid problems with interpreting the results. The majority of stiffness reduction curves deduced from the measured strain field of the cross-section of drilled cores in Figure 2.21 show a faster decrease with temperature compared

with results from material tests. The reason for this reduction is probably tensile cracking in the cold area induced by the stresses from the expansion of the hot area during heating.

To summarize: the specimens used for the gamma-ray spectrometer measurements described above do not crack in the same way as a real element exposed to rapid heating as during fire exposure. The slow heating and the geometry of the specimens limit the cracking from thermal stresses. This difference in effective permeability caused by cracking, especially in the colder zone during real fire exposure, might be the reason for the built up of a moisture clog during fire exposure. Recently experiments with the Nuclear Magnetic Resonance imaging technique on cores performed by van der Heijden (2011) actually do show an accumulation of moisture in front of the boiling front although a buildup of a thick fully saturated layer as in fire exposure as suggested in Figure 2.14 has not been reproduced with this type of measurement. This is probably because of the slow heating and limited specimen sizes used.

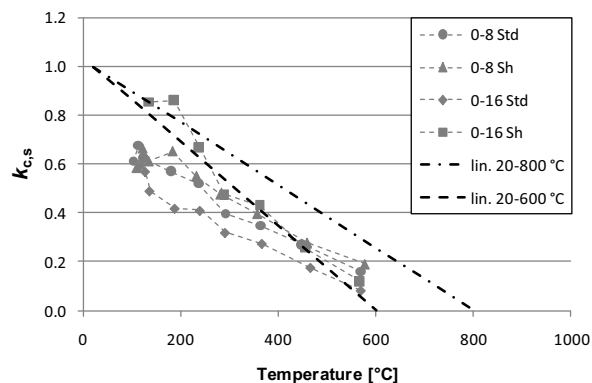


Figure 2.21 Residual stiffness reduction vs. exposure temperature in a cross-section exposed to standard fire (Std) or slow heating 10 degrees per minute (Sh). The high reduction in the 100°C region is believed to be caused by tensile cracking caused by stresses from thermal expansion in the in the hotter regions of the cross-section. Figure from Albrektsson et al. (2011)(2012).

2000

The BLEVE (Boiling Liquid Expanding Vapour Explosion) theory for fire spalling. The BLEVE theory can, according to Ichikawa (2000), be a component in the spalling process of high strength concrete. When the pressure is released from a pore including high temperature liquid water, the conversion into steam is very rapid as all energy accumulated during heating up over 100°C will be released in an instantaneous boiling process that is classified as an explosion. Petrov-Denisov et al. (1972) also present a theory including the rapid expansion of super heated water. According to their theory the walls between closed pores with super heated water and open pores with lower pressure can be

destroyed by the pressure difference and as Hertz (2003) points out this can lead to a progressive breakdown of the microstructure.

2.2. Observations of fire spalling of concrete

This Section includes observations of the fire spalling of concrete from both fire testing and real fires under different conditions, i.e. under unilateral or multilateral heating.

2.2.1. Spalling during unilateral heating

It is well known that concrete with low strength and low moisture content seldom spalls during fire exposure at least in the absence of external compressive loads. There are numerous examples from fire tests where no spalling is observed in fire exposed concrete, e.g. the concrete slabs used on a daily basis as a roof to cover the 5×3 m opening on the horizontal furnace at SP do not spall during fire testing. The concrete with 28-day compressive cube strength of approximately 30 MPa does not spall even under severe fire exposure. This absence of spalling for concrete with compressive strength 30 MPa was also observed by Cooke (2001) when testing precast concrete slabs either unloaded or loaded in bending. As real structures are sometimes made of concrete with a higher strength and/or often loaded in compression, some degree of spalling of concrete is a common phenomenon during real fires. In an inquiry made by the British Concrete Society Committee on Fire Resistance, fire spalling was mentioned in over 80% of nearly 100 reported fire accidents in concrete buildings, Malhotra (1984). An important conclusion from the study was that despite the spalling none of the investigated events led to collapse of the structure.

The influence of fire spalling on the safety of the structure is often low for ordinary low strength concrete as the spalling seldom is more than slight surface flaking and, according to Lennon (2004), there is a high safety margin in design values of the fire resistance for ordinary concrete elements. When analysing 80 fire tests on hollow core slabs, where 29 tests were run until failure, Fellingner (2004) concluded that explosive spalling was the cause of failure in three cases. The main causes of failure in the other tests were shear or anchorage failure. Despite this there are structures made of ordinary concrete that seem to be more sensitive to spalling. Regarding the performance of unconfined post-tensioned concrete members in fire, a literature study performed by Gales et al. (2011) reveals that all six real fire events studied exhibited some degree of spalling. They concluded that these structure types could not be designed purely based on minimum concrete cover as the tendons are sensitive to local heating.

Examples of surface spalling that did not jeopardize the load bearing capacity can be seen in Figure 2.22 – Figure 2.25, note that the original mix design of the concretes is unknown. This illustrates that a simplified or an advanced calculation of the load bearing capacity of such members, if assuming longer duration of fires than in this real cases, might be on the conservative side only if the loss of thermal protection of the reinforcement due to spalling is included. An additional important factor is then also the duration of the fire exposure. If the fire exposure is of short duration and the spalling occurs in the late stages of exposure, the consequences on the load bearing capacity are often small.



Figure 2.22 Fire spalling on an external concrete wall. The heat source was a burning tractor. Photo Robert Jansson.



Figure 2.23 Fire spalling in the roof in a garage. The heat source was a burning car. Photo Robert Jansson.

2.2. Observations of fire spalling of concrete



Figure 2.24 Fire spalling of the external wall of a garage. The heat source was three burning vehicles. Note the absence of spalling on the roof slab. The reason for the difference could be caused by (i) differences in concrete quality and/or (ii) difference in load situation where the wall element is loaded in compression. Photo Robert Jansson.

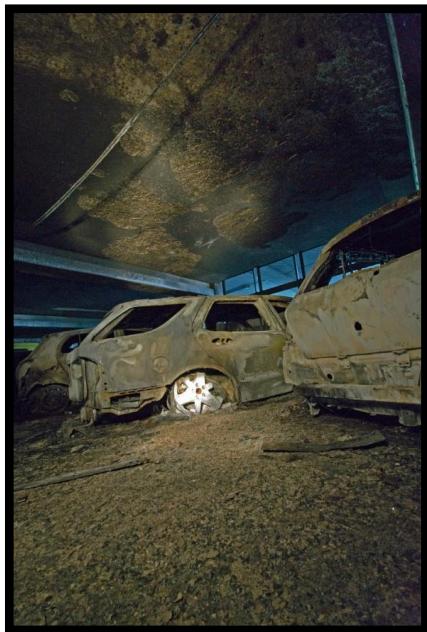


Figure 2.25 Fire spalling in concrete roof. The heat source was five burning cars. Photo Robert Jansson.

In Figure 2.26 the spalling of a box girder bridge is shown, Boström & Lindqvist (2006). The fire exposure in this case was from a burning lorry which was involved in an accident on the Heberg bridge in west of Sweden. Flammable liquid leaked under the bridge after the accident and ignited. The investigation that followed showed that the heat penetration was limited due to the very short heating period despite severe spalling of the surface layer. This bridge is now refurbished and back in service. In another fire under a concrete bridge, on motorway 57 outside Dormagen in Germany in 2012, extensive damage from heat exposure and spalling led to the decision to demolish the entire structure.



Figure 2.26 Fire spalling from a fire under a bridge. The heat source was solvents burning under the bridge coming from a lorry on the bridge. Photo Lars Boström.

The fire in Magazine 6 in the free port of Stockholm in 1966 is another example where it was possible to refurbish the structure after severe fire spalling. A detailed examination performed by Lindblad et al. (1966) of the effects of the fire showed severe fire spalling of the concrete at some locations. It is interesting to note that one of the authors of the original report was actually on top of the floor slab during the fire exposure from below and could hear the characteristic popping sound of concrete during spalling, for more details, see Jansson & Ödeen (2011), which is a translation to English of the original article written in Swedish by Lindblad et al. (1966) with some additional comments. When mapping the damage, a damage classification system with five different severity levels of fire spalling was used, see Table 2.5 and Figure 2.27. The damage assessment was also based on compressive strength tests, the Brazilian splitting strength test and tests on the tensile strength of the reinforcement. The fire occurred during the late stages of construction of the building and it was concluded in the fire investigation that if the flat slab had been loaded with its working load, it would have collapsed. Despite the severe damage, it was possible to refurbish the structure by shotcreteing.

2.2. Observations of fire spalling of concrete

Table 2.5 Degree of spalling severity defined by Lindblad et al. (1966).

Level of spalling severity during the Magazine 6 fire	Description
1	Slight spalling of the surface, see Figure 2.27a.
2	Bottom reinforcement partially visible, see Figure 2.27b.
3	Both layers of bottom reinforcement visible, see Figure 2.27c.
4	Bottom reinforcement totally uncovered, 8-10 cm of concrete spalled away, see Figure 2.27d.
5	Bottom reinforcement partly falling down, see Figure 2.27e.

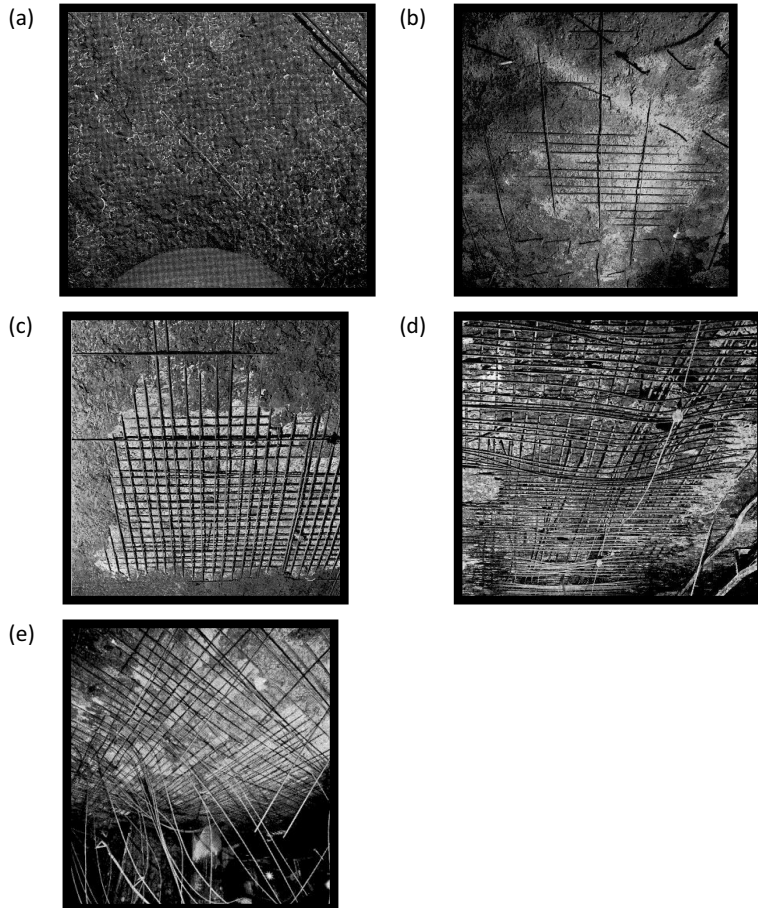


Figure 2.27 Photos showing the different levels of severity of spalling according to the investigation by Lindblad et al. (1966) (a) first level, (b) second level, (c) third level, (d) fourth level, (e) fifth level.

More severe cases of fire spalling when concrete is unilaterally exposed to fire have been recorded in tunnel fires. Due to durability demands these types of concrete are often made with lower water/cement ratio compared with ordinary concrete used for buildings. The two most cited examples seem to be the fire in the Great Belt Tunnel in 1994 and in the Channel tunnel in 2006 where extensive damage led to very expensive repair (see the time-line in the previous chapter for more details of these fire accidents).

Spalling during unilateral heating has also been observed during many fire tests. In particular high strength concrete or dense self-compacting concrete seem to be sensitive to fire spalling from unilateral fire exposure. Indeed, under certain circumstances, a whole cross-section can be deteriorated by spalling, see e.g. Figure 2.28 and Figure 2.29. The fire exposure during this test was the hydrocarbon (HC) fire curve and the self-compacting concrete tested had a water/cement ratio of 0.52 and included 120 kg/m³ limestone filler. As seen in the figures, the whole 200 mm thick cross-section was breached by spalling. Observations during the test showed that the spalling started after 2 minutes of fire exposure, see Figure 2.28, and the continuous flaking made the reinforcement visible after only 6 minutes. After 40 minutes the whole thickness of the cross-section was consumed by progressive surface spalling as shown in Figure 2.29.

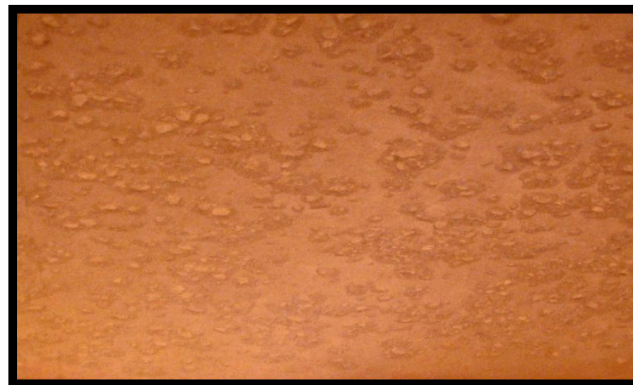


Figure 2.28 Continuous surface flaking after 2 minutes of fire exposure with the hydro carbon fire curve. Photo Robert Jansson.



Figure 2.29 Severe spalling breaking through the 200 mm thick concrete specimen after 40 minutes of exposure to the hydrocarbon fire curve. Photo Robert Jansson

Another example of fire spalling during a fire test with unilateral heating can be seen in Figure 2.30 where a real floor element made of high strength concrete was penetrated by fire spalling.



Figure 2.30 Severe fire spalling during fire testing of a high strength concrete floor slab exposed to unilateral fire. Photo Robert Jansson (published with permission of the client).

Influence of load or restraint

It is well known that not only the mix design but also the load or restraint is an important factor influencing the occurrence of spalling. Fire spalling can indeed occur in unloaded small concrete samples but the severity is often much less compared with large samples externally loaded or restrained by colder parts. In Figure 2.31, the effect of restraint from colder parts of the concrete can be seen, as the areas close to cold concrete, restrained from two directions, spalled more than the areas in the middle of the beam.

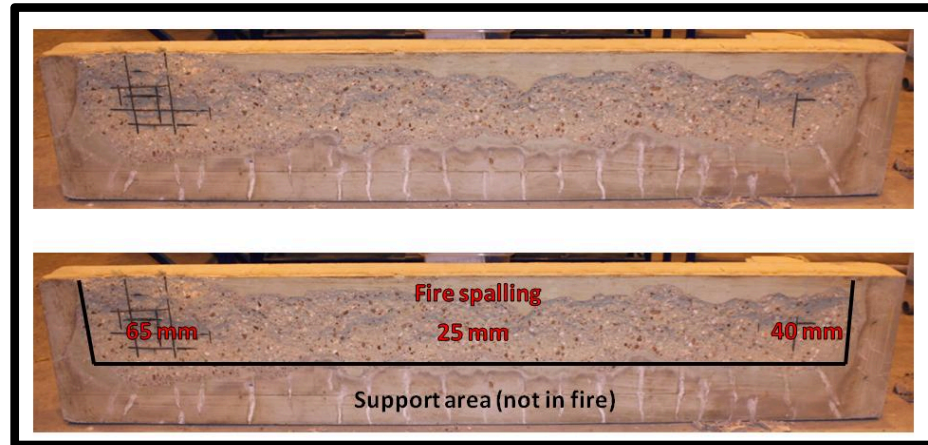


Figure 2.31 Concrete beam, $3.6 \times 0.4 \times 0.2$ m, partly exposed to fire. The effect from restraint from colder parts are illustrated. Photo Robert Jansson.

The effect of restraint from colder parts has previously been shown by Hertz (2003) when testing unloaded slabs with size $600 \times 600 \times 200$ mm³, heated from one side in the central 200×200 mm². During these tests, the cold concrete around the heated area functioned as a restraint for thermal expansion. During the tests, the concrete spalled heavily for 20 minutes until the frame of cold concrete cracked, leading to release of the restraint at which time the spalling immediately ceased. Dougill (1973) found, when conducting experiments in a smaller scale on restrained mortar slabs moulded in a brass ring with diameter 300 mm, that local heating in the centre of the specimen with an oxygen/acetylene flame did not lead to any spalling phenomenon as the local heating led to radial cracking releasing stresses. However, when a more general heating of the whole surface was applied the cracking caused by tensile stresses was limited by the brass ring which led to a more violent failure, i.e. spalling. Dougill (1973) even suggested that the beneficial effect of a limited amount of cracking due to tensile stress should be recognized in design.

During unilateral heating the resistance to bending of the whole specimen also seems to be important. This was clearly indicated in a French study performed by Feron et al. (2009) on self supporting shotcrete. The slabs including reinforcement were 3×1 m² with two thicknesses, 160 mm and 200 mm. The results, see Table 2.6, show a clear correlation between thickness and spalling of the slabs. The thicker slabs spalled more as thermal stresses were higher when bending was less meaning that more restraint was exerted by the colder area further away from the heat exposed surface.

Table 2.6 Measured spalling on shotcrete slabs with size 3×1 m² with two different thicknesses. Thermal exposure was the increased hydrocarbon curve.

Thickness of slab	Spalling of shotcrete without PP fibers		Spalling of shotcrete with 2 kg/m ³ PP fibres with diameter 32 µm	
	Average	Maximum	Average	Maximum
160 mm	40 mm	93 mm	0 mm	0 mm
200 mm	57 mm	110 mm	15 mm	15 mm

The most extreme case of restraint from a cold surrounding structure is probably when looking at a small hot spot on a cold surface. In this case no curvature of the whole cross-section will release stresses due to thermal expansion at the surface, as the scale of the heated zone is much smaller than the whole cross-section. In Figure 2.32 approximately 10 cm² of the surface of a 50 × 60 × 20 cm³ large specimen was heated extremely rapidly with a blow torch. After 30 seconds of heating an area of approximately 80 cm² was spalled away.

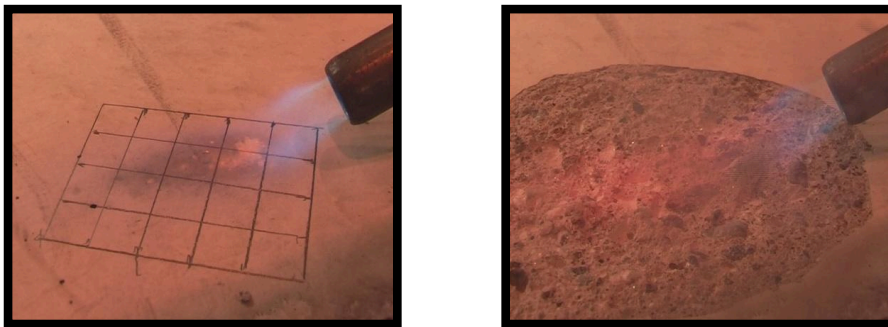


Figure 2.32 Small scale illustrative spalling test with blow torch, squares in the figure are 1 × 1 cm². (Left) Before spalling. (Right) Spalling from surface with one flake after 30 seconds of heating. Photo Robert Jansson

An additional illustrative example of the influence from restraint was shown by Jansson and Boström (2012). The corner created by two small slabs, one with the addition of PP fibres, was heated direct with a flame touching the concrete as shown in Figure 2.33 for 10 minutes, no spalling occurred. After letting the specimens cool down for approximately half an hour, the specimen without PP fibre addition was heated in the centre with the same flame and violent spalling started, illustrated in Figure 2.34. This shows clearly that restraint from surrounding areas is an important factor in the spalling phenomenon as no spalling occurred during exposure of the virgin corner.



Figure 2.33 First heating of the corners of the specimens, no spalling recorded (Jansson and Boström, 2012).

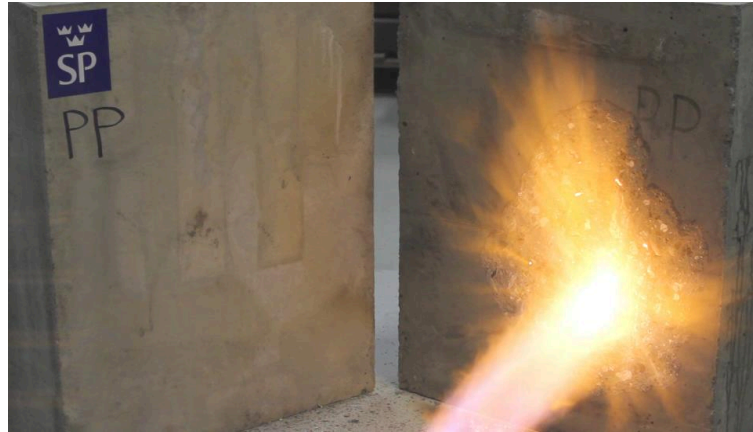


Figure 2.34 Second heating of the centre of the specimen without a PP fiber addition, violent spalling occurred (Jansson and Boström (2012)).

An example of when the lack of load and restraint on small specimens can lead to questionable conclusions regarding real concrete structures was observed by Boström and Jansson (2008) when testing self-compacting concrete slabs of different sizes. During one of the first tests in the test campaign, a slab with size $600 \times 500 \times 200 \text{ mm}^3$ which included 5 kg/m^3 polypropylene powder was fire tested without any restraint. As shown in Figure 2.35 no spalling was observed during this initial test but when a similar test was conducted with a compressive load of 4.6 MPa, which was 10% of the compressive strength at the time of testing, the whole surface spalled away. The maximum spalling depth measured in this loaded test was 45 mm with an average of 20 mm. If the test campaign had been limited to the initial unloaded test the interpretation could have been that PP powder is a good substitute for PP fibres but without the mixing problems that a PP fibre addition sometimes gives. When similar concrete mixes containing 10 or 0.5 kg/m^3 PP powder were later tested under loaded conditions no effect of PP powder could be seen (i.e. the treated samples spalled as much as concrete without PP powder addition). This should be compared to the addition of PP fibres that were shown to stop spalling in specimens loaded in compression. An illustrative example of the difference between the presence and absence of a compressive load when testing small slabs can be seen in Figure 2.36 where a compressive load leads to a horizontal crack in the direction of the load compared to the unloaded case when the concrete cracks vertically. Although these cracks, shown in the pictures, evolved sometime after a typical spalling event had started, they clearly show that the load or restraint conditions alter the stress field providing an explanation of the differences in spalling behaviour found between loaded and unloaded specimens.

2.2. Observations of fire spalling of concrete

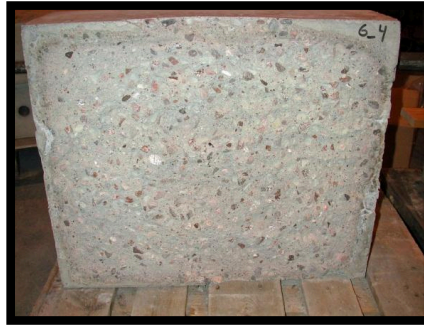


Figure 2.35 (Left) Concrete including PP powder unloaded during the test. (Right) Same concrete loaded in compression during the test.



Figure 2.36 One sided heating of small specimens from the underside. (Left) Small slab loaded in compression, example of crack evolution in the load direction. Water is pouring out from the horizontal crack. (Right) Unloaded small slab, cracks develop vertically from the heated surface.

Loaded tests of reduced specimen size can only serve as an indication of the spalling propensity of larger specimens. When testing specimens of size $600 \times 500 \times 200 \text{ mm}$, with a fire exposed area of $500 \times 400 \text{ mm}^2$, different boundary effects are present compared to specimens of larger sizes that are more representative for real structures. Figure 2.37 shows an example of the difference between these small specimens and a large $1700 \times 1200 \times 200 \text{ mm}^3$ slab with a fire exposed area of $1500 \times 1200 \text{ mm}^2$. In both these tests the concrete mix is the same and the load level and age are comparable but the result is very different. *Is it then totally irrelevant to do small scale testing of slabs?* No, as recommended by Jansson and Boström (2008), small loaded slabs can be used in preparatory studies for selecting concrete for larger tests as the small loaded slab indicates whether there is a spalling risk or not (although the actual spalling depth is size dependant). It seems also that a ranking system of spalling severity is possible to define based on tests conducted using small loaded slabs that is valid for the larger slabs.

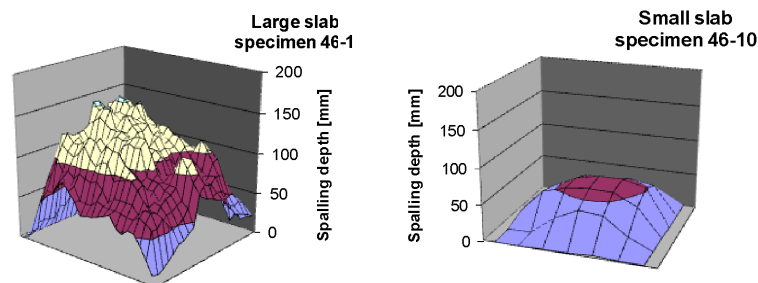


Figure 2.37 Large differences in spalling depth depending on test method as reported by Boström and Jansson (2008). Large slab with a fire exposed area of $1500 \times 1200 \text{ mm}^2$ compared with small slab with a fire exposed area of $500 \times 400 \text{ mm}^2$.

In larger elements the curvature of the temperature wave penetrating the material will be less and the effect of cracks reaching the side surfaces will be less in a larger part of the element compared with small elements. These cracks on the sides might reduce stresses directly and release moisture during a fire test.

2.2.2. Spalling of concrete subjected to bi-lateral or multilateral heating

It has been shown by Meyer Ottens (1972) that thin cross-sections made of ordinary concrete are especially sensitive to spalling when heated from two sides. There is a lower limit on web thickness of 80 mm in the Eurocode EN 1992-1-2 (2004).

During a study aimed at investigating whether shear failure would occur under fire exposure of beams with 80 mm thick webs, extensive spalling was observed by Bengtsson (1997). A detailed summary of these tests together with details of an additional test was written by Jansson & Boström (2011). As described in the previous section, the fire spalling of concrete under exposure from two sides was not an unknown phenomenon at the time of the I-beam tests but it was not seen to be a major problem before performing this tests. One of the tests is described in more detail in Table 2.7 and Figure 2.38 to Figure 2.40. A summary of all the tests can be seen in Table 2.8. As seen in these tables, pre-heating of the loaded 144 day old beam did not limit the spalling, but storage for 2162 days did. During this period, the concrete was exposed to an uncontrolled climate as it was stored close to the horizontal furnace at SP, which probably enhanced its drying compared to most building applications. Despite this, the result from the fire test confirms experimentally that aged and dry concrete has a lowered risk of fire spalling than new concrete of this type as no spalling occurred when the 2162 day old sample was tested.

2.2. Observations of fire spalling of concrete

Table 2.7 Observations during one of the I-beam tests of a loaded pre-stressed concrete beam with an 80 mm thick web during ISO 834 fire exposure.

Time [min:sec]	Observations
12:00	The area of the upper flange close to the middle of the span starts to spall, see Figure 2.38. This is an area with a corner and high compressive stresses, two factors that were traditionally seen to be risk factors regarding spalling. The spalled area spreads towards the support.
13:00	The spalled area at the upper flange reaches the $\frac{1}{4}$ point of the beam.
16:30	Water is pouring out in the transition from web to lower flange.
17:30	The vertical surface of the upper flange starts to spall.
19:45	The cover of the web from the middle to the $\frac{1}{4}$ point of the beam is spalled away, see Figure 2.39.
22:11	The spalling opens a hole with a diameter of approximately 10 cm close to the middle of the span.
27:30	A hole opens approximately 1 meter from the support, see Figure 2.40. Water is pouring out of a crack in the web.
30:20	The deformation caused by the load accelerates and a violent explosion opens a large area of the web. The test is terminated.



Figure 2.38 Loaded pre-stressed beam tested during the I-beam tests with ISO 834:1977 fire exposure. Spalling starts in the upper flange after 12 minutes of standard fire exposure.



Figure 2.39 Loaded pre-stressed beam tested during the I-beam tests with ISO 834:1977 fire exposure. The cover of the web from the middle to the $\frac{1}{4}$ point of the beam has spalled away.



Figure 2.40 Loaded pre-stressed beam tested during the I-beam tests with ISO 834:1977 fire exposure. A hole opens approximately 1 meter from the support. Water is pouring out from a crack in the centre of the beam.

Table 2.8 Summary of the I-beam tests, Jansson and Boström (2011).

<i>Specimen</i>	<i>Age [days]</i>	<i>Heat exposure</i>	<i>Spalling start [min]</i>	<i>Collapse [min]</i>
Loaded pre-stressed beam	132	ISO 834	12	30
Loaded beam with conventional ribbed bar reinforcement	144 (including additional heating at 90-120°C for 6.5 hours)	10 °C/min	53	62
Beam with conventional ribbed bar reinforcement, not loaded.	Slightly older than 144 days.	ISO 834	14	No collapse after 60 minutes (no load), but large holes in the web.
Loaded pre-stressed beam	2162	ISO 834	-	No collapse after 60 minutes.

2.2. Observations of fire spalling of concrete

During a fire test at SP on two loaded concrete columns embedded in a covering wall structure, a total instantaneous explosion of both the columns occurred when their load was removed. The columns (size 130×150 mm) were made of ordinary concrete with a moisture content of 3.2%. As they were inside the cross-section of a wall exposed to the standard fire the temperature rise measured on the concrete surfaces was almost linear up to 400°C during 200 minutes, i.e. 2°C per minute. At the moment when the load was removed at 200 minutes both columns exploded totally leaving only the reinforcement, see Figure 2.41.

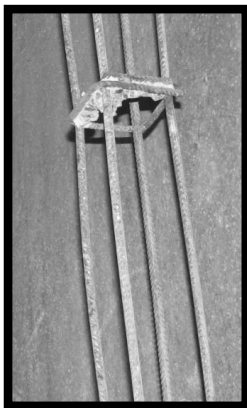


Figure 2.41 Only the reinforcement was left after the instantaneous explosion of the whole -sections.
Photo: Joakim Albrektsson.

This begs the question: is there a difference between “natural” compressive failure and failure by explosive spalling in these examples? During a fire test performed at SP on a loaded column, reported by Haksever and Anderberg (1981), the column “*exploded after 52 min due to the high moisture content*”. The column, $2000 \times 200 \times 200$ mm³, was loaded with 22.5 MPa corresponding to approximately 50% of the compressive strength measured on cube samples. As seen in Figure 2.42, the column was fire exposed from three sides with the standard fire exposure. The failure was instantaneous and according the authors a result of the high moisture content, 6%, measured in the 110 day old concrete. Is this a fire spalling failure or is this an example of the link between fire spalling and compressive failure, i.e. explosive failure caused by a high reduction in fracture energy and compressive strength caused by a thick saturated zone? It is worth noting that a mathematical model of the heat transfer and structural response presented by Haksever and Anderberg (1981) could fairly accurately predict the fire resistance time of this test despite the sudden failure. Further, the fire resistance in two additional fire tests without the same violent failure was predicted although the deformations predicted by the mathematical model were, according to the authors, not satisfactory. Later Forse’n (1982) made a refined model of these fire tests showing more accurate deformations.

Van Acker (2004) experienced failure with an explosion of an I-beam after 58 minutes of fire exposure apparently due to heavy compression in the web. In this case, he was not convinced whether it was the shape of the test specimen or the test setup that caused the failure. In another test made in a full scale building, referred to by Van Acker (2004), the same type of failure was not present.

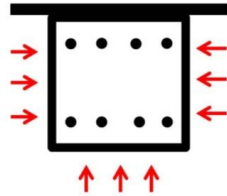


Figure 2.42 Fire exposure with ISO 834 from three sides in the test described by Haksever and Anderberg (1981).

During tests on pre-stressed roof girders made of self-compacting concrete with the concrete grade C50/60, a beneficial effect was shown by Balaz et al. (2010) from using polypropylene fibres and slag instead of limestone as filler. The tested pre-stressed beams were $3.4 \times 1.21 \text{ m}^2$ (length $\times$ height) with a web thickness of 60 mm and pre-stressing force of 130 kN. During the test, the beams were loaded with two point loads of 350 kN spread 0.5 m from the centre. Mix 1 included limestone filler and no polypropylene fibres and failed by severe spalling after 12 minutes of standard fire exposure, while mixes with 1 kg/m^3 PP fibres did not spall. An additional positive effect on the fire resistance time was shown by using slag instead of limestone as the filler, see Table 2.9.

Table 2.9 Results from tests on pre-stressed roof girders, Balaz et al (2010)

Concrete mix	Type of filler	PP fibres [kg/m^3]	Time to failure [min]
Mix 1 (reference)	Limestone	0	12 (severe spalling)
Mix 2	Limestone	1	42 (shear failure, no spalling)
Mix 4	Slag	1	67 (shear failure, no spalling)

To illustrate the phenomenon of the instantaneous spalling of a whole cross-section in one explosion, a test setup was designed for bilateral heat exposure¹¹. In the example shown here (Figure 2.43) the thickness of the specimen was 40 mm, i.e. a very spalling sensitive sample size according to the studies performed by Meyer-Ottens (1972). Further, a very spalling sensitive self-compacting concrete was chosen to be sure to have an explosion. The compressive stress from the load frame shown in Figure 2.43 was 3 MPa in the beginning of the test. After 11 minutes of standard fire exposure, when the thermal expansion had caused an 82% rise in the stress level from the restraining frame, the specimen exploded in one large explosion. The remaining fractions of concrete are shown in Figure 2.44. In the finest fraction, sand is present!

¹¹ The practical work performed with this illustrative test setup was performed by Julien Velar that during his practice at CSTB in France spent some time at SP in Borås, Sweden, in 2012.

2.2. Observations of fire spalling of concrete

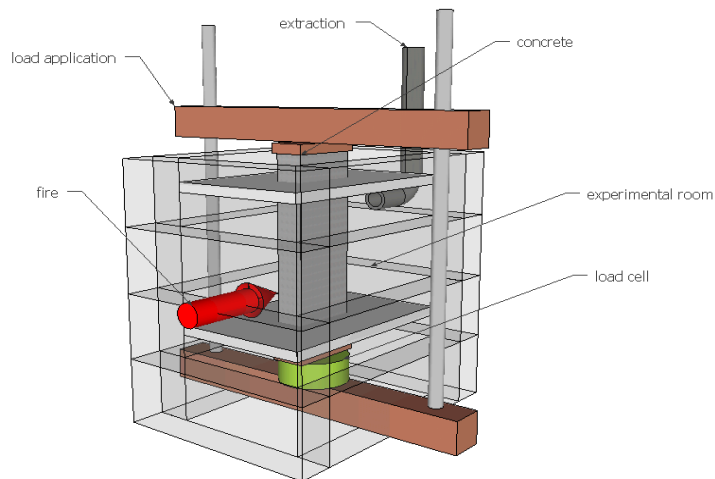


Figure 2.43 Test setup for illustrative test on spalling from bilateral heating of loaded concrete. The test specimen in the centre of the figure was protected with insulation on the side heading the gas burner ("fire" in the figure). Drawing by Julien Velar.

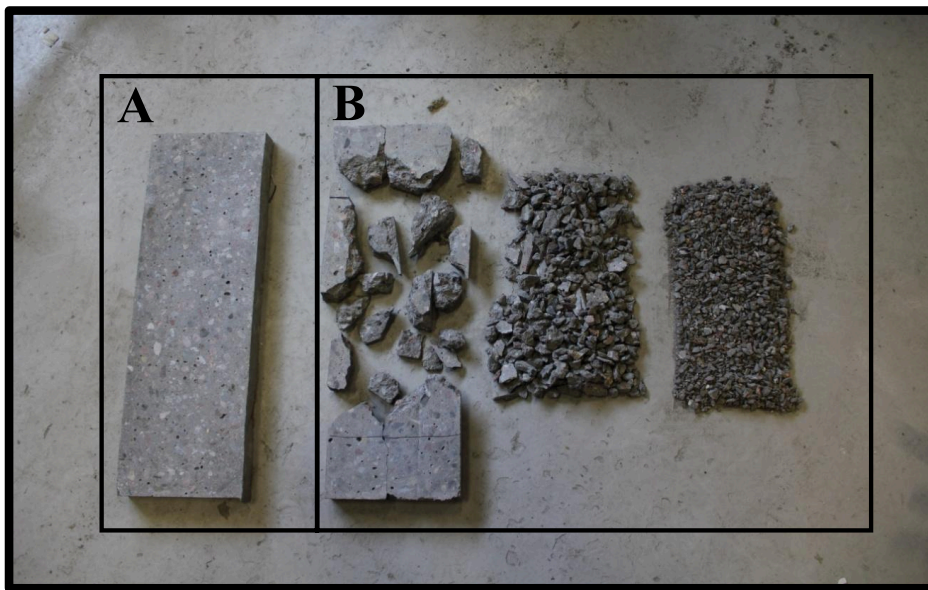


Figure 2.44 Specimens with thickness 40 mm made of 4.5 years old SCC, w/c ratio 0.4 with 140 kg/m^3 limestone powder. (A) A specimen before test. (B) Fractions of a specimen exploded after 11 minutes of standard fire exposure from two sides. Photo: Robert Jansson.

2.2.3. Spalling of shotcrete

Fire spalling of shotcrete was studied by Feron, Larive and Chatenoud (2008). Large test slabs of different thickness and PP fibre content were exposed to the French HC_{inc} fire curve. Major findings from the study were:

- That the spalling depth was higher for thicker elements. An effect caused by the fact that larger restraint is put on the heated surface by a thicker specimen.
- It was possible to protect the concrete by adding PP fibres and use the dry spraying technique despite the fact that a lot of fibres fly away during spraying (2 kg/m³ was used).

2.2.4. Spalling characteristics – sound, size and appearance in time

The sound from continuous surface spalling is almost like the sound of popping popcorn but sharper. There also seems to be a relationship between the sound and the thickness of the spalled flakes, where thicker flakes give a lower fundamental tone in the frequency spectrum. Two factors influencing the thickness of the flakes are the strength of the material and speed of heating. In Figure 2.45, a flake from a high strength SCC is compared to two flakes from normal strength SCC. The spalled flake from the high strength concrete is thinner than the examples from concrete with lower strength. The flake from the high strength concrete, shown in Figure 2.46, is in fact similar in shape to that spalled from a rock block made of granite. According to Anderberg (1997) the thickness of spalls from ordinary concrete is about 20-40 mm whereas the thickness from spalls of high performance concrete can be about 5-10 mm.



Figure 2.45 Flakes from spalling of normal strength SCC (left and middle flake) and high strength SCC >100MPa during fire testing, (right flake). The thickness of the spall from the high strength SCC is only a few millimetres. Photo Robert Jansson.



Figure 2.46 Flakes from spalling of granite and high strength SCC (> 100 MPa during fire testing). They exhibit a similar thickness of about 5 millimetres. Photo Robert Jansson.

Similarly, the intensity of the fire influences the thickness of the spalled flakes. Under slow heating with the heat ramp of 10°C/min, flakes are thicker than during fire exposure with the standard fire exposure or with higher intensity. Regarding the occurrence in time of the first flaking under exposure to different fire intensity, the more intense fires give an earlier onset of spalling. With fast heating as in the case of the hydrocarbon fire curve, progressive flaking often starts already after 1-2 minutes of fire exposure. During the standard fire exposure, which is less intense than the hydrocarbon fire, spalling often initiates between 7 and 25 minutes, while in the case of slow heating with 10°C/min spalling starts after 45-60 minutes. It is interesting to note that the maximum furnace temperature in all cases cited is between 500 and 700°C. This temperature is not equivalent with the temperature on the newly created spalled surface where the temperature can be as low as 100°C as liquid water has sometimes been observed.

2.3. Analysis of results from 110 fire tests

*“..in some tests 10 specimens
were tested with 5 spalling
and 5 non-spalling.”
fib (2007)*

*“For specimens from the
same batch, and under
identical conditions, some
could spall while others do
not.”
Majorana et al. (2009)*

In a state-of-the-art report on the fire design of concrete structures by *fib* (2007), the randomness of fire spalling testing is described as cited above. No more reference was given to the test method that was used or the spalling depths that were measured during the

experiments. As the variation in results during fire resistance testing can have a crucial influence on the fire rating this question deserves more attention. A test method previously used at SP Technical Research Institute of Sweden will be analysed in an effort to shed some more light on this issue.

The test program on SCC described by Boström and Jansson (2008) included both small and large specimens. This Section will include a more in-depth analysis of the result from the tests performed on the small slabs, $600 \times 500 \times 200 \text{ mm}^3$, equipped with an internal post-tensioning system. The goal of the analysis is to make a multiple least squares fit of all available material and test method dependent parameters, see Table 2.10, to predict the measured average spalling depth results as well as possible. The major question to answer is whether it is even possible to develop such a model or if an unknown randomization effect exists prohibiting this. Obviously some of the parameters are interdependent which complicates the interpretation of the results. As a consequence only limited focus will be placed on any conclusions drawn concerning the importance of single parameters as these are tentative at best.

Table 2.10 Span of values in the 110 fire tests on SCC analysed. Tests from Boström and Jansson (2008).

Factor in experiments and model	Span of values in experiments		Unit	Comment
	min	max		
Water/powder ratio	0.25	0.55	[-]	
Water/cement ratio	0.3	0.71	[-]	
Cement type	1*	2 *	[-]	CEM I or CEM II
Water in mix	168	230	kg/m ³	
Cement in mix	300	560	kg/m ³	
Limestone filler in mix	0	252	kg/m ³	
Air content during moulding	2	12	%	Some mixes were designed to include much air
T 50 during moulding	1	7.5	sec	
Strength at 28 days	35	82	MPa	
Fire curve	1*	4*	[-]	10 °C/min, slow heating curve, standard fire curve and hydrocarbon fire curve
Applied stress during fire test	0	10.6	MPa	
Moisture content at test day	4.1	6.6	%	
Age at test day	88	400	days	
Strength at test day	39	105	MPa	

* This is numerical values given to be able to investigate with a least squares fit whether an influence is detectable.

Previous analyses of data from these tests have only been conducted with one parameter at a time, see for example Figure 2.47. However, as several parameters were varied at the same time, it is a difficult task to isolate the impact of a single parameter. The only major influence that was clear from the original study was the impact of the presence or absence of load on the specimens. If a compressive load was applied with post-tensioned bars the spalling depth was greater than if it was absent, but no significant difference was observed between different load levels in the tested interval.

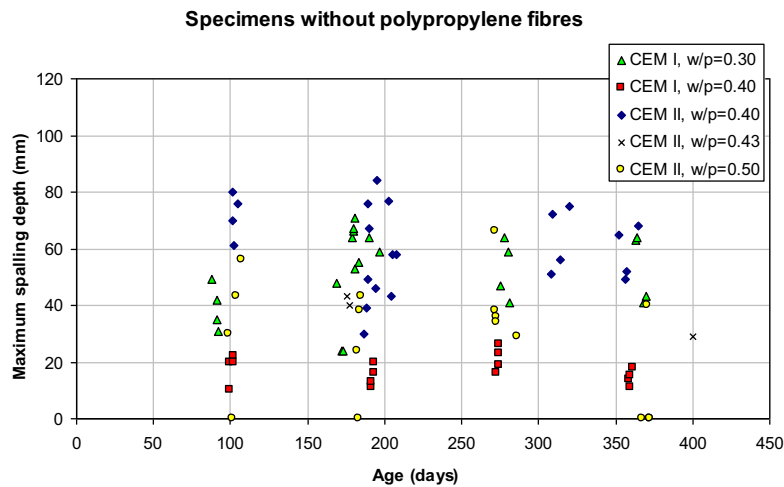


Figure 2.47 Effect of age on the maximum spalling depth, from Boström and Jansson (2008)

In this re-assessment of the results only tests conducted without the inclusion of PP fibres in the mix are analysed. The analysis is based on the mean depth of spalling measured on the fire exposed area of the slabs. Spalling depths for the different specimens were between 0 and 53 mm with an average spalling depth of 20 mm. Out of the 110 tests analysed, 100 were performed in pairs with identical test specimens. By analysing these 50 pairs we see that the average deviation in spalling depth between two identical tests was 6 mm (which is ± 3 mm from the mean value) and the greatest deviation in spalling depth between two identical tests was 21 mm (which is ± 11 mm from the mean value). This initial analysis shows that there is no large deviation between identical tests.

A multiple least squares fit of the 14 parameters listed in Table 2.10 was performed in the spread sheet program EXCEL. To optimize the model to the test data, nonlinear functions of the different test parameters were used. Each nonlinear function was optimized to obtain as high r^2 value as possible for the prediction. Using this approach, there is an obvious risk that the model will not work well outside the parameters studied but this has not been the aim of the application and it has only been tested within the range of input parameters. The best model, based on fitting all the 110 tests to spalling depth data, is shown in Table 2.11. The prediction made by this multiple least squares model is shown in Figure 2.48. This model's fit of the test data is good, especially when considering the deviation of test data between two tests described above.

Table 2.11 Indices defining the best fit of 14 parameters to spalling test data of all 110 tests (reported to 4 significant figures). The table should be read row after row. The span of values for each parameter represented in the test series inside which the fit is valid can be seen in Table 2.10.

	Fire curve ^	1	X	-4.074	+
+	Stress^	0.001	X	14.38	+
+	Cement type^	1	X	21.86	+
+	Moisture^	0.04	X	490.7	+
+	Age/100^	2	X	-1.132	+
+	Air^	-3	X	-57.74	+
+	T50^	0.5	X	7.699	+
+	w/p^	10	X	3727	+
+	w/c^	-5	X	-0.039	+
+	Limestone filler/100^	0.4	X	10.58	+
+	Strength/100^	1	X	86.81	+
+	water/100^	-10	X	-1983	+
+	cement/100^	1.5	X	2.563	+
+	28d strength/100^	1	X	-26.74	+
+	-605.1	=	Average spalling depth [mm]		

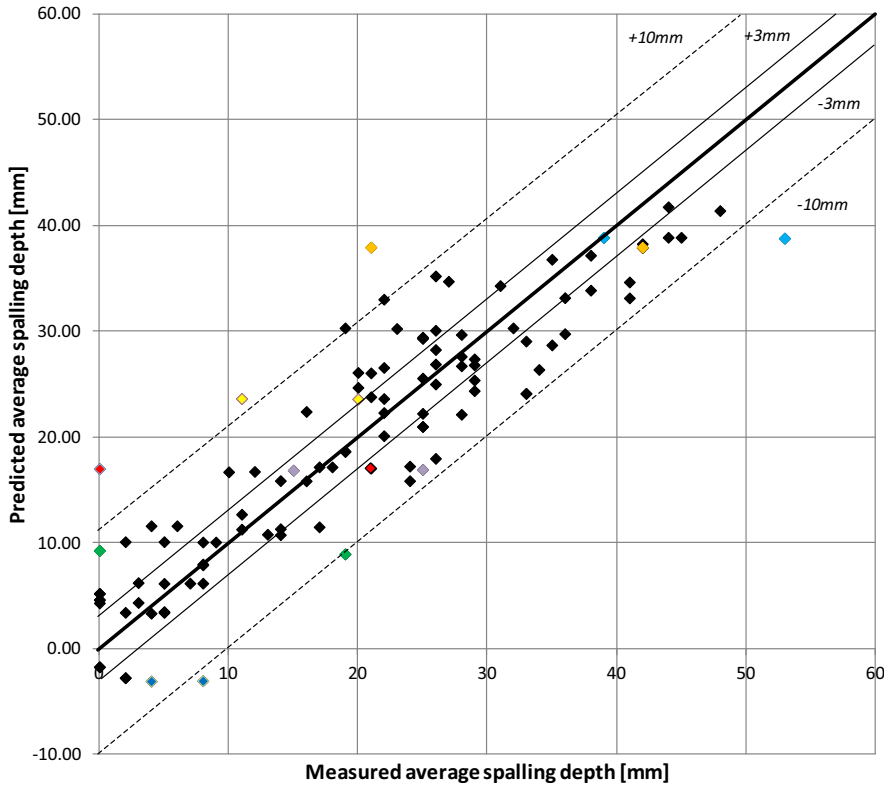


Figure 2.48 Measured vs. predicted values using the model in Table 2.11, $r^2 = 0.81$. Coloured dots in same colour show pairs of two identical tests.

The robustness of this approach will now be investigated. If 15 of the 110 tests are randomly removed from the multiple least squares fit and a new best fit is constructed based on the remaining 95 tests, this new best fit can be used to predict the 15 removed tests. The accuracy of these predictions gives an indication of how sensitive the modelling approach is to the data set. This approach was used ten times and the full results can be seen in the Appendix and are summarized in Table 2.12. No large deviation in the precision of the prediction, as represented by the r^2 values and shown in the diagrams in the Appendix, could be identified which indicates that the approach is sound.

Table 2.12 Prediction results. In each prediction 15 random tests were removed from the analysis and then predicted based on the analysis of the remaining 95 test. Tests from Boström and Jansson (2008).

Prediction	r^2	Average deviation [mm]	Maximum deviation [mm]
1	0.84	6.7	14.4
2	0.81	3.8	14.1
3	0.81	4.2	13.3
4	0.85	6.5	19
5	0.81	4.7	11.7
6	0.81	5.2	18.1
7	0.83	6.5	17.1
8	0.85	6.6	19
9	0.83	5.1	19.2
10	0.81	3.3	8.3
Average	0.83	5.26	15.42

The function found for stress that gave the best fit, $r^2 = 0.81$ instead of 0.76, was the function shown in Figure 2.49, i.e. the conclusion already drawn from the initial study that the application of an external load was important but the size of this load (given compressive stresses up to 10 MPa) was not as important. A similar conclusion was drawn by Copier (1979). As concrete used in practice often is in compression or restrained by its surroundings, a medium scale spalling test method is best designed by including this factor in some way, i.e. if tests without any load or restraint are conducted the spalling depths are much lower.

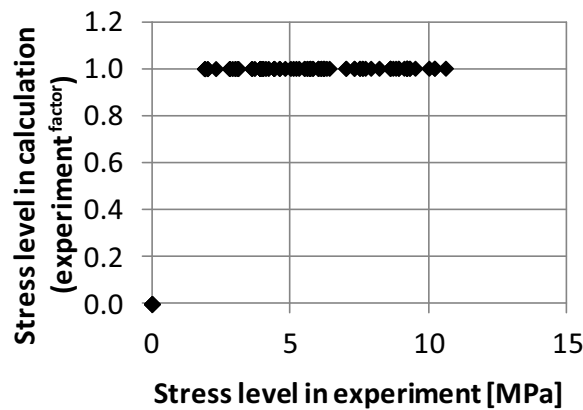


Figure 2.49 The function that gave the best fit for stress level was the stress level in the experiments to the power of 0.001, i.e. giving the stepwise function shown in this figure. The stress level in all 110 experiments analysed are included in this figure with 13 of the tests done without any post-tensioning (at the point 0 in the diagram).

In summary, this re-assessment of test data leads to three conclusions valid for the test series analysed and the chosen analysis method, i.e.:

- the spalling behaviour is dependent on many factors but it is possible to predict the spalling inside a dataset with a fairly high accuracy,
- the random scatter in results is not alarmingly large as indicated by the citation from *fib* (2007) in the beginning of this Section, and
- the application of a compressive load during testing of concrete in the medium scale tests influences the results substantially.

Chapter 3

Fire spalling theories

This chapter provides a summary of popular fire spalling theories without critical assessment of their individual or relative merits. A more critical assessment of some theories can be found in Chapter 7.

3.1. Thermal stress theories

“Unless the interior fail in tension the exterior will fail in compression. Spalling as a result of restraint will result in a gradual loss of concrete.”
Vickers (1974)

Thermal stresses are caused by a non-uniform temperature distribution through the structure/element or by thermal expansion of an externally restrained section. These stresses can, according to Bažant (2005), lead to a *“brittle fracture and delamination buckling caused by compressive biaxial stresses parallel to the heated surface”*. Bažant also highlights that stresses from pore pressure can indeed serve as a trigger for the fracture leading to spalling but that thermal stresses constitute the phenomenon driving the explosion. The reason for the secondary role of pore pressure in this phenomenon is according to Bažant (2005) that when a crack is opened the available volume for steam is suddenly increased by several orders of magnitude. Subsequently the apparent higher risk of fire spalling in high strength concrete is explained by the potential to store more strain energy in high strength concrete than in normal strength concrete. Indeed this is often referred to as proof for the vapour pressure theory described in the next section. This, combined with the fact that high strength concrete is far more brittle as higher strength is not complemented by the same rise in fracture energy, leads to the higher spalling sensitivity for higher strength concretes according to Bažant (2005). Assuming this postulate is correct, Bažant continues, the inclusion of steel fibres known to

reduce the brittleness of concrete should reduce the spalling propensity of such concrete. However, no clear indication of this has been seen experimentally and this can, according to Bažant (2005), possibly be explained by the fact that steel fibres can hinder the development of small cracks (i.e. reduce brittleness) but in return more energy will be stored merely delaying the inevitable explosion. This can be compared with Hertz (1993) empirical observations where he tested high strength cylinders with and without steel fibres concluding that steel fibres delayed the process in time but when the explosion occurred it was more violent. The addition of steel fibres to reduce fire spalling is according to Schneider and Horvat (2003) not a reliable method.

Saito (1965) stated that explosive spalling is initiated by thermal stresses leading to compressive failure, especially in pre-stressed concrete members where the tensile cracking in the central part is restricted. When no pre-stress or longitudinal restraint is present the compressive stress close to the surface is reduced by internal tensile cracking which is also the idea formulated in the opening quote in this chapter by Vickers (1974). The same mechanism is happening when pre-stressed concrete is subjected to bending moment where the compressive stresses on the heated side becomes lower leading to a delay in the spalling behaviour, according to Saito (1965).

A special case of spalling by restraint from the inner colder area of concrete during bilateral heating is described by Dougill (1972). This situation is in a sense analogous to a standard compressive test in a slightly flexible testing machine. The material in tension taking the place of the flexible testing machine and the part that is loaded in compression representing the specimen during the test. The accumulated energy in the tension zone then leads to the violent mode of failure that has been observed in e.g. the web of beams as described in section 2.2.

3.2. The vapour pore pressure and moisture clog theory

Miller (1905) observed that large quantities of water need to be driven off when testing young concrete and that water expansion could be the cause of the fire spalling of surface layers. This has since then been one of the most used explanation models for the fire spalling of concrete. Shorter and Harmathy (1961) first developed and Harmathy (1965) later refined this theory by describing the “moisture clog” phenomenon. When a concrete specimen is heated, the steam pressure in the pores rises close to the surface. The pressure gradient then drives moisture not only out of the specimen but also towards the inner colder regions. When the steam meets a neighbouring colder layer it will condense. This process will continue, moving further into the cross-section, until a fully saturated region of “considerable thickness”, Harmathy (1965), will be created. This region is the so called “moisture clog”. When the moisture clog is created, further movement of steam inwards towards the colder regions is restricted which will lead to a rapid rise in pressure during further heating. And when this pressure exceeds the tensile strength of the concrete, a piece of concrete will spall off. Direct experimental proof of the built up of this moisture clog was shown by Jansson and Boström (2009) by splitting concrete specimens and observing that a moisture clog was visible after 15 minutes of heating with the standard fire curve. Harmathy (1965) also made a calculation model to calculate a permeability threshold, under which spalling will appear. In an analysis of Harmathy’s model Connolly (1996) found that even a 5 day old concrete with a water to cement ratio of 0.7 would be under this permeability limit for spalling, showing that this model is of limited use in practical calculations (a concrete with this water to cement ratio

seldom spalls). Sertmehemetoglu (1977) refined the model by Harmathy to include the moisture that leaves the heated surface before the moisture clog is developed. Sertmehemetoglu (1977) also suggested that spalling is not dependent on moisture content *per se* but rather that a higher moisture content leads to a more complete hydration giving lower permeability. Further, the influence of external load that is seen from experiments was explained by the reduced permeability present when the load limits the thermal cracking during heating.

3.4. The fully saturated pore pressure theory

According to Ghabezloo et al. (2009) the thermal pressurization coefficient caused by water in a fully saturated cement paste is $0.6 \text{ MPa}/^{\circ}\text{C}$ at room temperature. Fellingner and Breunese (2005) created a curve with a peak at 150°C showing the changes of this pressurization effect between $0.2\text{-}1.6 \text{ MPa}/^{\circ}\text{C}$ from 10°C to the critical point of water at 373°C . This mechanism leads to very high pressures, well beyond the tensile strength of concrete, if a saturated pore without drainage is heated during a fire event. If more than 32% of a closed pore is initially filled with water, the water will expand during heating and force the trapped air into solution resulting in a fully saturated pore at elevated temperatures. The same phenomenon is used as the activation mechanism for sprinklers with bulb activation, where a glass container is filled with water and a bubble. When the temperature rises sufficiently the water expands and the air is forced into solution in the water until the whole bulb is filled and breaks due to the build up of hydraulic pressure. According to Khoylou (1997) and Breunese and Fellingner (2004) the hydraulic pressure development is a probable explanation for fire spalling.

3.4. The BLEVE theory

The Boiling Liquid Expanding Vapour Explosion (BLEVE) theory can, according to Ichikawa (2000), be a component in the spalling process of high strength concrete. When the pressure is released from a pore including high temperature liquid water the conversion into steam is very rapid as all energy accumulated during heating over 100°C will be released in an instantaneous boiling process that is classified as an explosion. Petrov-Denisov et al. (1972) also present a theory including the rapid expansion of super heated water. According to their theory the walls between closed pores with super heated water and open pores with lower pressure can be destroyed by the pressure difference and as Hertz (2003) pointed out this can lead to the progressive breakdown of the microstructure.

3.5. The frictional forces from vapour flow theory

The importance of frictional forces during vapour flow has been elucidated by Waubke (1966), Meyer-Ottens (1972) and Waubke & Schneider (1973). As the cross-section is heated, moisture will flow out on the fire exposed side. This flow will give rise to wall friction which will result in tensile stresses in the capillary system. The fundamental idea of the work by Waubke & Schneider (1973) was to conduct a reverse calculation¹², assuming that all moisture must be expelled during heating. Using a theoretical calculation, including a comparison of the influence of different parameters on this evacuation, they concluded that frictional stresses originating from vapour flow during fire exposure made spalling probable.

¹² Personal communication with Schneider, 2007.

3.6. Discussions from the literature on theories

Numerous discussions of the various theories presented above and their relative importance have been presented in the literature. Thelandersson (1974 b), Zhukov (1976) and Khoury and Anderberg (2000) pointed out that it appears that spalling occurs due to the combined influence of pore pressure and compression in the exposed surface region.

Ichikawa (2000) argued that the thermal stresses theory could not explain the apparent difference in spalling sensitivity between ordinary concrete and high strength concrete. The similarity in thermal conductivity does not explain that the thermal stresses are higher in one case and the success of including PP fibres to reduce spalling supports the theory that the pore pressure rather than the thermal conductivity is the dominant phenomenon.

Bazant (2005), on the other hand, has claimed that spalling by pore pressure is not the major cause. The reason for his statement is that directly when a crack is created the available space for water increases several orders of magnitude. As water flow from the surroundings is not an instantaneous process the pore pressure will drop significantly. One factor that might weaken Bazant's argumentation against pore pressure spalling is the special case when pressurized liquid water is present. In this case an instantaneous explosion will appear when the pressure is reduced. According to Bazant (2005) it is important to consider that no pore pressures close to the tensile strength of the material have been measured during experiments on heated concrete.

Chapter 4

The function of polypropylene fibres

4.1. Introduction

This chapter includes theories found in the literature concerning why polypropylene (PP) fibres reduce the fire spalling of concrete. PP fibres used for this purpose have a density of 0.9 kg/m^3 and are typically between $18\text{-}30 \text{ }\mu\text{m}$ in diameter with a length of $6\text{-}12 \text{ mm}$, but other sizes are also available.

To reduce the fire spalling of concrete in general $1 \text{ to } 2 \text{ kg/m}^3$ PP fibres are used in the concrete mix, although values both below and above this range are sometimes used. This amount corresponds to $0.4\text{-}0.8\%$ of the cement paste volume assuming that the cement paste occupies 30% of the volume of concrete. It is known from fire tests that fibres disappear in the heated area closest to the fire, see Figure 4.1. This has also been confirmed by microscopy studies.

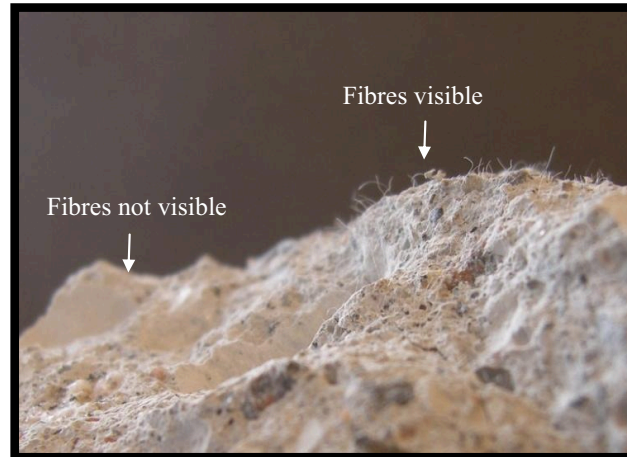


Figure 4.1 Surface created by splitting a concrete cross-section after one hour of fire exposure. PP fibres cannot be observed in the area 0-50 mm from the fire exposed surface (to the left in the photo). Photo: Robert Jansson

To obtain good dispersion during mixing, the fibres are coated with an agent (Khoury and Willoughby, 2008). This is to reduce the natural hydrophobic nature of the fibres. According to Sarvaranta (1995), the agents used for coating the fibres could be fatty acid esters of glycerides, fatty acid amides or cationic surfactants. The exact formulation is typically not disclosed by the producers of PP fibres.

The most common type of PP fibre starts to melt at around 160°C, at about 205°C the fibres disintegrate, the degradation reaction is completed at approximately 380°C according to Schneider and Horvath (2003), while Khoury and Willoughby (2008) report that melting starts at 150°C, peaks at 165°C and is completed at 176°C.

Before describing the theories on the function of fibres, two important observations will be described. Many measurements performed by Jansson and Boström (2008), Jansson (2008) and in Paper I of this thesis have shown that there is an extra peak in drying rate in the region 200-250°C, see Figure 4.2. At the same time there is as a plateau with close to zero thermal expansion when PP fibres are present in the mix, see Figure 4.3. Both the peak in drying rate and the plateau in thermal expansion of concrete including PP fibres have been confirmed by Huismann et al. (2011). In the experiments by Huismann et al. (2011), that also included acoustic emission tests and transient strain tests, the effect of PP fibres was described as a rise in drying shrinkage between 200 and 250°C and an increase in mechanically introduced strain over 250°C caused by micro-cracking.

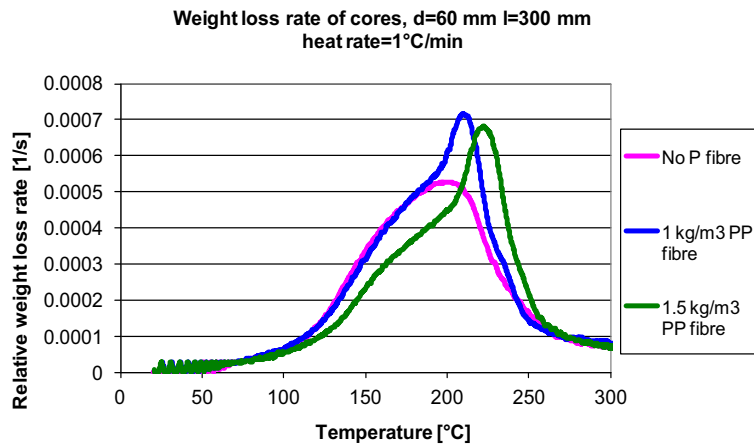


Figure 4.2 A peak in drying rate for concrete including PP fibres, tests from Jansson and Boström (2008).

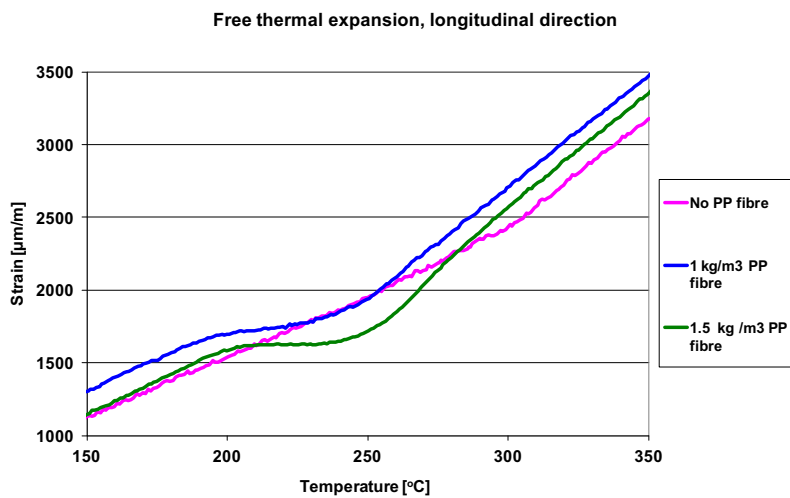


Figure 4.3 A plateau in the free thermal strain curve for concrete including PP fibres, tests from Jansson and Boström (2008).

The occurrence of an extra peak in the drying rate and an associated plateau in the free thermal strain curve, as shown in Figure 4.3, indicates that a rise in moisture movement or drying rate can lead to relaxation of stresses in the critical zone for spalling. A part of this relaxation might also be attributed to a decrease in pore pressure.

The following theories for the enhancement of permeability by the addition of PP fibres have been postulated:

- the formation of capillary pores
- the development of transition zones around the fibres
- the development of additional micro-pores during mixing
- the development of additional micro-cracks during heating and melting
- steam pressure release around fibres in the fibre bed.

An additional theory describes the fibre effect as the reduction of moisture movement to colder areas, i.e. a reduction of permeability caused by an addition of PP fibres.

These ideas will be discussed in more detail below.

4.2. Enhancement of permeability due to formation of capillary pores

When PP fibres melt, burn and gasify in the cement matrix, capillary pores are created leading to an improved permeability of the matrix at high temperature. Schneider and Horvath (2003) claim that the fibres must gasify before these channels are created whereas Kalifa et al. (2001) performed an experiment to show that PP can be absorbed by the cement paste during heating. In the experiment by Kalifa et al., a layer of PP fibres was placed on a concrete surface and covered by a concrete cube, see Figure 4.4. The experimental setup was heated at a heating rate of 1°C/min to target temperatures between 170 and 200°C which was followed by cooling. After cooling the upper cube was removed and a water droplet was placed on the spot where the fibres were resting. It was observed that after heating to the temperature 170°C the droplet stayed in place which meant that the PP attached had made the concrete impermeable whereas after heating to 180°C the droplet was absorbed by the concrete albeit at a slower rate than on virgin concrete. The conclusion drawn from this simple experiment was that the cement matrix is able to absorb melted PP.

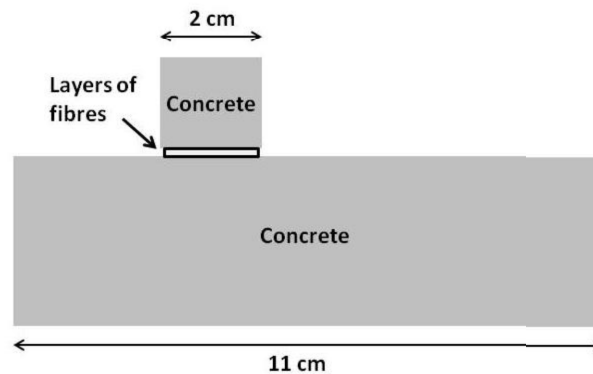


Figure 4.4 Test setup used by Kalifa (2001).

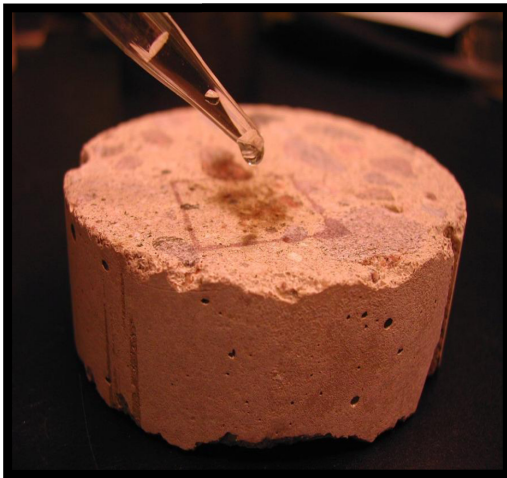
To investigate this further the experiment was repeated by the author of this thesis but the test setup was slightly modified as a piece of glass was put on top of the fibres to reduce the amount of PP leaving the surface by attachment to the upper concrete cube as might have happened in Kalifa et al.'s experiment. Figure 4.5 shows the test specimens with glass covers

4.2. Enhancement of permeability due to formation of capillary pores

inside an electrical furnace and Figure 4.6 shows when the water droplet was applied to the surface. The experiments performed show the same results as the original test.



Figure 4.5 Test specimens in oven with PP fibres between the concrete and the glass. Photo: Robert Jansson



(a)



(b)

Figure 4.6 Test with dropping water after heating to 170 °C. (a) before addition of droplet, (b) hydrophobic concrete surface with water droplet. Photo: Robert Jansson

The idea that PP can be absorbed into the cement matrix has been criticised by Khoury and Willoughby (2008) due to the high viscosity of the polymer melt which will limit this absorption whereas Richardson and Dave (2008) supported the idea of absorption of melted PP in the cement matrix. An observation that further supports (but does not confirm) the idea of absorption is that when heating specimens to 200°C and looking at a crushed specimen, PP

can be seen flowing out of the fibre beds, as illustrated in Figure 4.7 and observer by Liu et al. (2008). Also a wetting phenomenon was observed around PP fibres at the surface by Dehn (2004). Whether this flow is substantial during the transient heating that fire exposure represents is not possible to estimate from this type of residual observation.

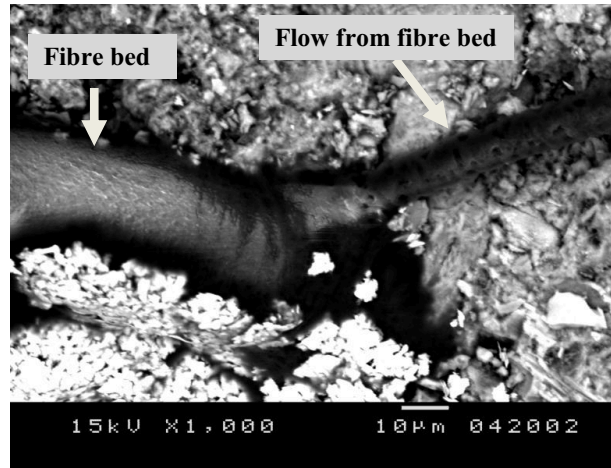


Figure 4.7 Polypropylene flow away from fibre bed after heating to 200°C. Electron microscopy: Robert Jansson

4.3. Enhancement of permeability due to development of transition zones around the fibres

By using a three dimensional micro-structural model for fibre reinforced high strength concrete and percolation theory, Bentz (2000) investigated the influence of adding PP fibres on the spalling phenomenon. By using this model, a hypothesis stating that percolation in the interfacial transition zones (ITZ) is the mechanism by which PP fibres work to improve their permeability at high temperature. According to the pore pressure theory, this increased permeability prevents the development of critical stresses due to vapour pressure. According to the theory, the ITZ of the fibres essentially connects the ITZ of the aggregates creating a more or less continuous system for moisture flow. In a patent from 1983 describing the use of thin polypropylene fibres (diameter 15 μm and length 6.4 mm) to eliminate the tendency of explosive spalling in refractory concrete, Long & Moeller (1983) highlight the development of diffusion transition zones near the fibres. This theory has also been postulated by Schneider and Horvath (2003) and Matesova et al. (2006).

4.4. Enhancement of permeability due to the development of additional micro-pores during mixing

Schneider and Horvath (2003) point out that during mixing the permeability might be enhanced by the introduction of additional micro-pores when PP fibres are included in the mix. These micro-pores could then assist moisture transport reducing the spalling propensity of concrete containing PP fibres.

4.5. Enhancement of permeability due to additional micro-cracks developed during heating and melting

PP fibres inside concrete expand in the radial direction and shrink in the longitudinal direction during the melting process giving an overall expansion of 7% according to Khoury and Willoughby (2008). They also concluded that the modulus of elasticity is between 5-30 times higher for concrete than polypropylene at room temperature. At elevated temperatures this difference is orders of magnitude higher.

According to Schneider and Horvath (2003), the permeability may be enhanced by cracking phenomena in the concrete close to the tip of the fibres as this will be a site for stress concentration. The explanation for a rise in permeability by the creation of additional micro-cracks developed during heating is also supported by Kalifa (2001), Chene and Galle (2001), Sullivan (2004), Larbi and Polder (2007) and Pistol et al. (2011).

4.6. Steam pressure release around fibres in the fibre bed

“Fibre shrinkage is not restrained as the fibres are not chemically bound in the matrix. Fibre shrinkage and endothermic melting create free space in the mortar material, allowing more possibilities for the evaporating free water to find an exit.”
Sarvaranta (1995)

Sarvaranta (1995) presented a theory whereby space created around the fibres allows release of pressure in the mortar (see quote). Khoury and Willoughby (2008) also presented a theory where the poor adhesion of the fibres to the mortar and the hydrophobic action of polypropylene are given as a reason for the creation of space around the fibres thereby allowing the possibility to release pressure along the fibres.

4.7. Reduction of moisture movement to colder areas

An innovative theory was presented by Persson (2004) where the increase in volume of the polypropylene between 105 and 200°C increased the resistance to water penetration. This resistance would then force moisture to move outwards to the surface thereby removing the moisture from the specimen and thus its possibility to contribute to the spalling phenomenon. This is presented as a reduction of moisture movement into colder areas but could equally be presented as the facilitation of moisture movement out of the element.

Chapter 5

Test methods for spalling assessment

5.1. Traditional fire resistance testing and testing of real elements

The occurrence of fire spalling of concrete is one of several factors that influence the fire resistance of concrete elements and structures. Thus, when conducting fire resistance tests the influence of this factor is integrated into the test results. When the test is conducted according to EN 1363-1 (2012), the general behaviour including the occurrence of spalling during the fire test, should be included in the observation protocol but no more specific requirement is started on the details of these experimental observations. Regarding the use of historical compilations of fire resistance tests for judging the spalling behaviour today care must be taken regarding the concrete mixes as it is not obvious that a concrete with the same cross-section and mix details moulded and tested 40 years ago behaves in the same way as an “equivalent” specimen moulded for a fire resistance test today. There are at least two potential sources of error in this comparison; (i) the grinding of the cement is nowadays finer leading to faster strength development¹³ which also potentially changes the response of curing and micro-structure development which together may influence fire spalling and (ii) the thermal boundary has been shown to be very different in some furnaces before the introduction of the plate thermometer which means that apparently similar tests may in fact be quite different in terms of thermal assault (see discussion in historical timeline entry for 1903 in Chapter 2).

5.2. Dedicated fire spalling tests

For research purposes and for comparison purposes several different setups for fire spalling tests have been designed. The simplest and unfortunately least reliable test for the prediction of fire spalling response in real structures is probably to heat unloaded standard cubes or cylinders, see further discussion in Section 2.2. Despite the lack of precision, this simple method is often used as a first ranking for detecting very spalling sensitive concrete. Further, some indication of spalling propensity can be deduced from material property tests according to the RILEM recommendations or similar test setups where loaded cylinders are heated

¹³ Personal communication with Christer Ljungkrantz, Cementa AB, Stockholm, 2011

inside a compression testing machine, although the heating rate is in this case very low compared to the heating rate of a flash over fire.

Here follows a short description of some other setups that have been used in a variety of dedicated fire spalling studies.

5.2.1. Unloaded spheres

In a study which aimed to compare the spalling propensity of different concrete mixes, a simple heating test of spherical specimens was proposed by Debicki et al. (2012). In the test series, spheres of diameter 12, 18 and 24 cm were equipped with thermocouples and pressure measurement pipes in the centre and one thermocouple at the surface as shown in Figure 5.1. The spheres were then exposed to a heating rate of 5°C/min. Results for the experiments show interesting differences in behavior for different sizes of spheres made of high performance concrete including silica fume with a 28 day compressive strength of around 85 MPa. The large spheres of diameter 24 cm spalled from the surface with the center intact whereas the 18 and 12 cm spheres disintegrated entirely, the latter one into smaller pieces. According to the authors this was because the moisture clog and associated pressure peak in the 24 cm spheres was not, contrary to the smaller spheres, in the centre of the specimen during the event.

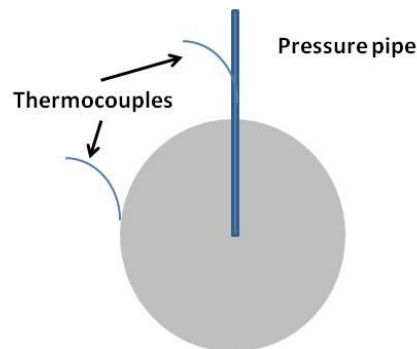


Figure 5.1 Test setup for fire spalling test on concrete spheres developed by Debicki et al. (2012). Sketch not in scale.

5.2.2. Loaded cylinders

A test method including fire exposure of one of the flat sides of cylinders with length 300 mm and diameter 150 mm has been developed at the Danish Technical University (DTU) by Kristiansen et al. (2003) and further described by Hertz and Sørensen (2005). During the test, the envelope surface is loaded with a half spherical iron muff as shown in Figure 5.2. The outer 2.5 cm of the radius on the fire exposed side were protected. Under the protection radial cracks developed during the test. The temperature rise was created by exposing the surface to a pre-heated furnace at 1000°C and characterized by measuring the surface temperature with a thermocouple shown in Figure 5.2.

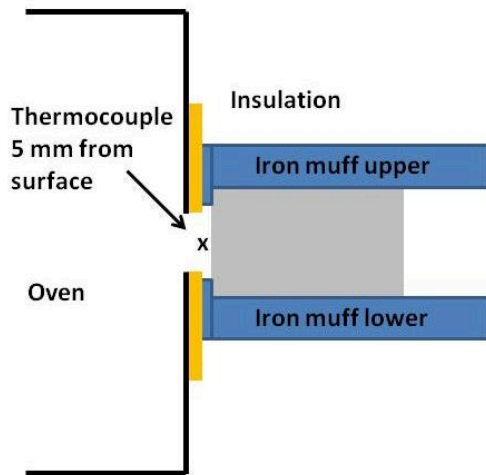


Figure 5.2 Test setup for fire spalling test on concrete cylinders developed by Kristiansen et al. (2003). Sketch not in scale.

Two types of behavior were recorded with this test; (i) spalling of flakes from the surface and (ii) top shear failure. Hertz and Sørensen (2005) concluded that the tests performed gave “results which accord well with the experience available”. However during a research project to develop a suitable reduced scale test method for spalling tests at SP, as reported by Boström (2004), samples were sent to DTU for comparison. As seen in Table 5.1 tests conducted using the DTU method and tests of small and large post-tensioned slabs of the same recipes, labeled concrete A to F, do not show the same order of spalling severity. The reason why the DTU method did not detect any spalling in concrete mix A that had the most severe spalling in the large scale test is not known. It is important to remember that all three methods had different heating rates, cross-section and mechanical boundary conditions. Nonetheless, this highlights the difficulty of comparing results from different scales and types of tests.

Table 5.1 Comparison by Boström (2004) between tests of small and large post-tensioned slabs tested at SP and the cylinder method developed at DTU.

Concrete	Comp. Strength at age 8 month [MPa]	PP fibres [kg/m ³]	Tests made at DTU		Tests on small slabs at SP*	Tests on large post-tensioned slabs at SP**	
			Amount of spalling [gram]	Area of spalling [% of surface]	Mean spalling [% of thickness]	Weight loss [%]	Mean spalling [% of thickness]
A	107	0	0	0	18	19.4	36
B	104	2	0	0	0	2.9	4
C	73	0	191	95	13	9.0	14
D	88	2	0	0	0	0.3	0
E	103	0	69	80	24	18.2	33
F	94	2	0	0	0	5.9	9

* Small post-tensioned slabs, $500 \times 500 \times 100 \text{ mm}^3$, and external loading system giving a compressive load of 2.5 MPa. The standard fire curve was used.

** Large post-tensioned slabs, $1800 \times 1200 \times 400 \text{ mm}^3$, internal loading system giving a compressive load of 2.1 MPa. The Malmö City tunnel fire curve defined by Ingason (2000) was used (i.e., very severe fire exposure).

A development of the DTU test method for confined cylinders was made by Zhao and Sanjayan (2010) where the specimen was placed both on the side of the furnace, as during the original DTU method, and alternatively on top of the furnace to achieve higher heating rates. In the modified tests, results from the exposure of confined cores were comparable to that of unloaded cores exposed to a standard fire exposure in a gas fueled furnace.

5.2.3. Loaded circular plates and slabs

In a study to investigate the mechanism of fire spalling, Connolly (1995) developed a small scale method for testing loaded circular plates with a diameter of 150 mm and thickness of 100 mm. The heat source was electrical coils heating from one side of the plates as shown in Figure 5.3.

Tanibe et al. (2011) also used circular specimens but in this case the specimens were 284 mm wide and 100 mm thick and restrained by steel rings as shown in Figure 5.4.

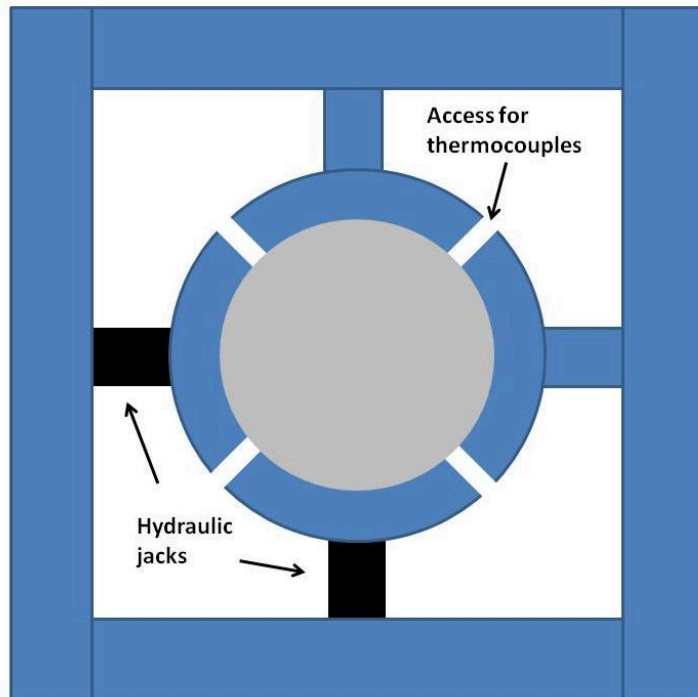


Figure 5.3 Test setup for fire spalling test on circular plates, diameter 150 mm and thickness 100mm, developed by Connolly (1995). Heating was imposed from the front with an electrical heating coil. Sketch not in scale.

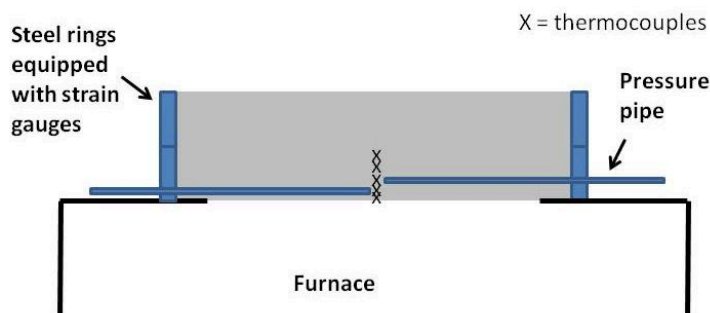


Figure 5.4 Test setup for fire spalling test on circular slabs developed by Tanibe et al. (2011). Sketch not in scale.

5.2.4. Loaded pipes complemented with unloaded cylinders

As a part of the project Newcon, TNO made an experimental study on different parameters influencing the fire spalling of concrete. Test specimens described by Brekelmans et al. (2008) were unloaded cylinders and loaded pipes placed on the floor of a horizontal fire

resistance furnace. The reason for testing the unloaded cylinders (diameter 300 mm and height 900 mm), which included mainly Lytag aggregate, was to investigate pore pressure spalling. Lytag has a very low thermal expansion coefficient so stresses developed were assumed to arise from pore pressure. The tests on unloaded cylinders were complemented by loaded concrete pipes, shown in Figure 5.5, addressing thermal stress spalling. The dimensions of the pipes were outer diameter 600 mm, inner diameter 300 mm and height 500 mm. In this case mainly river-gravel and granite were used as aggregate.

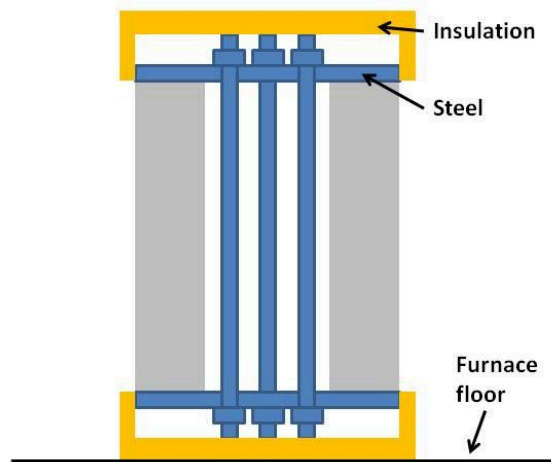


Figure 5.5 Cross-section of test setup for fire spalling test of concrete pipes developed by Brekelmans et al. (2008). Four steel bars are included in the setup. Sketch not in scale.

5.2.5. Pre-stressed and loaded slabs

Slabs have been used in several studies aimed at studying the fire spalling phenomena. At SP Technical Research Institute of Sweden, large and small post-tensioned slabs have been used as shown in Figure 5.6 and Figure 5.7. In a study by Kusterle et al. (2004) slabs were loaded in the longitudinal direction with an external hydraulic jack system and at the same time pre-stressed in the opposite direction as shown in Figure 5.8.

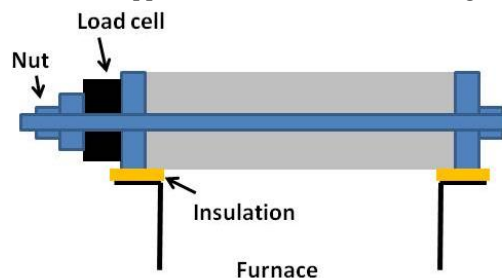


Figure 5.6 Small slab specimen used at SP. Specimen size $500 \times 600 \times 200 \text{ mm}^3$ equipped with three post-tensioning bars located in the centre of the cross-section, Boström and Jansson (2008). Sketch not in scale.

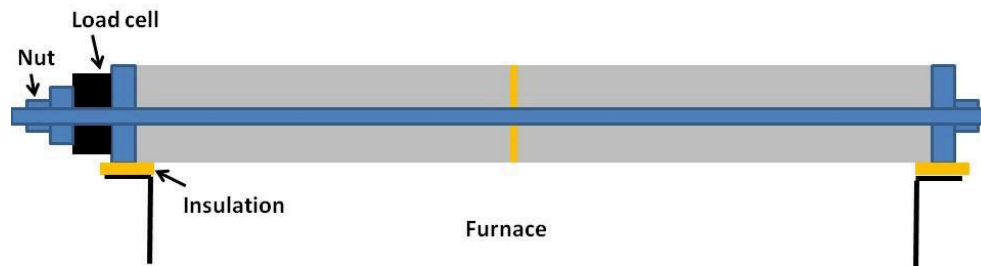


Figure 5.7 Large slab specimen used at SP. Specimen size $1700 \times 1200 \times 200 \text{ mm}^3$ equipped with six post-tensioning bars located in the centre of the cross-section, Boström and Jansson (2008). During the test two specimens were loaded together with the same bars and separated by insulation shown in yellow. Sketch not in scale.

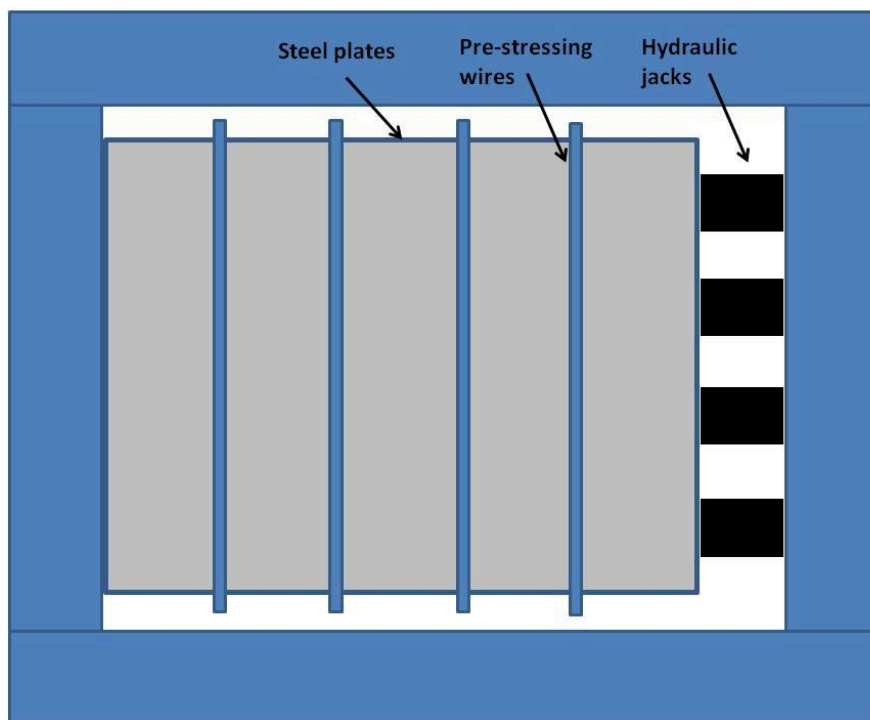


Figure 5.8 Slab tested by Kusterle et al. (2004) as seen from the upper side. Heated by a furnace from below. Sketch not in scale.

5.3. The moisture level in concrete during fires and fire testing

“It should be added that concrete remote from the surface, that is at depth, is hardly subjected to moisture movement, which affects only an outer zone, typically 30 mm deep, but occasionally up to a depth of 50 mm. In reinforced concrete this represents all or most of the depth of the cover”
Neville (1996)

The moisture content is often mentioned as the main parameter influencing the fire spalling of concrete. This factor is certainly important. Its relative influence compared with that of other factors, how it is defined and how it is measured, is discussed in this section.

5.3.1. The role of moisture described in the Eurocode 1992-1-2

An estimation of a level of moisture content under which spalling is unlikely to occur is included as a national choice in Eurocode 1992-1-2. The recommended value for this national choice is 3% by weight. Hertz (2003) and Bushev (1970) recommended this value whereas Zhukov (1976) found that for granite based concrete with a compressive strength of 40 MPa the spalling limit was 3% while for a 20 MPa concrete the limit was 4% (although only limited details on the test circumstances proving the statements have been given). The recommended value of 3% is the national choice in Sweden, but, as an example, Finland has chosen 2.5 % as a limit. One should note that the clause in the Eurocode containing the moisture limit, §4.5.1 (2), is (in Eurocode language) not a “principle” so alternatives are permitted although as it is stated in the document it is clearly a tool for engineers to base decisions on. The preceding clause, §4.5.1 (1)P is, however, a “principle” (as designated by being marked with a “P”) and states that “Explosive spalling shall be avoided, or its influence on performance requirements (REI¹⁴) shall be taken into account”.

A potential problem with the fixed 3% moisture limit is that other factors are excluded when engineers use this document. Further, if this limit is to be set sufficiently conservative it must be set so low that almost all concrete mixes used in ordinary buildings would need further investigation of the spalling behaviour to pass. It would be more useful to include a list of concrete qualities including local aggregates and maximum allowed load level where fire tests or well documented fires show that fire spalling does not reduce the fire resistance. This could be a part of the national choice in the Eurocode.

Important factors influencing the spalling propensity of concrete, other than moisture include:

- *The type of aggregate.* One early example of this influence on spalling is the Rockaway fire in 1916 described in the timeline in Chapter 2. During that fire the fire spalling behaviour was severe despite the fact that the building was 6 years old and most probably had a low moisture content. This is not a modern example but it is the

¹⁴ R = load bearing, E = Integrity and I = Insulation. These classes are followed by a numerical value representing the time, in minutes, that the requirement is fulfilled.

first known example to illustrate that parameters other than moisture may influence the spalling behaviour.

- *The cross-sectional shape of the concrete element.* Mayer-Ottens (1972) observed explosive spalling during bi- and trilateral heating of loaded specimens with thin webs despite moisture contents as low as 2-2.9%.
- *Compressive load or restraint situation.* Zhang (2010) observed spalling in two pre-stressed slabs with moisture content 1.8 and 2.8%.
- *Concrete mix and heating rate.* In the final report of the European project HITECO (1999) it is stated that the occurrence of spalling is influenced by many parameters and moisture content is only one of them. This test program included tests on loaded and unloaded columns made of C60, C70 and C90 and higher strength special concrete tested with the standard and hydrocarbon fire curve where some of the specimens were pre-dried down to 2% moisture content.

Further, a simple analysis of the choice of the unit in the Eurocode 1992-1-2, i.e. % by weight for a moisture limit under which spalling is unlikely to occur, reveals that the precision in this estimate is poor by its very nature. The following factors reduce the precision in the setting of this type of limit in the national choice:

- Aggregates with a higher density inherently make the concrete less likely to spall as the weight % of moisture goes down with the same amount of moisture per cement content as the overall concrete density is higher.
- The porosity of the concrete is not included in this factor meaning that the degree of capillary saturation can be different for the same weight % of moisture. The degree of capillary saturation is, according to Hedenblad & Nilsson (1985), often a better measure for defining the moisture status. Similarly, Connolly (1995) defined this as a more crucial measure than moisture content regarding the influence on fire spalling.
- The permeability is not included in this factor so in concrete with high permeability the moisture can be evacuated from the heated zone easily whereas in other cases the flow may be highly restricted despite the same weight % of moisture. As an example the addition of different fillers can change the permeability.
- The amount of cement in the mix changes the moisture content without any obvious change in spalling propensity, see Figure 5.9, due to the influence of cement content on the relative humidity balance.
- No information is given in the Eurocode concerning the influence of moisture gradients, see e.g. the quote by Neville at the start of this chapter¹⁵. Is it the % by weight value in the surface of concrete or on the total cross-section that is the critical parameter? If it is the surface value, what depth should be included? If it is the total cross-section that is relevant, how do we take into account the shape of the element, as

¹⁵ The statement by Neville is an obvious simplification but for concrete with low moisture diffusivity moisture gradients are always present. Further, the variation in relative humidity during the different seasons of the year makes an extra variation of the surface moisture content. See Nilsson (1980) and Hedenblad (1993) for a more detailed description on moisture movement in concrete.

the surface area/volume ratio has a significant influence during a drying process which will in turn significantly influence the % of moisture by weight.

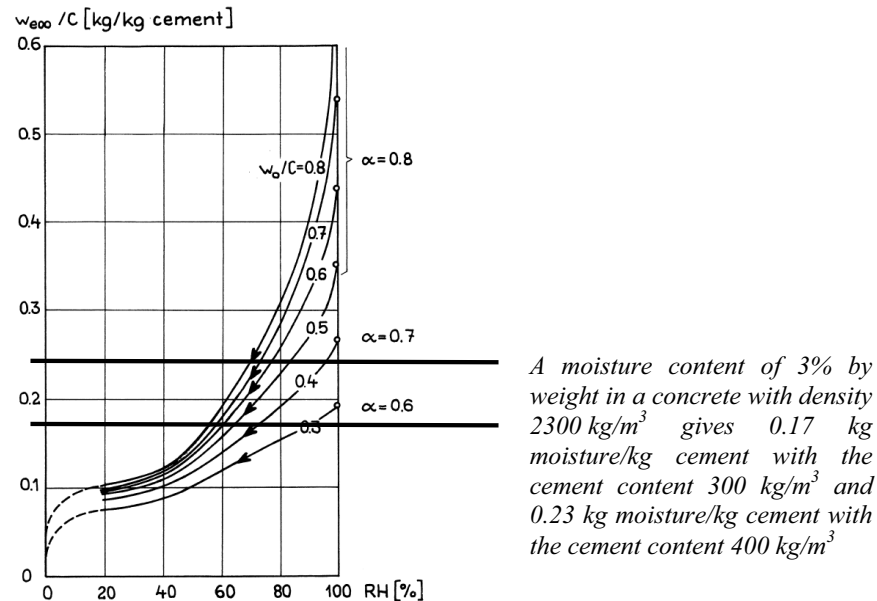


Figure 5.9 Desorption isotherms compiled by Nilsson (1980). Additional comment marked in red together with the diagram shows where the relative humidity balance during desorption at 3% moisture by weight is for different cement content and water to cement ratios. This shows the crudeness in stating a general % by weight limit for fire spalling.

As pointed out above, a limit value in the form of % by weight is questionable. The Eurocode also states that if the moisture level is higher than the limiting value a more accurate assessment of the spalling propensity of the concrete should be made based on moisture content, type of aggregate, permeability of concrete and heating rate. These recommended parameters are in line with what most researchers think are important factors to include in an assessment of the fire spalling of concrete. What is not described in the Eurocode is that it is presently not possible to reliably model the influence of these parameters. Despite this limitation Khoury (2005, 2006) has made attempts to produce a stochastic approach for including all the important factors to be able to make spalling assessments for normal concrete. A similar approach of quantification of risk factors has also been developed by the consultant company Arup (2005).

In lieu of fully understanding the phenomenon, empirical knowledge must be used to assess the risk of fire spalling, making fire tests or behaviour during real fires the only reliable sources of knowledge. As the nature of aggregates and traditions concerning mix design, especially when mixing self-compacting concrete, are often different in different countries a general European focus on moisture content is not easily defended.

5.3.2. What do the test standards for fire resistance testing say about the moisture levels during a test?

In general the moisture level in materials delays the penetration of heat as the latent heat of evaporation of water is substantial. Therefore it is stated in several standards that the specimens should be as close to real conditions as possible, which in the case of concrete leads to long pre-conditioning times before fire testing. In ASTM E119-11a (2011), it is stated that moisture conditions within the test specimen should be the same as in real buildings. The atmosphere in real buildings is defined as 50% relative humidity and 73°F (~23°C). When it is impossible or difficult to reach equilibrium with 50% relative humidity it is acceptable if the deepest portion of the test specimen, or 6 in (152 mm) from the surface of massive concrete structures, reaches a relative humidity in the range of 50-75%. If this second condition is impossible to fulfil after conditioning for a 12 month period, two different alternative solutions are given:

- Alternative conditioning methods like drying at elevated temperatures are permitted if they do not alter the structural or fire resistance characteristics compared with natural drying at RH 50% and temperature 73°F (~23°C)¹⁶.
- Test the specimen, as it is, if the strength is at least equal to the design strength after a minimum of 28 days of conditioning.

When the second method is followed, testing under high moisture conditions can occur. The fire resistance (provided no spalling occurs) will be higher than if the specimen were dried naturally to equilibrium, due to the high latent heat of evaporation of water. To compensate for this extra fire resistance from elevated moisture content, alternatively if a lower moisture content than natural is achieved by pre-drying, there is a special procedure in ASTM E119-11a (2011) for recalculating the fire resistance time. The method is based on the work by Harmathy (1966) and includes both the moisture content and an empirical factor for permeability. Furthermore equilibrium moisture content for a “general” cement paste at different relative humidities is given as a reference to compensate against. When studying Figure 5.9 it is easy to see that the assumption made by Harmathy that all cement pastes have the same moisture content at equilibrium leads to large errors in the compensation procedure especially for concrete which does not have a water to cement ratio of 0.55, which the tabulated values in the ASTM E119 -11a (2011) standard are closest to.

In the European fire resistance testing standard EN 1363-1 (2012) there is a requirement that the strength and moisture content in an element should be as in normal service. The normal level of moisture content by weight for concrete and masonry is set as 1-5%. Concrete specimens should be stored for at least three months before testing. A relative humidity of 75% should be reached at “relevant positions”. If this is not achieved in “reasonable” time, measurements of the moisture content at the time of testing shall be included in the test report. Accelerated conditioning is also permitted provided that the methods do not alter the

¹⁶ An interesting aspect of this alternative method when considering fire spalling of concrete is that there is no scientific proof that the fire spalling characteristics of concrete are not changed when drying at elevated temperatures (compared with natural drying). The moisture gradient in high strength concrete will certainly be altered depending on the drying method.

properties of the material. A similar but not identical approach for conditioning is given in ISO 834-1 (1999).

5.3.3. Artificial drying

In an experimental study to investigate the influence of artificial drying on fire resistance (not fire spalling), Abrams and Orals (1965) tested 15 cm thick concrete slabs made of a concrete with a water to cement ratio of 0.6. Major findings from the study were:

- Despite lowering the RH to 10% in the surroundings, nearly two years of drying were needed to reach 50% RH in the centre of the specimen.
- When testing at an RH level of 90, 75 and 50% in the centre of the slabs, the drying climate to reach this internal RH during natural drying had a low influence on the fire resistance.
- During drying at 93°C in a kiln or with an infrared radiation panel until 50% RH in the centre, the fire resistance was reduced by around 10% compared with naturally dried specimens with the same centre RH.
- Tests including re-humidifying of test specimens dried at elevated temperatures did not “restore” the fire resistance to the same as during natural drying. Sorption hysteresis made this a difficult task. The authors correctly concluded that relative humidity does not uniquely define the moisture content.
- When artificial drying is used it was concluded that compensation of the fire resistance is justified (see Section 5.3.2 on the method prescribed in ASTM E119 - 11a (2011)).

In the study no reference to or discussion on the influence of the drying method on the fire spalling propensity was made.

In the HITECO (1999) project artificial drying was used as a counter measure to reduce spalling of loaded columns. Specimens made of C70 and C90 SF (silica fume addition) concrete spalled during the initial testing so it was decided to mould new specimens to be exposed to artificial drying. The columns were dried in a climate of 40°C and RH 40% for five months down to 2 % moisture by weight and thereafter kept in 23°C and RH 50% for four months before the fire tests. The C70 concrete did not spall after this drying whereas the dried C90 SF spalled severely despite the artificial drying. No information can be found on the difference between normal temperature drying and elevated temperature drying with respect to spalling in the report. The only way of expanding the knowledge in this area seems to be to conduct fire resistance tests on representative concrete elements from buildings or real fire tests on whole structures.

5.3.4. Conclusions

The level of moisture in concrete is an important factor regarding the fire spalling of concrete. However, its relative importance is difficult to quantify for different test set-ups and concrete types due to the fact that several parameters influence the spalling propensity in conjunction with the moisture content. At first glance, a general fixed moisture limit for spalling seems like a good idea but this is not supported by the literature as so many inter-dependent factors are involved in the phenomenon.

Chapter 6

The influence of moisture

6.1. Determination of the pressure in the pore system

The moisture content and degree of saturation have a significant influence on the physical properties of materials when they are exposed to increasing temperature. As the magnitude of pore pressure is the major driving force for moisture movement during rapid heating of concrete, according to Bažant and Kaplan (1996), this pressure is a key property to measure. The pressure in the pore system of concrete has also been highlighted by many researchers as one of the major driving forces for fire spalling of concrete.

6.1.1. Indirect measurement of pressure caused by moisture

During several test series performed at SP Technical Research Institute of Sweden, the specimens were restrained in one direction by post-tensioned bars inside the cross-section. These bars were loaded before the test and the change in load during the fire test was measured with load cells, see typical test setup in Figure 5.6 and Figure 5.7. The thermal expansion close to the heated surface gave rise to higher stresses in the post-tensioned bars. In Figure 6.1 stresses developed in slabs of concrete with high spalling propensity and similar concretes with included PP fibres that did not spall are shown. Measurements are only shown until the spalling event starts and according to the results higher stresses caused by moisture pressure in the specimen that spalled cannot be seen. There can be two reasons for this absence, (i) the stresses are so small and local that they are overshadowed by the stresses caused by thermal expansion of the surface layers, or (ii) fire spalling in the shown cases was not caused by high moisture pressure in the capillary system. A conclusion is that moisture pressure induced spalling could not be detected with this method.

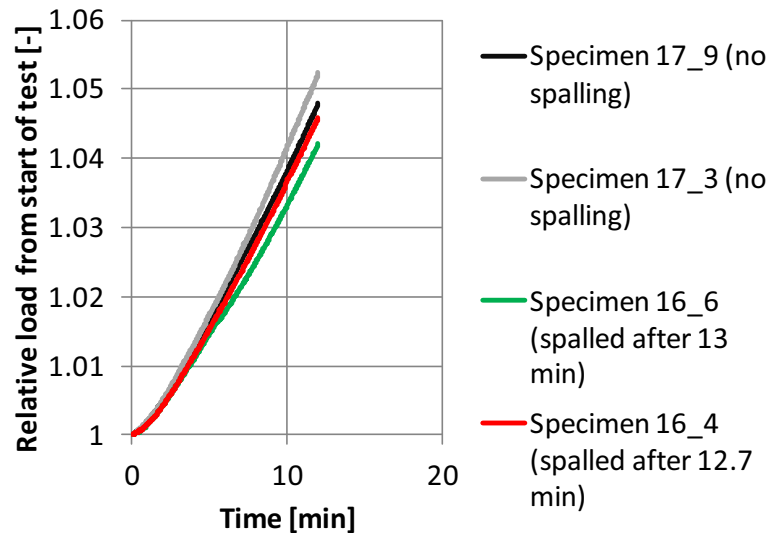


Figure 6.1 Change in load from restraining system during fire test of similar concrete with and without PP fibre addition, from test series performed by Boström and Jansson (2008).

6.1.2. Direct measurement of pressure caused by moisture

There are a handful of different techniques found in the literature to measure the pore pressure. This review will only focus on high temperature measurements although similar systems are used to measure capillary pressure during the setting of concrete, see Hammer (2006) and Slowik et al. (2008).

Measurements of the pore pressure in concrete have been done with either embedded or external measurement gauges. With embedded gauges, the measurement is performed in the high temperature zone. With external gauges, the pressure is transferred from the measurement point to a gauge on the cold side of the specimen by a pipe reaching inside the specimen.

When measuring the pressure development in concrete, the corresponding temperature is important. In some systems, the temperature is measured in the pressure measurement devices and in some experimental setups the temperature is measured externally. The most common pressure measurement setups (shown in Figure 6.2) include:

- A. **Embedded pipe**, which transforms the pressure to an external pressure gauge¹⁷. In this and other similar applications (B-D) the pipe exits the specimen away from the heat source.

¹⁷ Bremer (1967), Nekrasov et al. (1967), Thelandersson (1974), Harada and Terai (1996), Shekarchi (2003), Dal Pont et al. (2005), Jansson and Boström (2010),

- B. **Embedded pipe with internal rod**, which transforms the pressure to an external pressure gauge. The internal rod is used to reduce the volume in the pipe. A cavity is created around the measurement point¹⁸.
- C. **Embedded pipe with clamped sintered material in contact with the concrete**, which transforms the pressure to an external pressure gauge. A thermocouple is included in this method to monitor temperature. The thermocouple can be introduced either as a volume reducer in the pipe¹⁹ (as shown in Figure 6.2), or outside the pipe²⁰.
- D. **Embedded pressure gauge**²¹, for direct measurement of the pressure.
- E. **Embedded pipe**, which transforms the pressure to an external pressure gauge. In this application the pipe is parallel to the heated surface²².

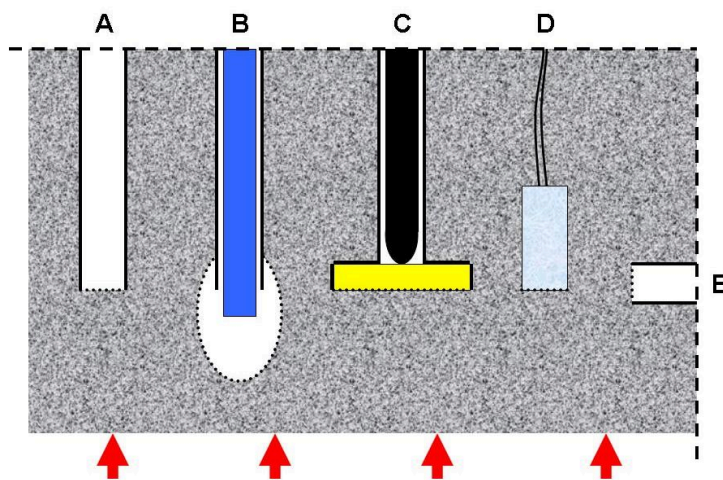


Figure 6.2 Different pressure measurement setups (not in scale). Concrete heated from below. Figure originally drawn by Jansson and published first time by Schneider et al. (2010).

In measurement setup types A, B, C and E, the pressure is transferred to the outside of the concrete using a medium in the pipe. In different applications of these methods, the following media have been used:

- a. Air²³
- b. Water²⁴
- c. Oil²⁵
- d. Mercury²⁶

¹⁸ Schneider and Herbst (1989)

¹⁹ Kalifa et al. (2000), Mindeguia (2009)

²⁰ Kusterle et al. (2004), Phan (2008), Suhaendi et al. (2008)

²¹ Consolazio et al. (1997), Dal Pont and Ehrlacher (2004), Yanko (2004)

²² Qzawa et al. (2009)

²³ Dal Pont et al. (2005), Kalifa et al. (2000), Mindeguia (2009), Schneider and Herbst (1989)

²⁴ Nekrasov et al. (1967), Thelandersson (1974)

²⁵ Dal Pont et al. (2005), Harada and Terai (1996), Jansson and Boström (2010), Ozawa et al. (2009), Phan (2008)

²⁶ Bremer (1967)

Kalifa et al. (2000) and Mindeguia (2009) uses air as a medium in the pipe but when doing the connection to the pressure measurement device (outside the concrete in ambient conditions) a silicon oil filled flexible tube was used.

6.1.3. Errors in pressure measurements

As seen, five different measurement methodologies (A-E) and four different pressure fluids (a-d) have been used for measurement of the pore pressure in concrete under the influence of elevated temperature. Unfortunately, as the various experiments have been performed on different concrete mixtures and under different boundary conditions, i.e. temperature and external stress, a direct comparison of the results from different methods is difficult. There is, however, one study published where the most common setups are compared. Bangi (2010) compared bare pipes, pipes with cups and cups containing sintered material. All the setups were also tested both with and without oil in the pipes. The results show that (i) the pipes filled with oil measured the highest pressures and (ii) the readings from the oil filled pipe equipped with a cup with sintered material showed the highest pressure of all devices containing oil, 20% higher than the bare tube and the cup without sintered material (in this case the measured pressure was 6 MPa without spalling). Regarding the influence of the thermal expansion of oil on the results Suhaendi (2007) and Jansson and Boström (2010) showed that this has a minor influence on the results (mainly because only the oil very close to the measurement point is heated).

Which are then the potential error sources in this type of measurement? Cracks around the sensor which could lead to depressurisation of the measurement point are of major concern. All systems could potentially suffer from this problem to some degree. Ultimately, a type D setup with a very small pressure gauge and the electrical wires exiting the specimen along the isotherms (horizontally in Figure 6.2) would be preferable. The type E setup with a pipe exiting along the isotherms as Ozawa et al. (2009) used is promising; but, if this system contains oil a careful analysis of the influence of oil expansion must be made, especially if there is spalling along the pipe causing hotspots that are not related to the measurement point.

Another factor which might influence the comparison between measurements is that measurements with system A, the bare pipe, are more local (leading to a higher degree of variation) whereas system C, the cup with sintered material, measures an average over a larger area, see Figure 6.3. However, this theory has not been proven experimentally.

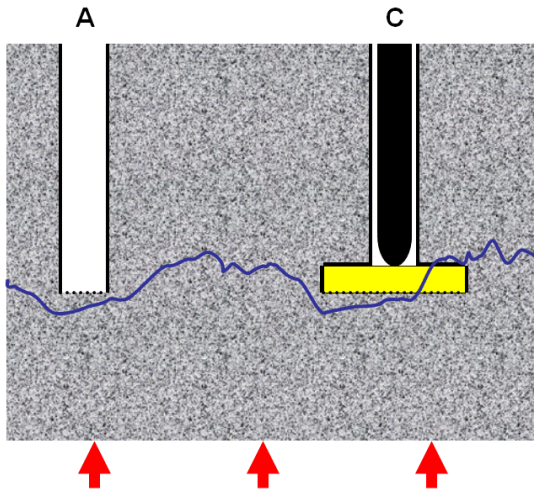


Figure 6.3 Pressure measurement system C has a larger pressure collecting area i.e. the readings are closer to the average pressure in the specimen. The horizontal line is an isobar that is influenced by the size and shape of the aggregates.

It has been shown experimentally by Jansson and Boström (2009) that a liquid moisture zone can be created in rapidly heated concrete. In the case of a Type C arrangement, a possible error might be that an extra portion of liquid moisture might be trapped in the sintered material compared with the surrounding concrete when the moisture clog moves, giving rise to a potential error as shown in Figure 6.4. When the heat continues to increase, this extra moisture will evaporate which will slightly decrease the rate of temperature rise and give an extra contribution to the pressure reading. In particular when the porosity of the sintered material is higher than the surrounding cement paste, this might be a factor influencing the reading. During a meeting in the RILEM HPB technical committee²⁷ Jansson proposed to introduce holes in the upper side of the metal housing of the sintered material. In theory, this would allow the moisture to pass through the measurement point without being trapped. To date no known experiments have been conducted to support or refute this proposal.

²⁷ RILEM TC HPB 227 "Physical Properties and behaviour of High-Performance Concrete at high temperature" meeting held in Milan, Italy, April 7-8, 2011

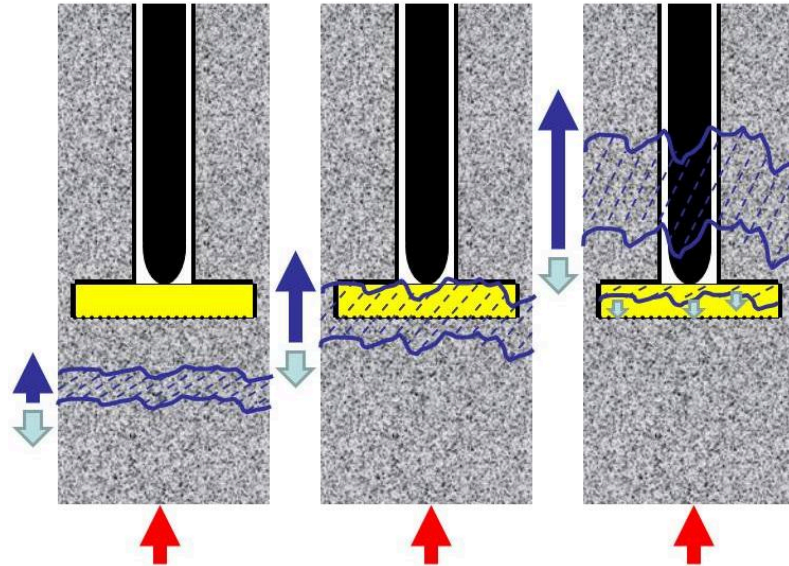


Figure 6.4 Possible phenomenon of trapped moisture in sensor made of sintered material. The horizontal lines are boundaries for the moisture clog influenced by the size and shape of the aggregates. Red arrows represent the fire, blue arrows show transport of liquid water from the point of highest pressure and light blue arrows represent transport of gas from the point of highest pressure.

6.1.4. Results from pressure measurements

Despite the above mentioned potential errors, pressure measurement studies to date have shown that:

1. The pore pressure development in heated high strength concrete is higher than in normal concrete, Schneider and Herbst (1989), Kalifa, Menneteau and Quenard (2000), Mindeguia (2009) and Phan (2008).
2. Higher initial moisture content leads to higher pore pressure, Phan (2008).
3. Slow heating generally leads to higher pore pressure than fast heating (standard fire), probably due to induced thermal damage during fast heating, Phan (2008), Mindeguia (2009) and Mindeguia et al (2009). At some depths these results are contradicted by results from Bangi (2010), but in these experiments the fastest heating rate was less than the standard fire.
4. The addition of polypropylene fibre reduces the pressure in concrete that does not spall, Mindeguia (2009), Phan (2008), Suhaendi et al. (2008), Mindeguia et al. (2009) and Kalifa et al. (2001).
5. The direct connection between pore pressure and fire spalling is weak during fire exposure of large externally loaded specimens, i.e. concrete with the addition of polypropylene fibres that does not spall often exhibits higher pore pressure than a concrete without polypropylene fibres that spalls, Phan (2008), Jansson (2008), Mindeguia et al. (2009), Jansson and Boström (2010).

6.2. The influence of moisture and temperature on some mechanical properties

6.2.1. The influence of moisture at room temperature

The presence of moisture influences the compressive strength of concrete at room temperature in several ways. First of all, if the concrete is wet cured surface cracking at an early age is reduced; and secondly, the presence of moisture helps to continue the hydration. These two factors lead to a gain in compressive strength. However, according to Neville (2006) there is also a well known fact that concrete that is dry or has a dry surface layer when tested has a higher compressive strength than the same specimen tested when fully saturated or surface saturated. In a literature review by Popovics (1998), it was reported that this effect can also be seen in rocks and porous glass. Two different hypotheses for the strength reduction from the presence of moisture is described by Popovics (1998):

1. The drying decreases the volume of the cement paste. This is due to the increased surface tension of water in small water filled pores during drying. This reduces the distances between the surfaces in the hardened cement gel leading to an increase in the bond between surfaces, i.e. the strength is increased by drying. When rewetted, the average distance is again increased leading to a reduction of the strength.
2. Internal pore pressure develops during a compressive strength test of wet concrete. Since the liquid in fully saturated pores cannot be transported away fast enough during a test the pore pressure developed increases the crack propagation thereby reducing the compressive strength of saturated samples.

Both theories seem reasonable, but Neville (1996) reported that soaking specimens in benzene or paraffin, that are not absorbed by the cement gel and therefore are only present in the capillary pores, does not lead to a decrease in strength. The obvious conclusion from this is that the second theory by Popovics (1998) is not valid for the case of saturation of the capillary pores (as illustrated by Neville's experiment), but the hypothesis might still be valid for the saturation of the gel pores.

If there is a moisture gradient in the specimen during compressive strength testing, the results are affected. When the moisture gradient is positive, i.e. the sample is dryer at the surface, the compressive strength is higher as the shrinkage at the surface restricted by the core leads to lateral compression of the centre of the core. This increases the uniaxial compressive strength in the longitudinal direction of the core according to Popovics (1998). In the opposite case when the surface is wetted, the surface wants to expand more than the inside leading to tensile stresses in the specimen which reduces the strength. Neville (1996) does not completely agree with this theory as he argues that well cured specimens without moisture gradients also exhibit this loss of strength due the presence of moisture. In fact, there is no clear contradiction between the two hypotheses regarding local and total wetting as one does not exclude the other.

Further, a local swelling can be seen on the top and bottom ends of a core when the surface region is wetted. This leads to compressive stresses in the soaked region and tensile stresses in the adjacent unsoaked region; but the influence of this on the measured compressive strength is deemed minor by Barlett & MacGregor (1994) because this region is confined by the loading plates of the test machine so the failure is initiated elsewhere.

The results of experiments by Pihlajavaara (1964), see Figure 67, clearly show the effect of moisture on the compressive strength. In these experiments the test specimens were first stored in water or sealed for 110 days followed by cycles of drying to equilibrium at 105°C and wetting in water to equilibrium. The change in strength from initial strength in both directions is up to 20% and seems to be almost reversible. According the Swedish publication Betonghandbok Material (1997), the initial drying to 105°C in these experiments ought to give some permanent strength loss due to micro-cracks developed during the first cycle.

A practical case when the influence from moisture on strength is considered is the Swedish rules where the factor 0.92 is used to re-calculate the compressive strength values determined on cubes stored in 5 days in water followed by 23 days in air to the values for 28 days of water storage.

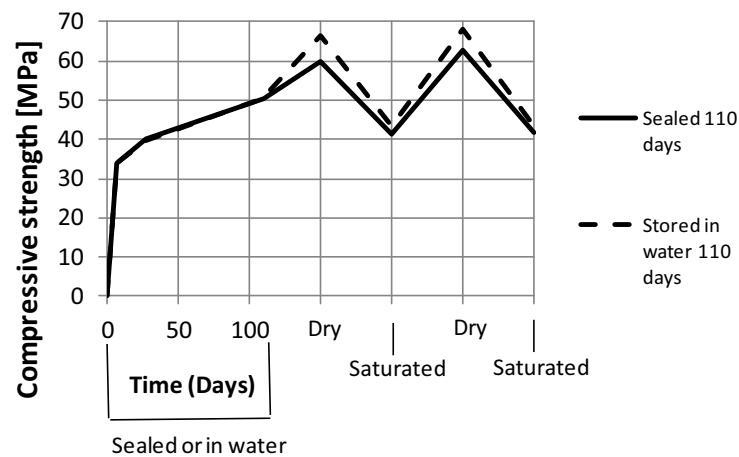


Figure 6.5 Compressive strength as a function of the moisture state by Pihlajavaara (1964). Sealed or stored in water before drying/saturation cycle.

6.2.2. The influence of moisture at elevated temperatures

Bazant and Prat (1988) made a study on the influence of moisture and temperature on the fracture energy shown in Figure 6.6. The wet tests were performed under water and a clear reduction of fracture energy when water is kept inside the specimen during the rise in temperature can be seen. Similarly, Lankard et al. (1971) showed that the compressive strength is reduced substantially if moisture is kept inside the test sample. These test results, from testing inside an autoclave having the saturation vapour pressure as a boundary, are shown in Figure 6.7. Similar results were reported by Crispino (1972) where a concrete with limestone aggregate and w/c ratio 0.43 was tested sealed and unsealed at room temperature and 150°C. Results from the high temperature sealed test show a reduction of approximately 33% compared with the room temperature value and the unsealed test at 150°C.

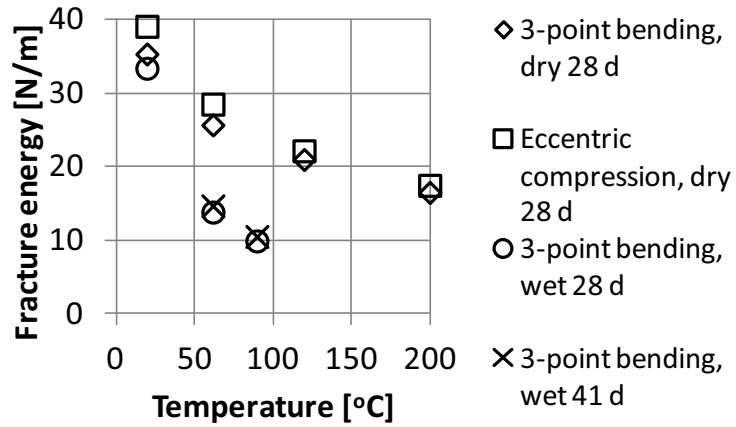


Figure 6.6 Fracture energy at different temperatures and moisture states by Bažant and Prat (1988).

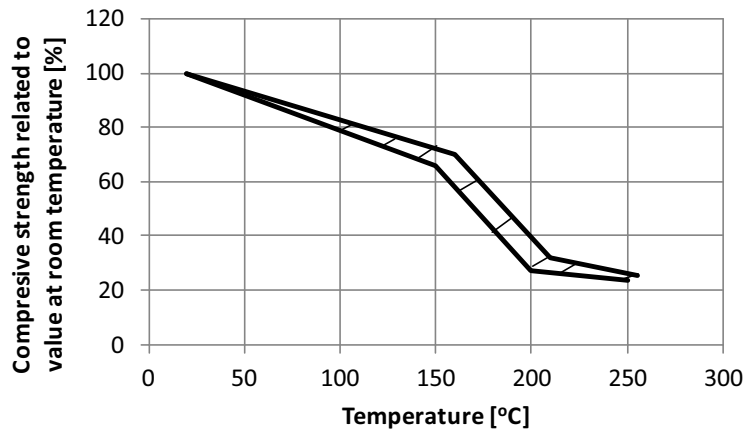


Figure 6.7 Compressive strength at high temperature compared with strength at room temperature when moisture is kept inside the specimens according to Lankard et al. (1971).

Chapter 7

Discussion on fire spalling

7.1. Introduction

“The grand aim of all science is to cover the greatest number of empirical facts by logical deduction from the smallest number of hypotheses or axioms.”

Albert Einstein

The aim of the following chapter is to condense the fundamental physical ideas presented thus far about the phenomenon fire spalling of concrete. The goal is to understand the physics governing the phenomenon. The hypotheses developed will be based on empirical observations as far as possible to avoid the proposition of potentially attractive ideas without the support of empirical evidence.

7.2. Summary of observations and fire spalling theories with additional comments

When discussing the phenomenon fire spalling of concrete a natural starting point is the pore pressure theory. Harmathy (1965) and Dwaikat and Kodur (2009) clearly highlighted the pore pressure as the main component of the fire spalling phenomenon. The former based his assessment on the fact that classical thermal stress theories²⁸ are not valid for concrete at high temperatures as concrete cannot be assumed to be an elastic material and at high temperature

²⁸ According to Harmathy (1965) the classical factor, or group of factors, which if increasing giving an increase in the resistance to thermal stresses spalling is $\sigma_f(1-\nu)/(E\alpha)$, where σ_f is the fracture stress, ν the Poisson's ratio, E the modulus of elasticity and α the coefficient of linear thermal expansion.

shrinkage might appear instead of expansion. It is not clear whether Harmathy (1965) considered the occurrence of transient strain effects as later was observed by Weigler and Fischer (1968) or if he had found some concrete that actually was shrinking without the influence from load. Two observations seem to be at the core of the moisture clog theory presented by Shorter and Harmathy (1961): (i) the size of spalls, when occurring, was about 1 inch (25 mm) thick but when a layer of 2-2.2 inches (50-60 mm) from the surface was pre-dried no spalling occurred; (ii) progressive spalling happens when the first spall causes the exposure of saturated concrete directly to the fire making the spalling process continuing further into the material.

If the pore pressure is to be ranked as the main component in the fire spalling phenomenon, this statement ought to be supported by some more empirical evidence reaching beyond the observations made by Shorter and Harmathy (1961). When examining the literature in more detail and conducting experiments as part of the work presented in this thesis, no clear evidence for a connection between measured moisture pressure development and fire spalling can be found, see Section 6.1 and Papers II and V in this thesis. Certainly the types of measurement conducted are crude and associated with uncertainties. First of all, the pressure in the gel pores is not measured. There might also be influences from cracking around the measurement devices. According to Mindeguia (2009), the property that is measured can be seen as a balance point where the evaporation and condensation in the area surrounding the sensor leads to a pressure that is transferred to the gauge, i.e. small cracks around the sensor make the value measured more averaged. However, when having a small pre-pressure of oil in the system no indication of pressure loss through cracks has been seen. Thus, to summarize from Section 6.1, attempts to measure pore pressure due to moisture show that:

- higher pressures are measured during slow heating than fast heating
- in many cases the pressure developed during heating does not reach substantial values before spalling occurs, i.e. the pressure is far below the tensile strength of concrete. This is more marked for slow heating where far lower pressures are measured than during fast heating.

The intention of questioning the pore pressure theory as presented by Harmathy (1965) is not to ignore its contribution to the spalling phenomenon in any way, rather to question its ranking as the main factor in the spalling phenomenon and present an alternative explanation that might also provide an explanation of how PP fibres can reduce spalling.

The hydraulic spalling theory based on the fracture of fully saturated pores according to Khoylou (1997) is difficult both to verify and to refute. Experimentally, no evidence of very high pressure build-up has been seen with liquid water or oil as a pressure carrier in pore pressure measurement systems; but on the other hand this phenomenon, if present, is more probably happening on a gel pore size which might be averaged out by the crude measurement techniques used. To conclude, without further evidence it is the author's conclusion that this theory should not be adopted.

Ichikawa (2000) put forward the idea that the Boiling Liquid Expanding Vapour Explosion (BLEVE) has a role in the phenomenon which is not implausible. With this factor included,

7.3. The influence of the presence and movement of moisture at temperatures below 250°C

the opposition against the pore pressure theory that Bažant (2005) presents²⁹ may lose some validity; but no indepth theoretical calculation of the magnitude of this factor has been presented. Thus it is the author's conclusion that without further evidence this theory should not be adopted.

Let us now consider some numerical "evidence" from advanced modelling of the movement of heat, movement of moisture and the build-up of stresses. When studying the localized behaviour that spalling from a surface represents, material data obtained from slowly heated test specimens have only tenuous validity. The stress relaxing transient strain effect that has been observed by Anderberg and Thelandersson (1976) when heating concrete slowly probably only has a small influence during the very high heating rate found in the outer layer of concrete exposed to a fully developed fire. This makes any type of detailed stress modelling applicable to the fire spalling phenomenon inexact until more refined constitutive relationships based on experimental proof can be implemented into the modelling.

Another factor that is crucial to include in an advanced model of spalling is the permeability development at high temperature. This, together with the permeability development in the cold zone, gives the balance that drives moisture movement. The common observation that cold liquid moisture is pouring out of a sample on the non-fire exposed surface of fire exposed concrete is an extremely difficult phenomenon to model. A model based on averaging of properties does not predict this phenomenon, i.e. the amount of moisture transported away from the warm surface is not sufficient to saturate the whole porosity throughout the whole thickness. Thus, localized transport along cracks must be present to explain moisture flow out of the cold side of the specimen. The team behind one of the most advanced models developed for modelling heat, moisture and stress development in heated concrete has chosen a very descriptive title for one of their publications which indicates the difficulties faced: *"Towards prediction of the thermal spalling risk through a multi-phase porous media model of concrete"* (Gawin, Pesavento and Schrefler, 2006). Advanced modelling might give us a tool for understanding the spalling phenomenon in the future but we are not there yet. Some more important factors must be determined experimentally to better understand the fundamentals. Without this understanding it is not possible to construct a model which will fully predict this behaviour.

7.3. The influence of the presence and movement of moisture at temperatures below 250°C

As discussed in Paper V, the critical region where a crack is opened, leading to the flaking off of concrete from the surface, can be found in the temperature region below 200°C. This is further illustrated by the surface temperatures at spalling measured by Connolly (1995) during different heating rates shown in Figure 7.1. The simplified approach that the saturation pressure from steam is a major component in this flaking process is contradicted by results from moisture pressure measurements and the fact that spalling can occur at this low temperature.

²⁹ Bažant (2005) claims that when a crack is opened the volume available for expansion of steam is immediately orders of magnitude higher, making it impossible for the pure pore pressure to shoot flakes away.

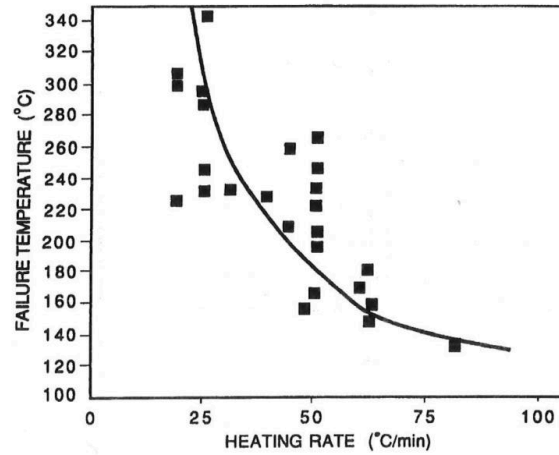


Figure 7.1 Surface temperatures at spalling for different heating rates measured by Connolly (1995). The surface temperature is always per definition higher than the temperature at the inner surface of the flake.

Without any doubt it has been proven that the addition of PP fibres in concrete reduces the amount of fire spalling, see Paper IV. An alternative explanation for the function of PP fibres is that they reduce the amount of moisture in the critical zone where the flake is formed, see Figure 7.2. This reduces the weakening effect of the presence of moisture in the critical zone. The experimental study shown in Paper V and results for fracture energy measurements conducted by Bažant and Prats (1998) together with the study performed by Lankard et al. (1971) on compressive strength confirm that the presence of moisture at high temperatures has a substantial weakening effect on cement based materials. This is a factor that needs to be included in a more detailed model or theory describing the fundamentals of fire spalling of concrete.

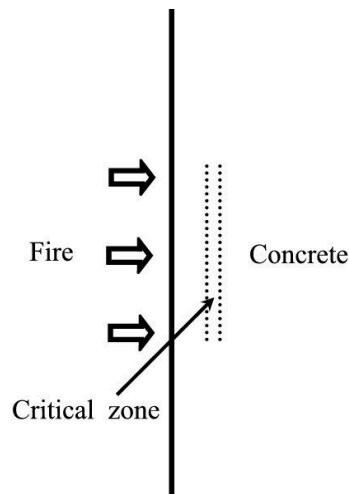


Figure 7.2 The critical zone where the crack leading to a flake is formed (Jansson, 2008).

If moisture is transported away from this zone by the PP fibre, more shrinkage and creep is also present so a local relaxation of stresses is possible. This is indicated by the plateau in thermal expansion for concrete including PP fibres at 200-250°C shown in Paper I, Paper V and by Huissman (2011) and in Figure 7.3. Obviously the experiments showing this plateau were not performed at heating rates directly equivalent to the critical zone shown in Figure 7.2 but it is highly probable that this is an important factor to properly understand the function of PP fibres in decreasing the fire spalling propensity of concrete.

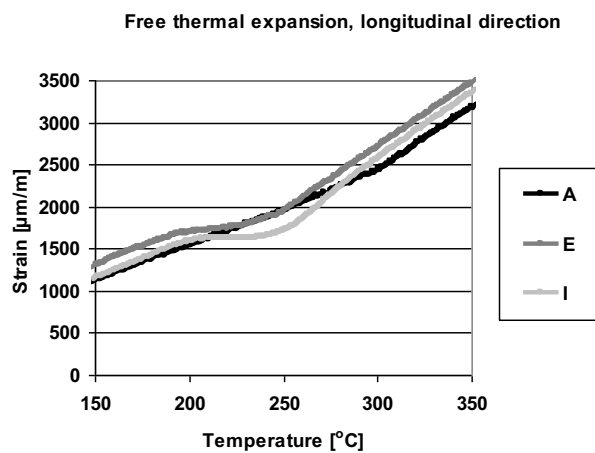


Figure 7.3 Plateau in free thermal expansion of specimens with PP fibres. A (no PP), E (1 kg/m³ PP) and I (1.5 kg/m³ PP). From Paper I.

7.4. The influence of specimen size

The influence of specimen size on the spalling behaviour has been discussed in Paper III, Paper IV and in Chapter 2. In the configurations studied, small loaded slabs did not spall to the same degree as larger loaded slabs with the same thickness and load level. This fact highlights one of the fundamentals often neglected concerning fire spalling of concrete –, it cannot and should not be treated as a material property! The influence of different boundary conditions and scaling effects has not yet been quantified. Further, the phenomenon also includes an on/off aspect that more traditional size dependent properties do not include.

During testing of slabs, the difference in spalling depth between different intensities of fire exposure is in many cases shown here low, see for example Paper III. This might be attributed to the thermally driven sagging of this type of member which counteracts the higher stresses in the surface region and leads to more intense cracking in the inner tensile region. When the spalling then proceeds into the cross-section from one side, this pre-cracking leads to higher permeability and stress relaxation, compensating for the higher thermal stresses from the more intense fire exposure. If this theory is correct, the amount of fire spalling for columns and beams exposed from two sides is more related to the fire intensity than elements that can

develop a curvature during heating. Some results from the HITECO project show the change in spalling behaviour when changing from a standard fire exposure to a more severe hydrocarbon fire exposure for columns exposed by fire from all sides (see year 1999 in the time line in Chapter 2). An experimental study performed by Felisetti et al. (2012) indicates that the phenomenon during bilateral heating is influenced by pore pressure which might be at least a part of the explanation for the apparent higher sensitivity to the heating rate for this type of cross sections.

The reason for knowing the spalling behaviour in the first place is to estimate its influence on the fire resistance of a member or, from a more global perspective, the fire resistance of the whole structure³⁰. If the scaling factor for spalling is not known between different geometries, full scale tests of fire resistance or statistics from well documented real fires are the only reliable methods for determining or estimating the fire resistance. Therefore, the development of better tools to estimate the fire resistance including the effect of fire spalling is urgently needed.

³⁰ When analysing the behaviour of whole structures during fire, redistributions of stresses might be beneficial for the fire resistance compared with single element analysis.

Chapter 8

Conclusions and further research

8.1. Conclusions

The focus of this thesis has been to achieve a better understanding of the fire spalling of concrete. This phenomenon presently limits the use of high strength and self-compacting concrete unless special attention is placed on the design of the cross-sections and mixing details of the concrete, e.g. by the addition of PP fibres in the mix. It has been shown for a post-tensioned concrete structure made of spalling sensitive concrete used for Swedish tunnels, that substantially lower amounts of PP fibres than $>2 \text{ kg/m}^3$, which is recommended in the Eurocode (1992-1-2:2004), can be used.

As part of this study, another important aspect has emerged, i.e. the large effect that the chosen test method can have on the fire spalling depths observed. Results from tests on unloaded cubes do not correspond to results seen on larger loaded slabs. None of the tested cubes spalled whereas some of the large slabs spalled to the degree that the reinforcement became fire exposed. Further, the difference in spalling depths between small and large post-tensioned slabs was shown to be substantial; although in general the ranking in severity from least to greatest spalling correlated between these two sizes. The correlation to larger specimens was vaguer in the case when the small slabs were not loaded in compression.

From a more detailed analysis of 110 fire tests performed on small slab type specimens, the spalling behaviour was shown to have good repeatability between two identical tests. This shows that the sometime mentioned random factor related to spalling was low for the chosen data set. It was also possible to make a multiple least squares fit of 14 material and test parameters that could be used to predict the spalling behaviour (within the range of the parameters), which also underlines the fact that a substantial stochastic factor was not present. A clear influence from applying an external load was also shown but the spalling depth was not sensible to the size of this load when loading up to 10 MPa.

Regarding the influence of different factors, the results compiled on the influence of ageing of SCC show that for three of the mixes the amount of spalling was reduced with age whereas

for the fourth mix (which included the highest amount of limestone filler, 140 kg/m^3) the spalling was not reduced for higher age. In this test series, which includes fire tests of 28 large slabs and 54 small slabs, no systematic influence of the intensity of the fire, between standard fire exposure and the more severe hydrocarbon fire, on the spalling depth was detected. This might be attributed to the thermal curling of this type of members which reduces the stresses in the surface region and leads to more intense cracking in the inner tensile region. When the spalling then proceeds into the cross-section this pre-cracking leads to higher permeability and stress relaxation compensates for the higher thermal stresses from the more intense fire exposure. If this theory is correct the amount of fire spalling for columns and beams fire exposed from two sides or more would be more dependent on the fire intensity than unilaterally exposed concrete members.

Pressure measurements conducted as part of the work within this thesis, supported by results from the literature, indicate that there is no simple relationship between pressure from moisture and fire spalling. Two alternative factors for explaining the function of PP fibres have been presented. In this context, PP fibres are assumed to (i) reduce the moisture content in the critical zone close to the heated surface which affects the mechanical properties advantageously, and (ii) amplify moisture movement leading to larger drying creep and shrinkage which locally relaxes the thermal stresses.

To investigate the influence of the presence of moisture on the compressive strength, specimens were tested after being boiled for varying periods of time in a water bath. The study showed a remarkable reduction of strength due to boiling of the mortar specimens. After boiling mortar in a water bath for 3, 10 or 20 minutes, i.e. approximately the same time span as the initiation of fire spalling during fully developed fires, the strength is only 64% compared to corresponding value for a dry specimen. As no strength change was detected between the specimens boiled 3, 10 or 20 minutes, and that the corresponding saturation pressure for steam at 100°C is negligible compared with the tensile strength of concrete, it was concluded that pore pressure is not a significant contributor to the measured reduction in strength. It appears that the presence of moisture is the most important factor reducing the strength.

A further aspect on the function of PP fibres was that a plateau in the free thermal expansion curve for concrete and mortar containing PP fibres was found whereas concrete without PP fibres had a continuous thermal expansion in this interval. This plateau was shown to correspond to a temperature interval just over 200°C where extended release of water was present for the mixes including PP fibres so drying shrinkage or drying creep effects seem to be components in this behaviour. The occurrence of this plateau indicates relaxing stresses in a zone close to where the crack that leads to the spalling phenomenon “surface flaking” is normally created.

8.2. Further research

The reason for the desire to know more about the fire spalling of concrete phenomenon is that it influences the fire resistance of concrete elements and in more global perspective the fire resistance of whole structures. As shown in Section 5.2 a lot of effort has been spent on different specially designed test setups for investigating different aspects of the phenomenon.

With the present knowledge the results, expressed as observed amount of spalling, from test with specially designed setups cannot be directly translated into conclusions regarding fire resistance of arbitrary concrete elements. No refined scaling system or ranking system for translating spalling results between different elements made of the same concrete exists. As fire resistance testing of elements or whole structures in most cases is expensive, it might be attractive to design a special purpose spalling index scale where different mixes can be ranked against each other. Important is then that the test setup for making this ranking should be designed to give a continuous scale, i.e. only in very special circumstances no spalling should be measured with the method. This might be achieved by using a cross-section with variation in web thickness and/or different pre-stress levels in the same specimen making one end of the specimen very sensitive to spalling during fire exposure. Then the results from this ranking should be compared with tests of different types of real elements to verify and define the area of use of this spalling index method.

In the Eurocode 1992-1-2 (2004) a moisture content limit under which spalling is not probable is given. As discussed in Section 5.3, the use of a general moisture limit is a rough assessment method. This use of a moisture limit was probably more relevant in the past when “simpler” concrete with higher permeability was more used, but today’s use of different admixtures and advanced mix design makes this method less precise. If possible, alternative general rules of thumb for “spalling safe” concrete members would be attractive to postulate in the Eurocode.

The theoretical idea, presented in Section 7.3, suggesting that the spalling behaviour of elements that cannot easily be bent during fire exposure is more influenced by the heating rate needs further investigation.

Regarding the question of the physics of the phenomenon, further effort needs to be put on measurement technique. Without refined measurement technique of relevant behaviour and material properties, a more detailed description of the real origin of fire spalling could hardly be achieved.

Chapter 9

Resume of appended papers

Paper I: Experimental Study of the Influence of Polypropylene Fibres on Material Properties and Fire Spalling of Concrete

The addition of polypropylene fibres in concrete prevents or reduces the amount of fire spalling. The mechanism, or mechanisms, leading to this reduction of spalling by PP fibres is not known in detail. However, the research presented in this paper shows that the PP fibre addition resulted in:

- reduction or prevention of fire spalling
- modification of the capillary saturation close to the surface of concrete
- the limitation of the internal destruction at moderate heating, 5°C per minute.
- modification of the drying behaviour at high temperature
- introduction of a plateau in the free thermal strain curve.

Other findings, from a limited study of material properties, indicated that concrete without PP fibres heated with a thermal shock to 600°C had twice the residual permeability as concrete heated at a heating rate of 1°C per minute to the same target temperature. The same test performed with a target temperature of 400°C did not reveal any measurable difference.

Paper II: The Influence of Pressure in the Pore System on Fire Spalling of Concrete

Moisture pressure measurements of fire exposed SCC and vibrated concrete designed for tunnel structures are presented in this paper.

In general, the highest pressures in the two test series presented were measured in the concretes that did not exhibit fire spalling, i.e., in those concrete specimens that included PP fibres. The main conclusion from the test series is that pressure in the capillary system is not the driving force for spalling under fire exposure of the investigated concretes. However, pressure is involved in the redistribution of moisture during fire exposure. As an alternative to the common theory of the function of PP fibres as “pressure releasers”, a new theory based

on aspects of the presence and movement of moisture is put forward to explain the function of PP fibres in reducing the propensity of concrete to spall. In this context, PP fibres are assumed to (i) reduce moisture content in the critical zone close to the heated surface which affects the mechanical properties advantageously, and (ii) amplify moisture movement leading to larger drying creep which locally relaxes the thermal stresses.

Paper III: Factors Influencing Fire Spalling of Self-Compacting Concrete

Results from fire tests on four different mixes of SCC with a small and a large test setup are presented in this paper. The major findings from the test series are:

- The design of test specimens affects the probability and the extent of spalling. Small slabs, $600 \times 500 \times 200 \text{ mm}^3$, loaded with post-tensioned Dywidag bars spalled substantially less compared to large slabs, $1800 \times 1200 \times 200 \text{ mm}^3$, with the same size of compressive load and the same type of loading system.
- A clear influence from applying a compressive load could be seen on the spalling sensitivity of the small slabs. The time for the first spall did not change by applying a load but the surface flaking process continued much longer in the loaded case. The reason for this is believed to be the stress release by cracks in the tensile zone inside the specimen, which is higher in unloaded concrete. This observation is in agreement with experiments made by Hertz (2003) where spalling stopped when the restraint from colder areas was lost by extensive cracking and theories postulated by Bažant (2005) where the restraint from unheated concrete is identified as an important factor.
- No effect on the amount of fire spalling was found due to the fire severity, i.e. the standard fire compared with the more severe hydrocarbon fire, could be found in the experimental study.
- The addition of PP fibres removed the risk of dangerous fire spalling for the mixtures included in the tested SCCs.
- A SCC with limestone filler content of 140 kg/m^3 spalled substantially more than a corresponding concrete without filler but identical w/c ratio and strength at 28 days.
- The tests on SCC with limestone filler content of 140 kg/m^3 and w/c ratio 0.4 did not show any sign of a reduction in spalling degree after an extended storage period. In the tests on large slabs no reduction in spalling depth was measured after 3.9 years compared with tests at the age of 0.5 year. On the small slab tests spalling depth was lower after 3 month compared with tests performed after 6–12 month.

Paper IV: Reduction of Fire Spalling of Concrete with Small Doses of Polypropylene Fibers

Results from fire tests on 26 large loaded concrete slabs made of typical Swedish tunnel concrete mixes with a w/c ratio of 0.40 showed that the spalling behaviour was greatly reduced with the addition of even small amounts of PP fibres, i.e. doses substantially under the recommended value found in the Eurocode. Compared with a concrete without fibres the addition of 0.2 kg/m^3 reduced the amount of spalling to about half; and by including 0.6 kg/m^3 or more PP fibres in the mix, the average spalling depth was reduced to less than 20 mm or in the majority of tests to zero.

Other conclusions from these test series were the following:

- The severity of fire exposure did not change the fire spalling behaviour.
- The amount of spalling was dependent on the amount of PP fibres in the mix rather than the compressive strength measured on the day of testing.
- Fire spalling results from small unloaded specimens did not correspond to results on larger loaded concrete slabs. None of the small specimens spalled whereas some of the corresponding large slabs spalled beyond the layer of reinforcement.

Paper V: Fire Spalling of Concrete

The phenomenon of fire spalling of concrete has been investigated. Experience from fire testing of concrete indicates that the following factors are of great importance for understanding the phenomenon:

- Restraint from colder parts of the structural member leads to more fire spalling
- External compressive load leads to more fire spalling
- The temperature at the surface of the flake can be $< 200^{\circ}\text{C}$ which excludes the classical pore pressure theory as the universal explanation for fire spalling.
- No correlation has been found between pore pressure and fire spalling.

It is a well-known fact that the addition of PP fibres totally hinders or significantly reduces the occurrence of fire spalling of concrete. As shown previously, this effect might be connected to the rapid loss of water and may also be related to the occurrence of a plateau detected in the free thermal strain curve. Moisture is clearly an important component in the fire spalling phenomenon but, instead of being the source of high developed stresses through saturated steam pressure, the action of water might be better explained by its impact on the strength of the concrete at elevated temperatures due to the presence of moisture. Thus, the reason for fire spalling, i.e. the opening up of cracks, at relatively low temperatures where no significant saturation pressures from steam are developed, can be explained.

To separate the effect of the presence of moisture and temperature on concrete compressive strength, tests have been performed on mortar specimens manufactured according to the standardized procedure including the use of a standardized sand quality. Results from this study show a remarkable reduction of strength by boiling the material in a water bath. If boiling mortar in 3, 10 or 20 minutes, the same as the initiation of fire spalling during fully developed fires, the strength is only 64% compared with a dry specimen. As no strength change was detected between the specimens boiled 3, 10 or 20 minutes, and that the corresponding saturation pressure for steam at 100°C is negligible compared with the tensile strength of concrete, it was concluded that pore pressure is not a significant contributor to the measured reduction in strength. It is the presence of moisture that is the most important factor.

The reduction of strength of concrete by the presence of moisture is a main factor in the fire spalling phenomenon during fire exposure from one side. Without including this effect the function of the addition of polypropylene fibres cannot be explained.

Resume of appended papers

Bibliography

Abrams M. S. and Orals D. L. (1965) “Concrete drying methods and their effect on fire resistance”, Research and Development Laboratories of the Portland Cement Association, Bulletin 181, USA.

Akhtaruzzaman A. A. and Sullivan P. J. E. (1970) “Explosive spalling of concrete exposed to high temperature”, Concrete Structures Research Report, Imperial College, Great Britain,, as cited by Malhotra H. L. (1984).

Albrektsson J. et al (2011) “Assessment of concrete structures after fire”, SP Report 2011:19, SP Technical Research Institute of Sweden, , Borås, Sweden.

Albrektsson J., Jansson R., Flansbjer M. and Lindqvist J-E. (2012) “Quantification of fire damage of concrete for tunnel applications”, Proceedings from the Fifth International Symposium on Tunnel Fire Safety and Security, March 14-16, 2012, New York, USA.

Anderberg (2005) “SS-EN 1992-1-2: Eurokod 2: Dimensionering av betongkonstruktioner – Del 1-2: Allmänna regler – Brandteknisk dimensionering”, SIS Eurokodnytt, Nr 2, (in Swedish).

Anderberg Y. (1997) “Spalling phenomena of HPC and OC”, Proceedings from the International Workshop on Fire Performance of High-Strength Concrete, NIST, February 13-14, 1997, Gaithersburg, USA.

Anderberg Y., Magnusson S. E., Pettersson O., Thelandersson S. and Wickström U. (1978) “An analytical approach to fire engineering design of concrete structures”, Paper presented at Douglas Mc Henry International Symposium on Concrete and Concrete Structures in Mexico City, October 1976, Printed in Bulletin 65, Lund Institute of Technology, Lund, Sweden.

Anderberg, Y. and Thelandersson, S. (1976) “Stress and deformation characteristics of concrete at high temperatures 2. Experimental investigation and material behavior model“, Lund institute of technology, Lund, Sweden.

Arup (2005) ”HSE- Fire resistance of concrete enclosures- Work Package 8: Spalling guidance”, Report on Job number 116718, London, United Kingdom.

ASTM E119-11a (2011) “Standard Test Methods for Fire Tests of Building Construction and Materials” West Conshohocken, Pennsylvania, United States.

Babrauskas V. (1976) “Fire endurance in buildings” PhD thesis at the University of Berkeley, USA.

Background Documents to EN 1992-1-2 (2004) “Eurocode 2: Design of concrete structures – Part 1-2: General rules – Structural fire design”, July 5, 2004.

Bibliography

Bangi M. R. (2010) "Study on Pore Pressure Spalling in Hybrid Fibre – High Strength Concrete at Elevated Temperatures" Master's Thesis No. EG-M 80□ Division of Environment and Resources Engineering Graduate School of Engineering, Hokkaido University September, Hokkaido, Japan.

Barlett F. M. & J. G. MacGregor (1994) "Assessment of concrete strength in existing structures" Structural Engineering Report No. 198, Department of Civil Engineering, University of Alberta, Canada.

Barret (1854) "On the French and other methods of constructing iron floors", Civil Engineering and Architect's Journal, Vol XVII, pp 94.

Balaz G. L., Lubloy E. & Mezei S. (2010) "Potentials in mix design to improve fire resistance", Concrete Structures, pp 67-72

Bažant, Z. P. (2005) "Concrete Creep at High Temperature and its Interaction with Fracture: Recent Progress", Concreep-7 Conference: Creep, Shrinkage and Durability of Concrete and Concrete Structures, Nantes, France, pp 449–460

Bažant Z. and Goangseup Z. (2003) "Decontamination of Radionuclides from Concrete by Microwave Heating. I: Theory" Journal of Engineering Mechanics, July 2003

Bažant Z. P. and Kaplan M. F. (1996) "Concrete at high temperatures-material properties and Mathematical models" Book published by Longman Group Limited, London, United Kingdom.

Bažant, Z.P., and Prat, P. C. (1988) "Effect of temperature and humidity on fracture energy of concrete", ACI Materials Jour. Vol 84, pp. 262–271.

Bengtsson O. (1997) "Brandpåverkade balkar med slanka tvärsnitt", SP Rapport 1997:35 Brandforsk Projekt 273-94 (in Swedish).

Bennet J., Claesson J. and Thelandersson S. (1976) "Calculations of temperature, moisture, and pressure distributions in concrete exposed to fire" Report from the Department of Mathematical Physics, Division of structural Mechanics, University of Lund, Lund, Sweden

Bentz D. B. (2000) "Fibers, Percolation and Spalling of High Performance Concrete", ACI Materials Journal, Vol 97, No 3, PP 351-359.

Betonghandbok Material (1997) "Concrete Handbook- Materials", Svensk Byggtjänst, second edition, Stockholm (in Swedish).

Boström L & Lindqvist J-E. (2006) "Investigation of damage to a bridge caused by a road tanker fire", Brandposten, No 34, Borås, Sweden, pp 28-29.

BRANDFORSK (1999) "Våldsam spjälkning av brandpåverkade betongbalkar", Official summary of a concrete project from Brandforsk (in Swedish).

Brekelmans J. W. P. M., Breunese A. and Vervuurt A. H. J. M. (2008) "Research on spalling of concrete during fire- CUR, Newcon" Report 2007-D-R1329 to 2007-D-R1332, TNO, Delft, The Netherlands, (test reports cited with permission).

Bremer F. (1967) "Multi-Layer (Double-Wall) Prestressed Concrete Pressure Vessel" Nuclear Engineering and Design, No 5, pp 183-190.

Breunese A.J., Fellingner J. H. H. (2004) "Spalling of Concrete - An Overview of Ongoing Research in the Netherlands", Workshop - Structures in Fire, Ottawa, Canada.

Chandra S., Berntsson L. And Anderberg Y. (1980) "Some Effect of Polymer Addition on the Fire Resistance of Concrete" Cement and Concrete Research vol. 10, pp. 367-375.

Coates J. (1996) "HSE warned of fire risk three years ago Chunnel: They have been told." Construction News No. 6494, December 5, 1996.

Connolly R. J. (1995) "The spalling of concrete in fires", PhD thesis, Ashton University, Birmingham, United Kingdom.

Consolazio, G. R.; McVay, M. C.; Rish, J. W. (1997) "Measurement and Prediction of Pore Pressure in Cement Mortar Subjected to Elevated Temperature", Proceedings of the International Workshop on Fire Performance of High-Strength Concrete, NIST SP 919; September 1997, pp.125-148

Copier, W.J. (1979) "Spalling of normalweight and lightweight concrete on exposure to fire", Report 24 (2), Heron, The Netherlands.

Dal Pont S., Colina H., Dupas A. and Ehrlacher A. (2005) "An experimental relationship between complete liquid saturation and violent damage in concrete submitted to high temperature", Magazine of Concrete Research, 57, No. 8, October, pp. 455–461.

Dal Pont S. Ehrlacher A. (2004) "Numerical and experimental analysis of chemical dehydration, heat and mass transfers in a concrete hollow cylinder submitted to high temperatures" International Journal of Heat and Mass Transfer Vol 47, pp 135–147

Debicki G., Hanishe F. and Delhomme F. (2012) "An experimental method for assessing the spalling sensitivity of concrete mixture submitted to high temperature" Cement & Concrete Composites, Vol 34, pp. 958–963.

Dehn F. (2004) "Temperature Behaviour of Ultra High Performance Concrete (UHPC) - A Micro Analytical Reflect", Ultra High Performance Concrete (UHPC) Proceedings of the International Symposium on Ultra High Performance Concrete, Kassel, Germany September 13-15, 2004

Diederichs U., Jumppanen U-M. & Schneider U. (1995) "High Temperature Properties and Spalling Behaviour of High Strength Concrete", Proceedings of the Fourth Weimar Workshop on High-Strength Concrete: Material Properties and Design Held at Hochschule fur Architektur und Bauwesen (HAB), Weimar, Germany, Oct. 1995

Diederichs U & Schneider U. (2007) Personal communication, September 14, 2007 during the RILEM TC HPC meeting in Wien. Technische Universität Wien, Institut für Hochbau und Technologie

Dougill J. W. (1971) “The Effects of High Temperature on the Strength of Concrete with Reference to Thermal Spalling “ PhD thesis, University of London, United Kingdom.

Dougill J. W. (1972) “Modes of failure of concrete panels exposed to high temperatures” Magazine of Concrete Research, Vol 24, No 79.

Dougill (1973) “Some observations on failure of quasi brittle materials under thermal stress” Cement and Concrete Research, Vol 3, pp. 469-474.

Dwaikat M. B., Kodur V. K. R. (2009) “ Hydrothermal model for predicting fire-induced spalling in concrete structural systems“, Fire Safety Journal, No 44, pp. 425–434.

Efnarc (2006) Specification and Guidelines for Testing of Passive Fire Protection for Concrete Tunnels Linings, March 2006.

Ehm C. & Schneider U. (1985) ”The high temperature behaviour of concrete under biaxial conditions”, Cement and concrete research. Vol. 15, pp. 27-34

EN 1363-1 (2012) Fire resistance tests – Part 1: General Requirements, Brussels, Belgium.

Felisetti R., Lo Monte F. and Pimienta P. (2012) “The influence of pore pressure on the apparent tensile strength of concrete” Proceedings of the 7th International Conference on Structures in Fire, Zürich, June 6-8, 2012.

Fellinger J. H. H. and Breunese A. J. (2005) “Evaluation of the fire test procedure for the spalling behaviour of concrete mixes” TNO Report of NewCon project, Project number 006-47110, Delft, The Netherlands

Feron C., Larive C. and Chatenoud G. (2008) “Spalling of sprayed concrete under tunnels fire conditions” Proceedings of Concrete Repair, Rehabilitation and Retrofitting II, 2nd International Conference on Concrete Repair, Rehabilitation and Retrofitting, ICCRRR-2, Cape Town, South Africa, 24-26 November, 2008

Fib (2007) “Fire Design of Concrete Structures – Materials, structures and modelling”, State-of-the-art Report, fib Working Party 4.3-1, Bulletin 38

F.I.P. (1965) “Fire resistance of prestressed concrete” Proceedings of a symposium on the fire resistance of prestressed concrete, held under the auspices of the F.I.P. Commission on Fire resistance of prestressed concrete at Braunschweig, Germany, June 1965.

Forse'n Nils Erik (1982) “A theoretical study on the fire resistance of concrete structures” SINTEF Report No: STF65 A82062, Cement and Concrete Research Institute, Norwegian Institute of Technology, 1982.

Gary, M. (1911) “Brandproben an Eisenbetongbasuten”, Deutcher Ausschlutss für Eisenbetong, Heft 11, Berlin, Germany,(in German).

Gary, M. (1916) “Brandproben an Eisenbetongbasuten”, Deutcher Ausschlutss für Eisenbetong, Heft 33, Berlin, Germany, (in German).

Gary, M. (1918) “Brandproben an Eisenbetongbasuten”, Deutcher Ausschlutss für Eisenbetong, Heft 41, Berlin, Germany”, (in German),

Gawin D, Pesavento F and Schrefler B. A. (2006) “Towards prediction of the thermal spalling risk through a multi-phase porous media model of concrete” Comput. Methods Appl. Mech. Engrg. Vol 195, pp. 5707–5729.

Ghabezloo S, Sulem, J and Saint-Marc J (2009) ”The effect of undrained heating on a fluid-saturated hardened cement paste” Cement and Concrete Research No 39, pp. 54–64.

Goangseup Z. and Bažant Z (2003) “Decontamination of Radionuclides from Concrete by Microwave Heating. II: Computations” Journal of Engineering Mechanics, July 2003

Grimberg Carl (1922) “Swenska folkets underbara öden” Book from P- A. Norstedt & Sons publishing firm, 1922, (in Swedish)

Haksever A. Ehm (1987) “Application of Biaxial Concrete Data for Bearing Members under Fire Attack”, Fire Safety Journal, No 12, , pp 109 – 119

Hammer T. A. (2006) “The use of Pore Water Pressure to Follow the Evolution from Fresh to Hardened Concrete” Proceedings of the 2nd International Symposium on Advances in Concrete through Science and Engineering, Quebec City, Canada, 11-13 September, 2006.

Hannant D. J. (1978) “Fiber Cements and Fiber Concretes” Book published by John Wiley & Sons, Ltd, United Kingdom, 1978.

Harada K., Terai T. (1996) “Heat and Mass Transfer in the Walls Subjected to Fire” Thirteenth meeting of the UJNR panel on fire research and safety, Gaithersburg, USA, March 13-20, 1996.

Harmathy, T. Z.(1965) “Effect of moisture on the fire endurance of building materials”, Moisture in Materials in Relation to Fire Tests, ASTM Special Technical Publication No. 385, pp 74-95, 1965.

Harmathy, T. Z. (1966) “Experimental Study on Moisture and Fire Endurance,” Fire Technology, Vol 2, No. 1, February 1966

Hasenjäger (1935) “Über das Verhalten des Betons und Eisenbetons im Feuer und die Ausbildung von Dehnungsfugen im Eisenbetonbau” Dissertation, Technische Hochschule Braunschweig, cited in Meyer-Ottens C. (1972) “Zur Frage der Abplatzungen an

Bibliography

Betonbauteilen aus Normalbeton bei Brandbeanspruchung”, PhD-thesis, Braunschweig, Germany, 1972.

Hedenblad G. (1993) “Moisture and Permeability of mature concrete, cement mortar and cement past”, PhD Thesis, Lund Institute of Technology, Lund, Sweden.

Hedenblad G. & Nilsson L.-O. (1985) “Degree of capillary saturation- A tool for accurate determination of the moisture content in concrete” Report TVBM-3022, Lund, Sweden, 69 pp (in Swedish)

Helsing Atlassi E. (1993) “A quantitative thermogravimetric study on the nonevaporable water in mature silica fume concrete”, PhD Thesis, Chalmers University of Technology, Göteborg, Sweden,

Henderson J. (1858) “On the methods generally adopted in Cornwall, in dressing tin and copper ores. (including plate)”, Proceedings of the Institution of Civil Engineers, Vol 17, 1858.

Hertz K. (1982) “Explosion og reststyrke af varmepåvirket silikabeton” (in Danish), Report 162, Danmarks tekniske Højskole, Lyngby, 1982.

Hertz K. (1984) “Explosion of Silica-fume Concrete” Fire Safety Journal, no 8, 1984/85

Hertz K. (1992) “Danish Investigations on Silica Fume Concretes at Elevated Temperatures” ACI Materials Journal, July-August, 1992

Hertz K. (2003) “Limits of Spalling of Fire-Exposed Concrete” Fire Safety Journal 38 (2003), pp.103-116.

Hertz K. and Sørensen L. S. (2005) “Test method for spalling of fire exposed concrete” Fire Safety Journal, No 40, pp. 466–476.

Hesselius Andreas (1698) “Dissertatio historica de Vandalis” Thesis preses J Arrhenius. Upsala Sweden, 42 pp. (in Latin)

Himmelwright A. L. A. (1906) “The San Francisco Earthquake and Fire - a brief history of the disaster, A Presentation of Facts and Resulting Phenomena, with Special Reference to the Efficiency of Building Materials Lessons of the Disaster, the Roebling construction company Fuller building, New York, USA

HITECO (1999) Final technical report HITECO (High Temperature CONcrete), Brite Euram III BRPR-CT95-0065.

Hyatt T. (1877) “Portland-cement-concrete combined with iron, as a building material, with reference to economy of metal in construction, and for security against fire in the making of roofs, floors, and walking surfaces”, Printed for private circulation, Chiswick Press, London

United Kingdom. (Reprint in ACI Publication SP-52, American Concrete Institute, Detroit, USA)

Huisman S., Weise F., Meng B., Schneider U. (2011) “Transient strain of high strength concrete at elevated temperatures and the impact of polypropylene fibers” Materials and Structures, Published online November 2, 2011.

Hull W. (1920) “Fire tests of concrete columns”, Proceedings of the Sixteenth Annual Convention, American Concrete Institute, Chicago, USA.

Høj N. P. & Tait C. (1998) “Great Belt Tunnel Repairs and Refurbishment Following a Fire” Proceeding of the 2nd International Conference on Tunnel Management, Operation and Maintenance, Seminar on Tunnel Fires, Hong Kong, China, February 16-18, 1998.

Ichikawa Y. (2000) “Predictions of pressures, heat and moisture transfer leading to spalling of concrete in fire”, PhD Thesis, Imperial College, London, Great Britain, 2000.

Ingason H. (2000) “Time temperature curves for X2000 and the Öresund trains” Report P003814, SP Technical Research Institute of Sweden, Borås, Sweden, (in Swedish),

Ingberg et al. (1925) “Fire tests of building columns” Technologic paper No. 184, U. S. Bureau of Standards, USA.

Ingle J. (1866) “Recent improvements in the application of concrete to fire-proof constructions”, London Civil Engineering and Architects’ Journal.

ISO 834-1 (1999) Fire resistance tests — Elements of building construction - Part 1: General requirements, Switzerland, (dated 1999-09-15).

Jansson R. (2008) “Material properties related to fire spalling of concrete” Licentiate Thesis. Report TVBM-3143, Lund University of Technology, Lund Sweden.

Jansson R. and Boström L. (2009) “Fire spalling – the moisture effect”, 1st International Workshop on Concrete Spalling due to Fire Exposure - From Real Life Experiences and Practical Applications to Lab-scale Investigations and Numerical Modelling, MFPA Institute Leipzig, Germany, September 3 – 5, 2009.

Jansson R. and Boström L. (2010) “The influence of pressure in the pore system on fire spalling of concrete” Fire Technology, Vol 43, No 1, pp 217-230.

Jansson R. and Boström L. (2011) “Fire Tests of Loaded Beams” Proceedings from the 2nd International RILEM Workshop on Concrete Spalling due to Fire Exposure, October 5-7, 2011, Delft, The Netherlands.

Jansson R. and Boström L. (2012) “Determination of fire spalling of concrete – relevance of different test methods” Proceedings from the 7th International Conference on Structures in Fire, M. Fontana, A. Frangi, M. Knobloch (Eds.), Zurich, Switzerland, June 6-8, 2012.

Jansson R. and Ödeen K. (2011) “Fire in Storehouse 6 in the Free Port of Stockholm” Proceedings from the 2nd International RILEM Workshop on Concrete Spalling due to Fire Exposure, October 5-7, 2011, Delft , The Netherlands.

Johansson L. (1974) “Flame cleaning of concrete”, Report 7424, Swedish Cement and Concrete Research Institute, (in Swedish).

Kalifa and Sallee (1998) “Moisture and temperature distribution in a specimen heated on one face” TASK 2.3: Final report Brite Euram III – HITECO programme BE-95-1158, 1998

Kalifa P., Chene G and Galle C. (2001) “High-temperature behaviour of HPC with polypropylene fibres - From spalling to microstructure” Cement and Concrete Research, no 31 (2001) 1487–1499

Kalifa P., Menneteau F-D, Quenard D. (2000) “Spalling and pore pressure in HPC at high temperatures” Cement and Concrete Research, No 30 pp 1915-1927.

Khoylou N. (1997) “Modelling of moisture migration and spalling behaviour in non-uniformly heated concrete”, PhD thesis, University of London, London, United Kingdom.

Khoury G. (2000) “Effect of fire on concrete and concrete structures” Progress in Structural Engineering and Materials Volume 2, Issue 4, pp 429–447.

Khoury G. (2005) ”Spalling Review- Types, Assessment and Prevention” UPTUN report WP 4, Project GRD1-2001-40739, 5th Framework Programme of the European Union Competitive and Sustainable Growth.

Khoury G. (2006) ” Tunnel Concrete under fire: Part 1 - Explosive spalling”, Concrete, November 2006

Khoury G. (2008) ”Polypropylene fibres in heated concrete. Part 2: Pressure relief mechanisms and modelling criteria” Magazine of Concrete Research, Vol 60, No. 3, April, pp.189–204.

Khoury G. (2008b) “Concrete spalling assessment methodologies and polypropylene fibre toxicity analysis in tunnel fires” Structural Concrete , Vol 9, No 1, pp 11-18.

Khoury G. and Anderberg Y. (2000) “Concrete spalling review”, Report submitted to the Swedish National Road Administration, Borlänge, Sweden.

Khoury G. and Willoughby B. (2008) ”Polypropylene fibres in heated concrete. Part 1: Molecular structure and materials behaviour” Magazine of Concrete Research, Vol 60, No. 2, March, pp.125–136

Kordina K. (1965) “Fire resistance of prestressed concrete” Proceedings of a symposium on the fire resistance of prestressed concrete, held under the auspices of the F.I.P. Commission on Fire resistance of prestressed concrete at Braunschweig, Germany.

Korzen M., Rodrigues J. P. And Laim L. M. S. (2013) “Fire resistance tests on circular concrete columns” Proceedings of the 13th international Fire science and Engineering Conference Interflam, London, UK.

Kristiansen F., Hertz K. and Schiøt Sørensen L. (2003) “Explosiv avskalning av betong- Nyutvecklad prövningsmetod” Rapport BYG-DTU R-05, Danmarks Tekniske Universitet, 2003, Lyngby, Denmark, (in Danish).

Kusterle W. et al. (2004) “Brandbeständigkeit von Faser-, Stahl- und Spannbeton“ Bundesministerium für Verkehr, Innovation und Technologie in Zusammenarbeit mit der Eisenbahn – Hochleistungsstrecken AG. Stressenforschung. Heft 544. ISSN 0379-1491. Bundesstrassensverwaltung, Vienna, Austria, 221 pp.

Lankard DR, Birkimer DL, Fondriest FF, Snyder MJ (1971) “Effects of moisture content on the structural properties of portland cement concrete exposed to 500 F”. ACI Special Publication SP 25, Detroit, USA.

Larbi, J. A. and Polder, R. B (2007) “Effects of polypropylene fibres in concrete: Microstructure after fire testing and chloride migration”, HERON 52 (4). pp 289-306.

Lauriello P. L. (1974) “Application of a Convective Heat Source to the Thermal Fracturing of Rock” International Journal of Rock Mechanics and Mining Sciences & Geomechanics Abstracts, Vol. 11, pp. 75-81.

Lea F. C. (1920) “The effect of temperature on some of the properties of materials”. Engineering, August 1920, pp. 293-298

Lennon T. (2004) “Fire safety of concrete structures: Background to BS 8110 fire design” BRE Report 468.

Lin T. D. Et al. (1992) “Fire Resistance of Reinforced Concrete Columns” Bulletin RD101B PCA Research and Development. Skokie, USA.

Lindblad Å., Pettersson O., Schmidt B. and Ödeen K. (1966) “Fire in storehouse 6 in the free port of Stockholm”, Väg- och vattenbyggaren, No 12, (in Swedish)

Liu X., Ye G., De Shutter G., Yuan Y. and Taerwe L. (2008) “On the mechanism of polypropylene fibres in preventing fire spalling in self-compacting and high-performance cement paste” Cement and Concrete Research 38 pp. 487-499

Long W. G. & Moeller H. H. (1983) “Rapid Fire Refractories” United State Patent 4,419,451, December 6, 1983.

Lord Viscount Mahone (1778) “Description of the most effectual method of securing buildings against fire, invented by Charles Lord Viscount Mahon, F. R. S.” Philosophical Transactions of the Royal Society of London, Vol 68, pp 884-890

Magnusson and Thelandersson (1970) “Temperature –time curves of complete process of fire development. Theoretical study of wood fuel fires in enclosed spaces” Acta Polytechnica Scandinavia civil engineering and building construction series, No 65, Stockholm, Sweden.

Malhotra H. L. (1974) “Determination of flame spread and fire resistance” Building Research Establishment, CP 72/74, July 1974, United Kingdom.

Malhotra H. L. (1984) “Spalling of concrete in fires”, Technical note 118, CIRA, London, UK.

Matesova D., Bonet D., Shah S. P. (2006) ” Factors affecting the resistance of cementitious materials at high temperatures and medium[0] heating rates” Materials and Structures, Vol 39:4 ,pp. 919–935.

Majorana C. E., Salomoni V. A., Mazzucco G. and Khoury G. (2009)” An approach for modelling concrete spalling in finite strains” Mathematics and Computers in Simulation, published online, 2009

Meyer-Ottens C. (1972), “Zur Frage der Abplatzungen an Betonbauteilen aus Normalbeton bei Brandbeanspruchung“, PhD-thesis, Braunschweig, Germany.

Miller R. P. (1905) Contribution to the discussion at the end of the report “Investigation of the Effect of Heat Upon the Crushing Strength and Elastic Properties of Concrete” by Ira Woolson, Proceedings of the American Society for Testing Materials, Philadelphia, USA.

Mindeguia J-C. (2009) “Contribution Experimentale a la Comprehension des Risques D’instabilite Thermique de Betons“, PhD thesis, Université de Pau et des pays de l’Adour, France

Mindeguia J-C., Pimienta P., Carre H., La Borderie C. (2009) “Experimental study on the Contribution of Pore Vapour Pressure to the Thermal Instability Risk of Concrete”, Proceedings of the 1st international Workshop of Concrete Spalling due to Fire Exposure, Leipzig, 2009.

Nekrasov K. D., Zhukov V. V. and Shevchenko V. I. (1967) “Investigation of Heating Large Blocks of Refractory Concrete From One Side” Refractories and Industrial Ceramics Volume 8, Nos. 5-6 / May

Neville A. M. (1996) “Properties of Concrete” Fourth and Final Edition, John Wiley & Sons, Inc, Essex, United Kingdom.

Nilsson L-O. (1980) “Hygroscopic Moisture in Concrete – Drying, Measurements & Related Material Properties”, PhD thesis, University of Lund, Lund, Sweden.

Ongah R. et al (2002) “Fire performance of high strength reinforced concrete walls“ Advances in Mechanics of Structures and Materials, Proceedings of the 17th Australasian Conference on the Mechanics of Structures and Materials, ACMSM 17, Gold Coast, Queensland, June 12-14, 2002, pp.199-204.

Ozawa M., Iizuka T., Rokugo K. and Morimoto H. (2009) "Relationship Between Spalling Behaviour and Internal Vapour Pressure of High-Strength Concrete Reinforced with Natural Fibre Under High Temperature" Proceedings of the 1st international Workshop of Concrete Spalling due to Fire Exposure, Leipzig, 2009.

Persson B. (2004) "Fire resistance of self-compacting concrete, SCC" Materials and Structures, Vol. 37, November 2004, pp 575-584.

Petrov-Denisov V.G., Maslennikov L.A. and Pitckob A.M. (1972) "Heat- and moisture transport during drying and first heating of heat resistant concrete. Concrete and Reinforced Concrete 1972;2: 17-8 (In Russian). as cited by **Hertz (2003)**

Pettersson O. (1971) "The possibilities of predicting the fire behaviour of structures on the basis of data from standard fire resistance tests" Bulletin 20, Lund Institute of Technology, Lund, Sweden.

Pettersson O. And Magnusson S. E. (1977) "Fire test methods – background, philosophy, development trends and future needs" Nordtest doc gen 011, January, 1977

Phan L. T. (2008) "Pore pressure and explosive spalling in concrete" Materials and Structures Vol 41, pp 1623-1632.

Preston F. W., White H. E. (1934) "Observations on spalling" Journal of the American Ceramic Society, Volume 17, Issue 1-12, pp 137-144.

Pihlajavaara (1964) "On the interrelation of the moisture content and strength of mature concrete and its reversibility" Report from the State Institute for Technical Research, Finland.

Pistol K, Weise F., Meng B. and Schneider U. (2011) "The mode of action of polypropylene fibres in high performance concrete at high temperature" Proceedings of the 2nd International RILEM Workshop on Concrete Spalling due to Fire Exposure, Delft, The Netherlands, October 5-7, 2011.

Popovics S. (1998) "Strength and related properties of concrete – A quantitative approach" Book published by John Wiley & Sons Inc., USA, 1998.

"Red Books" of the fire prevention committee No 80 (1904) The first quinquennial report issued by the executive of the British fire prevention committee, London, United Kingdom.

Richardson A., Dave U. V. (2008) "The effect of polypropylene fibres within concrete with regard to fire performance in structures" Structural Survey Vol. 26 No. 5, pp. 435-444.

Saito H. (1965) "Explosive spalling of prestressed concrete in fire" Fire resistance of prestressed concrete; proceedings of a symposium on the fire resistance of prestressed concrete, held under the auspices of the F.I.P. Commission on Fire resistance of prestressed concrete at Braunschweig, Germany, June 1965.

Bibliography

Sanjayan G. & Stocks L. J. (1993) "Spalling of High-Strength Silica Fume Concrete in Fire" *ACI Materials Journal*, Vol 90, Issue 2, pp 170-173..

Sarvaranta L. (1995) "Fiber cement mortar composites under thermal exposure" PhD Thesis, Tampere University of Technology, Tampere, Finland.

Schneider U., Alonso M. C., Pimienta P. and Jansson R. (2010) "Physical Properties and Behaviour of High Performance Concrete at High Temperature" *Proceedings of the Sixth International Conference on Structure in Fire*, Michigan State University, USA

Schneider U., Ehm C. and Diederichs U. (1983) "The behaviour of concrete under attack of liquid steel" *Proceedings of the SMiRT 7 Conference*, Chicago, IL, USA, August 22-26, 1983.

Schneider U., Herbst H. J.(1989) "Pressure Development in Heated Concrete Members" *Proceedings of the SMiRT 10 Conference* Anaheim, CA USA August 14-18, 1989.

Schneider U. and Horvath J. (2003) "Behaviour of ordinary concrete at high temperature " Heft 9, Technical University of Vienna, Austria.

Sertmehmetoglu Y. (1977) "On a mechanism of spalling of concrete under fire conditions" PhD thesis, University of London, King's College, United Kingdom.

Shekarchi M., Debicki G., Billard Y. and Coudert L. (2003) "Heat and Mass Transfer of High Performance Concrete for Reactor Containment Under Severe Accident Conditions" *Fire Technology*, Vol 39, pp 63–71.

Shorter G. W. & Harmathy T. Z. (1961) Discussion on the article "The fire resistance of concrete beams" by Ashton and Bate, *Proceedings, Institute of Civil Engineers*, Vol. 20, p. 313.

Shuttleworth (1997) "Fire performance of concrete for tunnel linings", Channel Tunnel Rail Link Technical Report, Arup as cited in the report Arup Group Ltd, Fire resistance of concrete enclosures, Work Package 2: Spalling categories, report for the Nuclear Safety Directorate of the Health and Safety Executive, October 2005.

Silfwerbrand J. (2011) "Swedish Recommendations for Preventing Fire Spalling in Concrete Structures for Civil Engineering Purposes" *Proceedings from the 2nd 22 International Workshop 23 on Concrete due to Fire Exposure*, 5-7 October 2011, Delft, The Netherlands.

Slowik V., Schmidt M., Fritzsche R. (2008) "Capillary pressure in fresh cement-based materials and identification of the air entry value" *Cement & Concrete Composites* Vol 30, No 7, pp.- 557–565.

Suhaendi S. L. (2007) "Properties of fiber reinforced high strength concrete under high temperature conditions" PhD thesis, Hokkaido University, Hokkaido, Japan.

Suhaendi S. L., Huriguchi T, Shimura K. (2008) “Effect of polypropylene fibre geometry on explosive spalling mitigation in high strength concrete under elevated temperature conditions”, Concrete for Fire Engineering - Proceeding of the International Conference held at the University of Dundee, Scotland, UK, July 10, 2008.

Sullivan P. J. E. (2004) “A probabilistic method of testing for the assessment of deterioration and explosive spalling of high strength concrete beams in flexure at high temperature” Cement & Concrete Composites 26, pp155–162.

Sundius N. (1931) “Investigation of fire exposed concrete by microscopy” Betong, No 2, 1931, (in Swedish).

Swedish Concrete Association (2004) “Preliminary guidelines for avoiding fire spalling in fire exposed concrete structures” Betong, May, 2004, (in Swedish).

Swedish Tariff Association (1959) “Concrete and Fire” (in Swedish), A book published by the Swedish Tariff Association, Stockholm, Sweden.

Sönnerberg S. (1952) “The fight against fire” (in Swedish), A book published by Berneces Förlag AB, Malmö, Sweden.

Tait & Høj (1996) “Storebaelt Eastern Railway Tunnel: Dania Tunnel Boring Machine Fire-Analysis and Recovery”, Proceedings of the Institution of Civil Engineers, Supplement to Civil Engineering, Vol 114, Special issue 1.

Tanibe T, Ozawa M., Lustoza D. R. Kikushi K., and Morimoto H. (2011) “Explosive spalling behavior of restrained concrete in the event of fire” Proceedings of the 2nd International RILEM Workshop on Concrete Spalling due to Fire Exposure, Delft, The Netherlands. 5-7 October 2011.

Thelandersson S. (1974) “Mechanical Behavior of Concrete Under Torsional Loading at Transient, High-Temperature Conditions” Bulletin 46, University of Lund, Lund, Sweden.

Thelandersson S. (1974 b) “Concrete constructions at high temperatures -an overview” VAST, September (in Swedish).

Thomas F. G.& Webster C. T., (1953) “The fire resistance of reinforced concrete columns”, National Building Studies Research Paper 18, Building Research Station, London, United Kingdom.

Trafikministeriet (1995) “Sikkerhet ved Transport gennem Storebealtstunnelen” Official report from Trafikministeriet, Denmark, (in Danish).

Ulm F.J, Acker P., Levy M. (1999) “The "Chunnel" Fire. 2: Analysis of Concrete Damage” Journal of Engineering Mechanics, March 1999, pp 283-289.

Bibliography

van Acker P. (2004) “Research versus industry”, Proceedings from the fib Task Group 4.3 workshop “Fire Design of Concrete Structures: What now? What next?”, Milan, Italy, December 2-3, 2004.

van der Heijden G. (2011) “NMR imaging of moisture inside heated porous building materials” PhD thesis, Eindhoven University of Technology, Eindhoven The Netherlands, 2011

Van Keulen J. (1974) “Comparison of heat transfer in several wall furnaces” TNO Report No BVI-74-17, 1974, as cited in **Kristiansson C. and Paulsen O. (1977)** “Calibration of fire test furnaces” SP Report 1977:1, SP Technical Research Institute of Sweden, Borås, Sweden.

Vickers E. F. (1974) “The fire endurance of reinforced concrete Structures” MSc thesis, McMaster University, Hamilton , Ontario, Canada.

Waubke N. V. (1966) “Transportphänomene in Betonporen“, Dissertation, Technische Universität Braunschweig, Germany, (in German).

Waubke N. V. and Schneider U. (1973) ”Tensile stress in concrete due to fast vapour flow“, Proceedings of the international RILEM symposium “Pore Structure and Properties of Materials”, Prague, September, 1973.

Weigler M. and Fischer R. (1968) “Betong bei temperature von 100°C bis 750°C” Beton, 2, February, as cited by **Thelandersson S. (1974 b)**

Wikström U. (1986) “A proposal regarding temperature measurements in fire test furnaces”, SP Report, 1986:17, SP Technical Research Institute of Sweden, Borås, Sweden.

Wickström E. (2010) “Joakim Albrektsson’s PhD project: concrete exposed to fire” in the English edition of Brandposten No 41.

Wierig H. J. (1963) ” Das Verhalten von Betonwaren und Stahlbetonfertigteilen im Feuer” Betonstein-Zeitung, 29 (8): 395-407; (9): 443-451; (10): 503-510, 1963: translated to English by National Research Council of Canada, Technical Translation 1317.

Willam K., Xi Y., Lee K. and Kim B. (2009) ”Thermal response of reinforced concrete structures in nuclear power plants” Report SESM No. 02-2009, University of Colorado at Boulder, Boulder, USA.

Woolson I. (1905) “Investigation of the Effect of Heat Upon the Crushing Strength and Elastic Properties of Concrete”, Proceedings of the American Society for Testing Materials, Philadelphia, USA.

Woolson I. (1918) “Fire in a reinforced concrete warehouse at Far Rockaway, New York, U.S.A” RED BOOKS of the British Fire Prevention Committee, No. 21.

Yanko W. A. (2004) “Experimental and numerical evaluation of concrete spalling during extreme thermal loading” PhD Thesis, University of Florida, Gainesville, USA.

Zhao and Sanjayan (2010) "Test method for concrete spalling using small electric furnace" Fire and Materials. 2010; 34: pp.189–201.

Zheng W. Z. et al. (2010) "Experimental study on concrete spalling in prestressed slabs subjected to fire", Fire Safety Journal no 45, (2010) pp. 283–297.

Zhukov V. V. (1976) "Reasons of Explosive Spalling of Concrete by Fire", Beton Zhelezobeton (Concrete and Reinforcement Concrete), No. 3, 1976

Ödeen K. (1963) "Theoretical study of fire characteristics in enclosed spaces" Bulletin 10, Division of building construction, Royal Institute of Technology, Stockholm, Sweden.

Ödeen K. (1970) "Standard fire endurance tests- Discussion, criticism and alternatives" Fire test performance – American Society for Testing and Materials, Special technical publication 464, Philadelphia, USA.

Ödeen & Nordström (1972) "Thermal properties for concrete at high temperatures" Cement och Beton, 1972:1,(in Swedish).

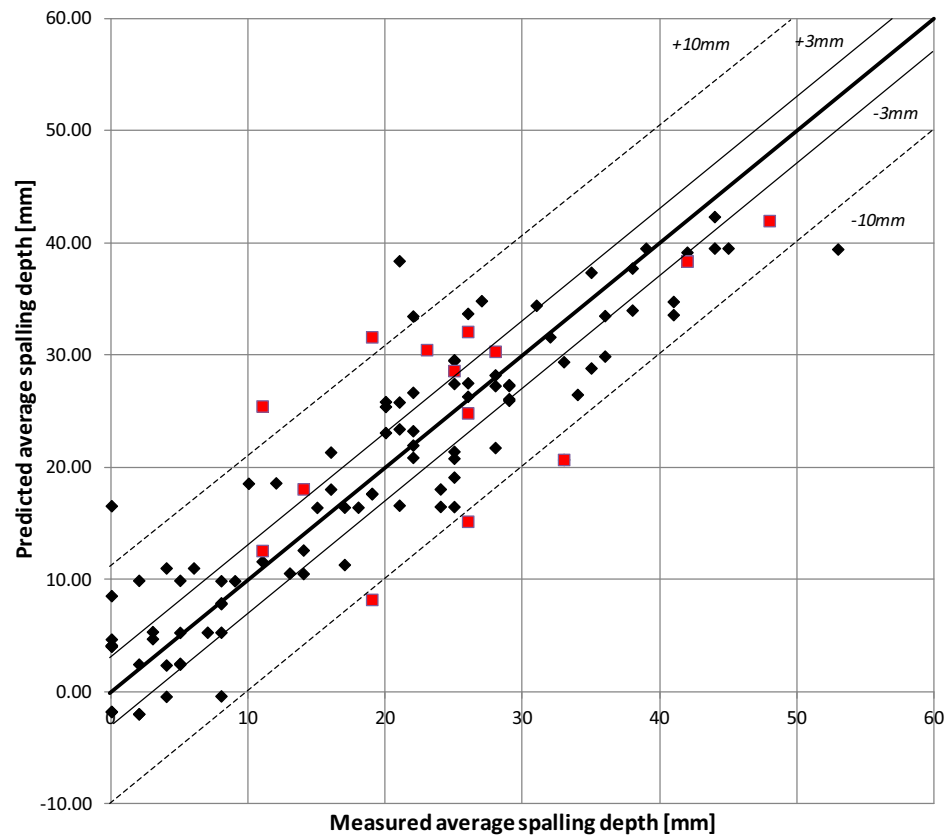
Bibliography

Appendix

Details of statistical test

This section includes 10 statistical tests on the 110 tests analysed in Chapter 2.3. In each test 15 random tests taken out from the analysis then predicted based on the analysis of the remaining 95 test. This was done to assure that the chosen method was sound.

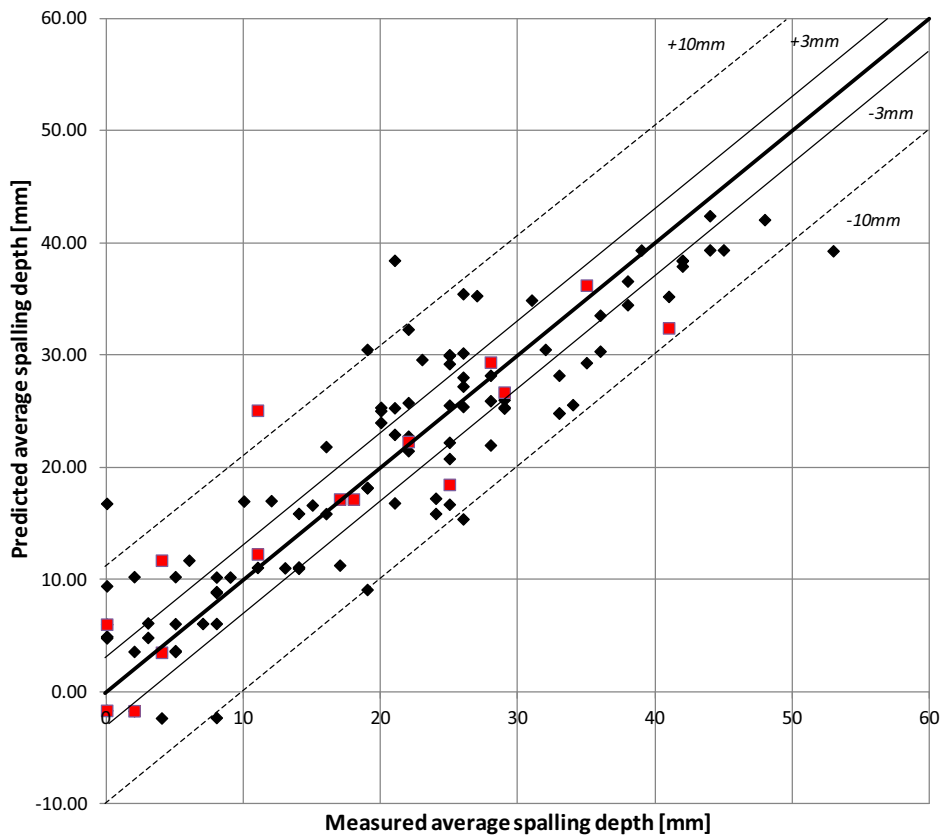
Statistical test 1



$r^2=0.84$,

Model based on 95 fire tests and predicting the results from 15 tests randomly chosen from the original 110 tests. Predicted tests, not included in the calculation of the model, marked with red squares. This prediction was deviating in average 6.7 mm with the largest error 14.4mm.

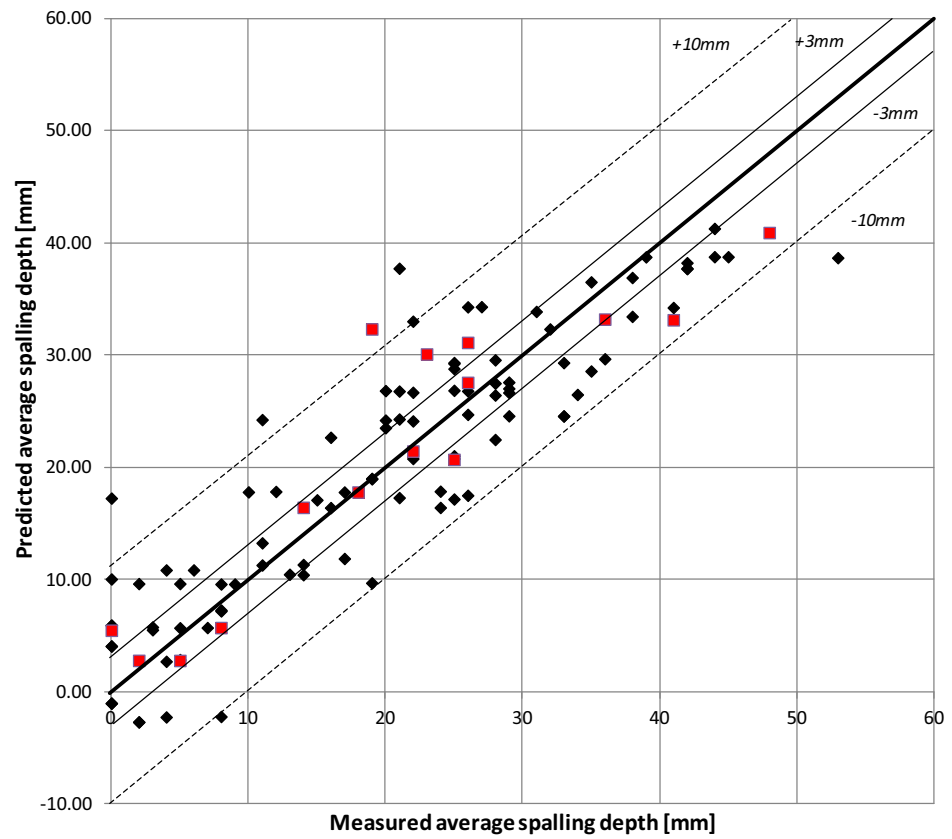
Statistical test 2



$$r^2=0.81,$$

Model based on 95 fire tests and predicting the results from 15 tests randomly chosen from the original 110 tests. Predicted tests, not included in the calculation of the model, marked with red squares. This prediction was deviating in average 3.8 mm with the largest error 14.1mm.

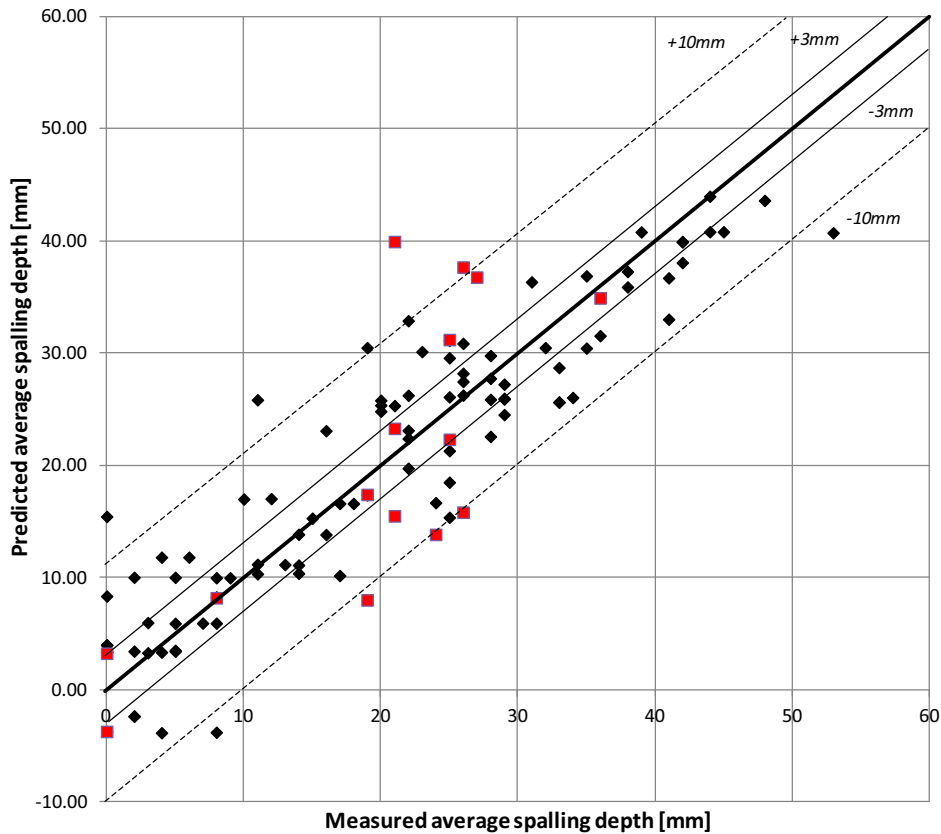
Statistical test 3



$r^2=0.81$,

Model based on 95 fire tests and predicting the results from 15 tests randomly chosen from the original 110 tests. Predicted tests, not included in the calculation of the model, marked with red squares. This prediction was deviating in average 4.2 mm with the largest error 13.3mm.

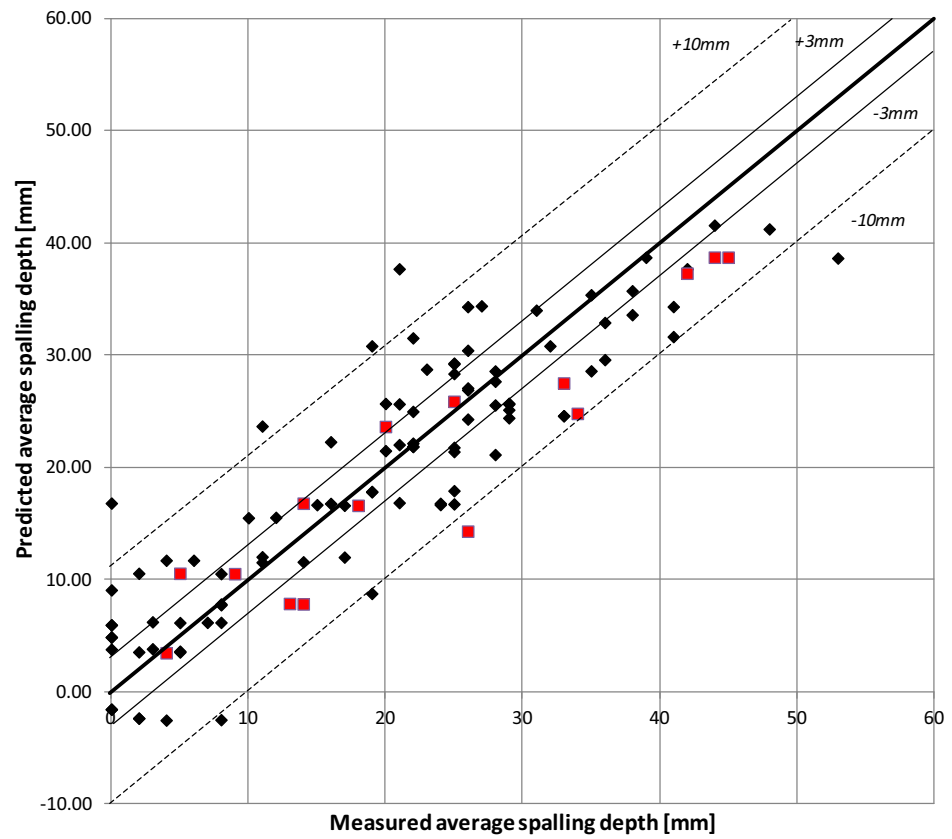
Statistical test 4



$r^2=0.85,$

Model based on 95 fire tests and predicting the results from 15 tests randomly chosen from the original 110 tests. Predicted tests, not included in the calculation of the model, marked with red squares. This prediction was deviating in average 6.5 mm with the largest error 19.0mm.

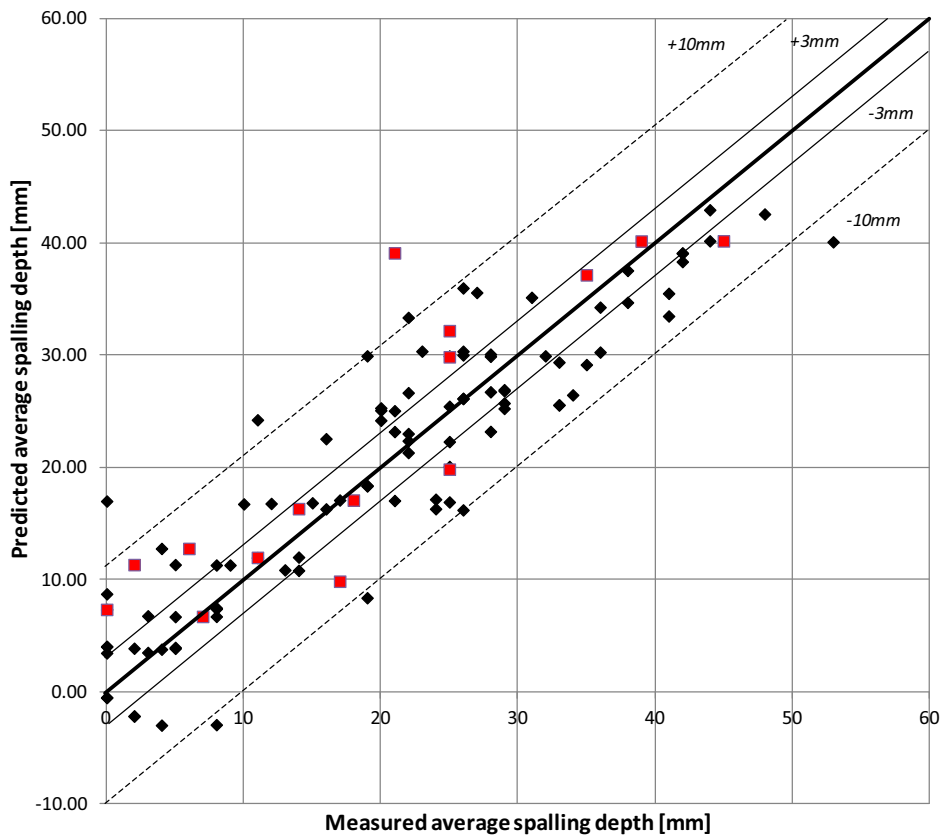
Statistical test 5



$r^2=0.81$,

Model based on 95 fire tests and predicting the results from 15 tests randomly chosen from the original 110 tests. Predicted tests, not included in the calculation of the model, marked with red squares. This prediction was deviating in average 4.7 mm with the largest error 11.7mm.

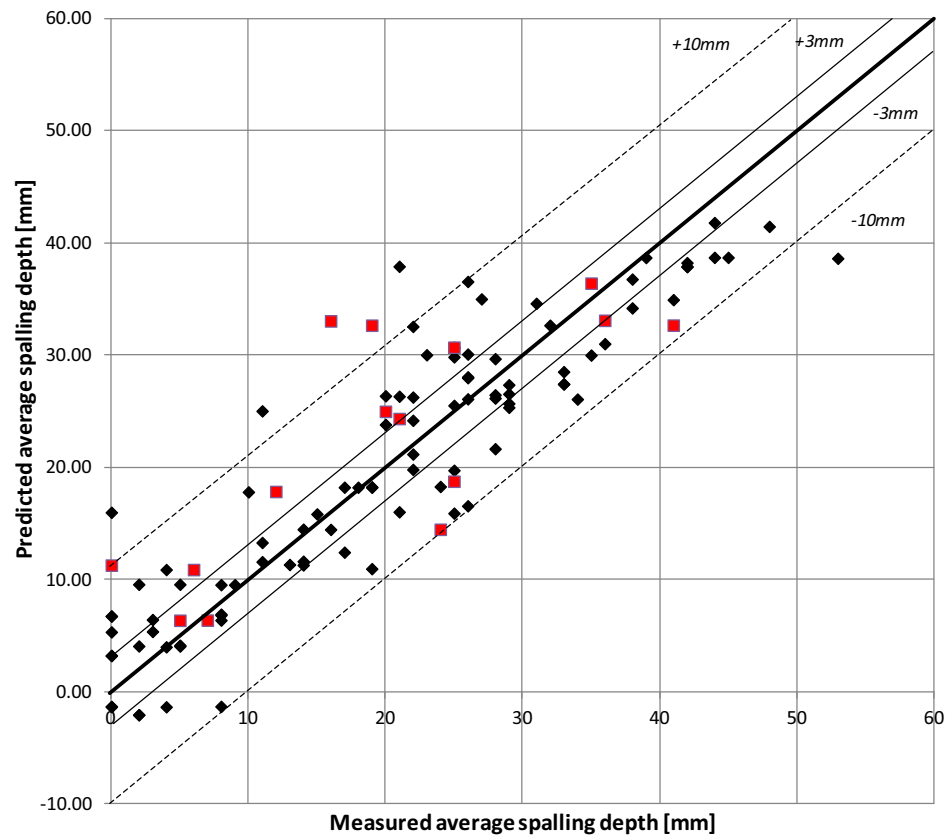
Statistical test 6



$r^2=0.81$,

Model based on 95 fire tests and predicting the results from 15 tests randomly chosen from the original 110 tests. Predicted tests, not included in the calculation of the model, marked with red squares. This prediction was deviating in average 5.2 mm with the largest error 18.1mm.

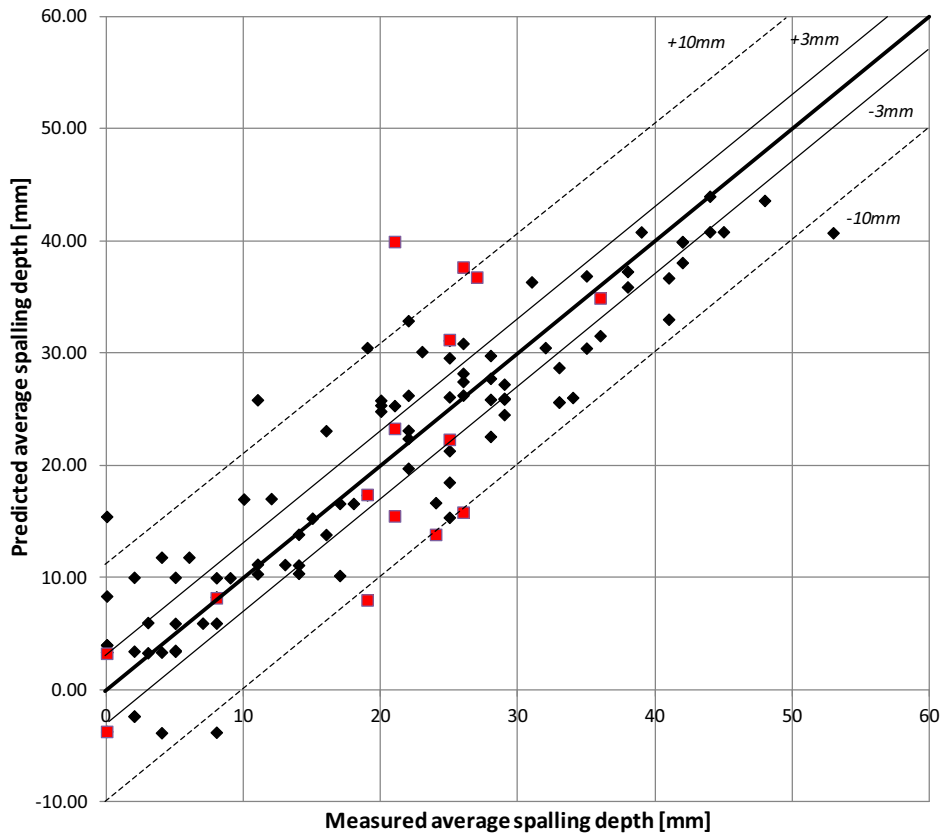
Statistical test 7



$r^2=0.83$,

Model based on 95 fire tests and predicting the results from 15 tests randomly chosen from the original 110 tests. Predicted tests, not included in the calculation of the model, marked with red squares. This prediction was deviating in average 6.5 mm with the largest error 17.1mm.

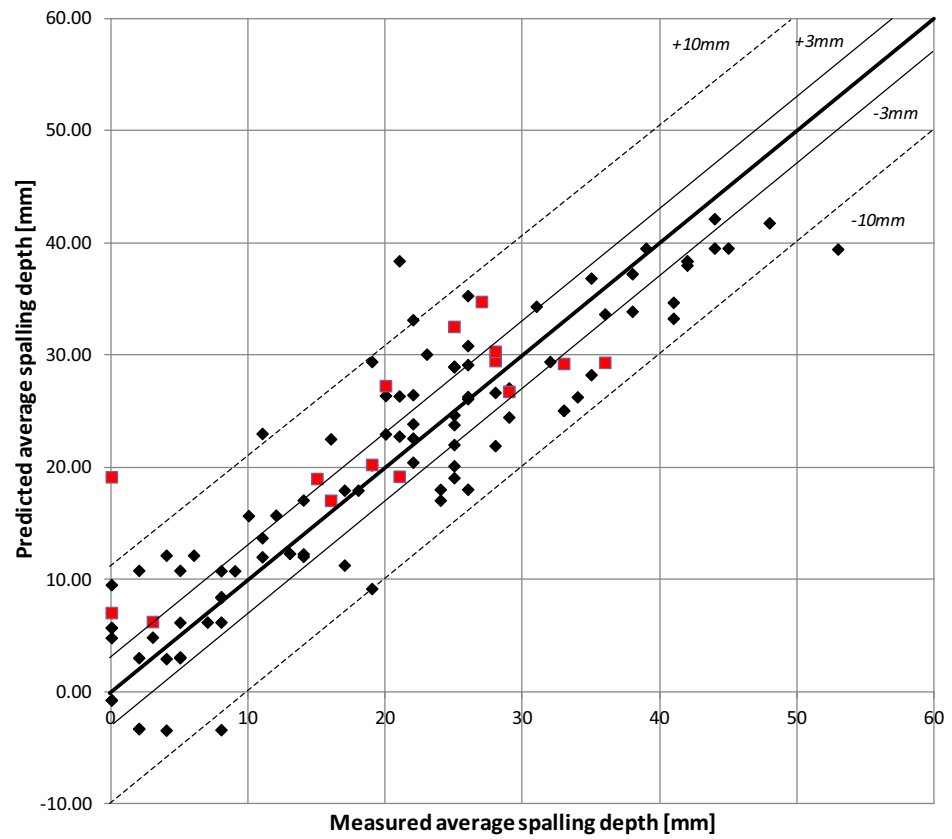
Statistical test 8



$$r^2=0.85,$$

Model based on 95 fire tests and predicting the results from 15 tests randomly chosen from the original 110 tests. Predicted tests, not included in the calculation of the model, marked with red squares. This prediction was deviating in average 6.6 mm with the largest error 19.0mm.

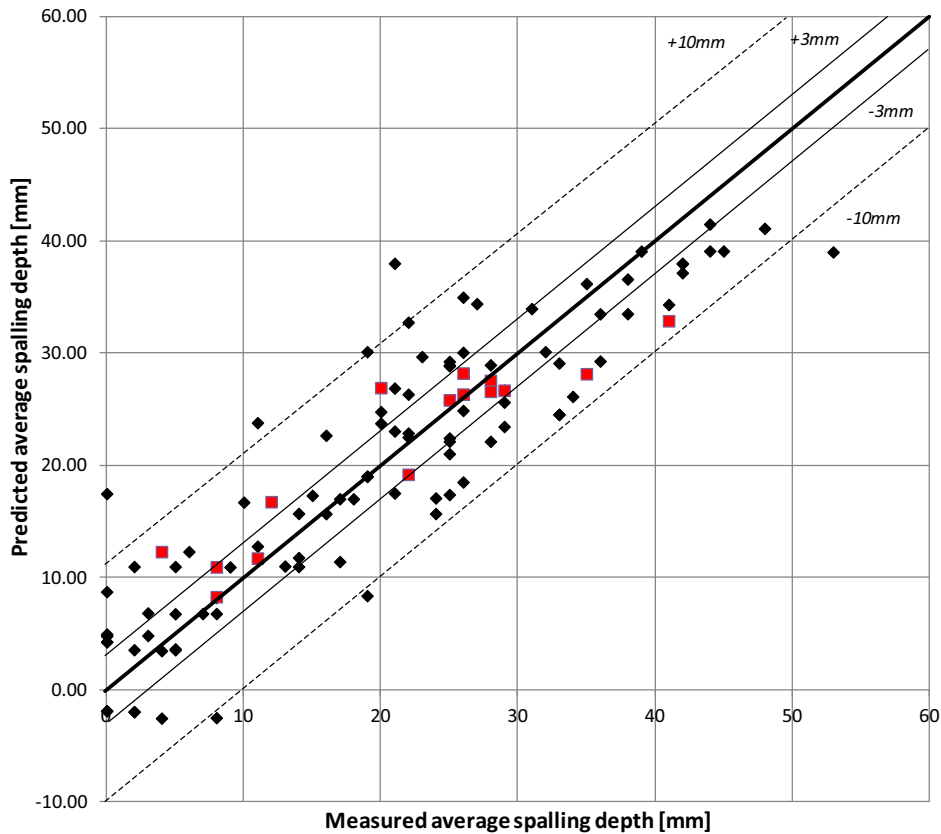
Statistical test 9



$r^2=0.83$,

Model based on 95 fire tests and predicting the results from 15 tests randomly chosen from the original 110 tests. Predicted tests, not included in the calculation of the model, marked with red squares. This prediction was deviating in average 5.1 mm with the largest error 19.2mm.

Statistical test 10



$$r^2=0.81,$$

Model based on 95 fire tests and predicting the results from 15 tests randomly chosen from the original 110 tests. Predicted tests, not included in the calculation of the model, marked with red squares. This prediction was deviating in average 3.3 mm with the largest error 8.3mm.

Details of statistical test

TRITA-BKN. Bulletin 117, 2013

ISSN 1103-4270

ISRN KTH/BKN/B—117--SE