



Proceedings of the  
**International Fire Safety**  
**Symposium 2015**

**Organizers:**

**cib - International Council for Research and  
Innovation in Building Construction**

**UC - University of Coimbra**

**albrasci - Luso-Brazilian Association for Fire Safety**

**Editors:**

**João Paulo C. Rodrigues**

**George V. Hadjisophocleous**

**Luís M. Laím**

**Hélder D. Craveiro**

**Coimbra, 20-22 April, 2015  
Portugal**

# **Proceedings of the International Fire Safety Symposium 2015**

## **Organizers:**

CIB - International Council for Research and Innovation in Building Construction  
UC - University of Coimbra  
ALBRASCI - Luso-Brazilian Association for Fire Safety

## **Authors:**

João Paulo C. Rodrigues  
George V. Hadjisophocleous  
Luís M. Laím  
Hélder D. Craveiro

**Proceedings of the International Fire Safety Symposium 2015**

held at the Department of Civil Engineering of the University of Coimbra, Portugal  
20<sup>th</sup>-22<sup>nd</sup> April 2015

ISBN 978-989-98435-5-4

ISSN 2412-2629

A Symposium organised by



International Council  
for Research and Innovation in  
Building and Construction  
([www.cibworld.nl](http://www.cibworld.nl))

• U



C •

University of Coimbra  
([www.uc.pt](http://www.uc.pt))



ALBRASCI  
Luso-Brazilian Association  
for Fire Safety  
(<http://www.albrasci.com>)

All rights reserved. No part of the publication may be reproduced, stored in a retrieval system, or transmitted in any form or by any means, electronic, mechanical, photocopied, recording or otherwise, without prior permission of the Publisher.

No responsibility is assumed by the Publisher for any injury and/or damage to people or property as a matter of products liability, negligence or otherwise, or from any use or operation of any methods, products, instructions or ideas contained in the materials herein.

## **Organizing Committee**

**João Paulo Correia Rodrigues, UC - University of Coimbra, Portugal (Chairman)**

Greg Baker, BRANZ, New Zealand (Co-chairman)

Cristina Calmeiro dos Santos, UC - University of Coimbra, Portugal

C.J. Walsh, Sustainable Design International Ltd., Ireland

Ehab Zalok, Carleton University, Canada

Hélder David da Silva Craveiro, UC - University of Coimbra, Portugal

Hugo Caetano, UC - University of Coimbra, Portugal

Luís Miguel dos Santos Laim, UC - University of Coimbra, Portugal

## Scientific Committee

### **George V. Hadjisophocleous, University of Carleton, Canada (Chairman)**

Ahmed Kashef, National Research Council, Canada

Ali Nadjai, University of Ulster, UK

Brian Meacham, WPI, USA

Charlie Fleishman, University of Canterbury, New Zealand

Dhionis Dhima, CSTB, France

Ehab Zalok, Carleton University, Canada

Euripidis Mistakidis, University of Volos, Greece

Frantisek Wald, Technical University of Prague, Czech Republic

George Boustras, European University of Cyprus, Cyprus

Geraldine Charreau, INTI, Argentina

Gintaris Kaklauskas, Technical University of Vilnius, Lithuania

Gordon Andrews, University of Leeds, UK

Guillermo Rein, Imperial College of London, UK

Guo-Qiang Li, Tongji University, China

Jean Marc Franssen, Liège University, Belgium

João Paulo Correia Rodrigues, University of Coimbra, Portugal

Jose Torero, The University of Queensland, Australia

Juan de Dios Rivera, Pontificia Universidad Católica de Chile

Karen Boyce, University of Ulster, UK

Kathrin Grewolls, Ingenieurbüro Für Brandschutz Grewolls, Germany

Manfred Korzen, BAM, Germany

Manuel Romero, Universidad Politecnica de Valencia, Spain

Maria Cruz Alonso – Instituto Eduardo Torroja, Spain

Paulo Vila Real, University of Aveiro, Portugal

Pierre Pimienta, CSTB, France

Pietro Gambarova, Politecnico de Milano, Italy

Raffaele Landolfo, University of Naples, Italy

Ricardo Cruz Hernandez, Universidad de Santander, Colombia

Rita Fahy, National Fire Protection Association, USA

Rosária Ono, University of São Paulo (School of Architecture), Brazil

Simo Hostikka, VTT, Finland

Sunil K. Sharma, Fire Research, Central Building Research Institute, India

Takashi Horiguchi, University of Hokkaido, Japan

Tan Kang Hai, Nanyang Technological University, Singapore

Ulf Wickstrom, Lulea University of Technology, Sweden

Ulrich Krause, University of Magdeburg, Germany

Valdir Pignatta e Silva, University of São Paulo (School of Engineering), Brazil

Venkatesh Kodur, Michigan State University, USA

Wan-ki Chow, Hong Kong Technical University

## PREFACE

On behalf of the Organising and Scientific committees, as well as the CIB W-14 Commission on Fire Safety it is our pleasure to welcome you to the International Fire Safety Symposium - IFireSS 2015, which is organised by the CIB's Commission W14-Fire Safety, ALBRASCI and University of Coimbra. The Symposium aims to contribute to the exchange of ideas and knowledge in the area of Fire Safety and assist in planning future research activities in this area.

CIB W14-Fire Safety is a Working Commission of CIB (International Council for Research and Innovation in Building & Construction) and its main objectives are:

- To create an ongoing research and innovation focus for the development of a comprehensive, coherent, rational and empirical basis for a safe and sustainable built environment, which includes fire science and engineering practices and design methodologies;
- To promote the acceptance of Fire Science and Engineering Practices, Procedures and Design Methodologies worldwide, and to encourage their use in Building and Fire Safety Legislation, Codes, Regulations and Standards;
- To provide technical input, from a Fire Science and Engineering Perspective, to other relevant CIB Working Commissions and Task Groups;
- To facilitate the transfer of state-of-the-art Fire Science and Engineering Technology at international level;
- To encourage capacity building for Fire Science and Engineering worldwide.

The Luso-Brazilian Association for Fire Safety (ALBRASCI) was established recently by Portuguese and Brazilian specialists in the area of Fire Safety to create a platform for the development of Fire Safety in Portugal and Brazil.

The University of Coimbra (UC) is a reference in higher education and research in Portugal, due to the quality of the courses taught and to the advances achieved in pure and applied research in various areas of knowledge. UC is also well-known around the World due to the research and training in Fire Safety with an MSc and PhD in the area.

The Symposium has participants from researchers around the world and covers a wide variety of research areas including: Structural Fire Safety; Mechanical and Thermal Properties of Materials; Fire Chemistry, Physics and Combustion; Fire Reaction; Fire Safety in Vehicles and Tunnels; Fire Risk Assessment; Smoke Control Systems; Firefighting and Evacuation; and Fire Regulations, Standardization and Construction Trends.

Joao Paulo C Rodrigues  
President of the Organizing Committee

George Hadjisophocleous  
President of the Scientific Committee

# CONTENTS

## FIRE SAFETY OF STRUCTURES

LOCALIZED FIRE TESTS ON THE STEEL COLUMNS FOR DIFFERENT CROSS SECTION AND CEILING CONDITIONS <i>Ali Nadjai, Sanghoon Han, Vassart Olivier and Obiala Renata</i>	3
NUMERICAL MODELS OF COLD FORMED STEEL COLUMNS MADE OF SQUARE TUBULAR SECTIONS SUBJECT TO FIRE <i>Waghner C. Rocha, Tiago A. Pires and José J.R. Silva</i>	9
SHEAR BUCKLING EVALUATION IN STEEL PLATE GIRDERS WITH NON-RIGID END POSTS SUBJECTED TO ELEVATED TEMPERATURES <i>André Reis, Nuno Lopes and Paulo Vila Real</i>	19
PARTIALLY ENCASED SECTION: STRENGTH AND STIFFNESS UNDER FIRE CONDITIONS <i>Paulo Piloto, David Almeida, A.B Ramos-Gavilán and Luís M.R. Mesquita</i>	29
RECENT APPLICATION OF EN1993-1-2 IN GERMANY <i>Martin Mensinger, Florian M. Block, Christian Maierhofer, Rudolf O. Reisch and Walter Borgogno</i>	39
TEMPERATURES IN BLIND-BOLTS CONNECTIONS TO HOLLOW AND CONCRETE FILLED TUBULAR COLUMNS <i>Ana M. Pascual and Manuel L. Romero</i>	51
EXPERIMENTAL INVESTIGATIONS ON THE THERMAL AND MECHANICAL BEHAVIOUR OF COMPOSITE COLUMNS WITH MASSIVE STEEL CORE IN FIRE <i>Peter Schaumann and Inka Kleiboemer</i>	61

FIRE BEHAVIOR OF COLD FORMED COLUMNS – EXPERIMENTAL TESTS <i>Wagner C. Rocha, José J.R. Silva, Tiago A. Pires and Leonardo M. Costa</i>	71
FIRE REACTION OF CONCRETE WITH AND WITHOUT PP FIBRES: EXPERIMENTAL ANALYSIS AND NUMERICAL SIMULATION <i>Paulo Piloto, Luís M.R. Mesquita and Carlos Balsa</i>	79
EXPERIMENTAL INVESTIGATION ON THE BEHAVIOUR OF COLD-FORMED STEEL COLUMNS SUBJECTED TO FIRE <i>Hélder D. Craveiro, João P. Rodrigues and Luís Laím</i>	89
INCLINED COAL HANDLING BRIDGE AFTER FIRE <i>Kamila Horová, Petr Hejtmánek, Slavomír Entler and František Wald</i>	99
IN-PLANE LOADED CONCRETE SLABS SUBJECTED TO FIRE: A NOVEL TEST SET-UP TO INVESTIGATE SPALLING <i>Francesco Lo Monte, Roberto Felicetti, Chiara Rossino, Alessandra Piovan and Gabriele Scaciga</i>	107
BEHAVIOR OF A STEEL-CONCRETE JOINT UNDER A ROBUSTNESS SCENARIO - INFLUENCE OF THE BEAM SPAN LENGTH AND THE BEAM AXIAL RESTRAINT <i>Cécile Haremza, Aldina Santiago and Luís Simões da Silva</i>	117
BEHAVIOUR OF UNPROTECTED AND PROTECTED CELLULAR BEAMS HAVING DIFFERENT OPENING SHAPES IN FIRE CONDITIONS <i>Ali Nadjai, Sanghoon Han, Faris Ali, Klelia Petrou, El Hadí and Ali Naili</i>	125
INFLUENCE OF HEAT AND MASS TRANSPORT ON MECHANICAL BEHAVIOUR OF TIMBER ELEMENTS IN FIRE <i>Robert Pečenko, Staffan Svensson and Tomaž Hozjan</i>	135

BOLTED TIMBER CONNECTIONS UNDER HIGH TEMPERATURES <i>Eduardo Schneid, Carolina da Rosa and Poliana Dias de Moraes</i> .....	145
PARAMETRIC STUDY ON COLD-FORMED STEEL COLUMNS MADE WITH OPEN CROSS- SECTIONS SUBJECTED TO FIRE <i>Hélder D. Craveiro, João P. Rodrigues and Luís Laím</i> .....	155
ACCURACY OF AVAILABLE ANALYTICAL MODELS FOR FIRE DESIGN OF COLD-FORMED STEEL OPEN FLEXURAL MEMBERS <i>Luís Laím, João P. Rodrigues and Hélder D. Craveiro</i> .....	165
INFLUENCE OF INDUSTRIAL FAÇADES AND TRAPEZOIDAL SHEETING ON STEEL MEMBERS WITH INTUMESCENT COATING <i>Martin Mensinger and Peter Kraus</i> .....	175
VERIFICATION OF WEB TAPERED BEAM-COLUMNS IN CASE OF FIRE USING THE GENERAL METHOD OF EUROCODE 3 <i>Carlos Couto, Pedro Duarte, Paulo Vila Real and Nuno Lopes</i> .....	185
A PARAMETRIC STUDY ON THE APPLICABILITY OF THE 500°C ISOTHERM METHOD FOR INVESTIGATING INTERACTION CURVES OF COLUMNS EXPOSED TO FIRE <i>Lijie Wang, Robby Caspeepe and Luc Taerwe</i> .....	195
FIRE RESISTANCE OF WOODEN CELLULAR SLABS WITH RECTANGULAR PERFORATIONS <i>Jorge Meireles, Elza Fonseca, Paulo Piloto and Débora Ferreira</i> .....	203
NUMERICAL EVALUATION OF THE BEHAVIOR OF PARTIALLY ENCASED COMPOSITE BEAMS IN FIRE <i>Fabio M. Rocha and Jorge M. Neto</i> .....	213

ASSESSMENT OF THE SHEAR BEHAVIOUR OF T-SHAPED CONNECTORS AT ELEVATED TEMPERATURES <i>Luís Laím and João P.C. Rodrigues</i>	223
FIRE TESTS ON SLENDER CONCRETE FILLED TUBULAR COLUMNS SUBJECTED TO LARGE ECCENTRICITIES <i>Ana Espinós, Manuel L. Romero, Enrique Serra and Vicente Albero</i>	233
THERMO-STRUCTURAL ANALYSES OF RC BEAMS IN FIRE <i>Gabriela B.M.L. Albuquerque, Valdir Pignatta Silva and João Paulo C. Rodrigues</i>	243
PARAMETERS WITH INFLUENCE ON THE BEHAVIOR OF COMPOSITE TUBULAR COLUMNS SUBJECTED TO FIRE <i>Tiago A.C. Pires, João P.C. Rodrigues and José J.R. Silva</i>	253
FIRE BEHAVIOUR OF TABIQUE WALLS <i>Alexandre Araújo, Elza Fonseca, Débora Ferreira, Paulo Piloto and Jorge Pinto</i>	263
MECHANICAL RESPONSE OF TWO-LAYERED CURVED REINFORCED CONCRETE BEAM EXPOSED TO NATURAL FIRE CONDITIONS <i>Dušan Ružić, Miran Saje, Igor Planinc, Robert Pečenko and Tomaž Hozjan</i>	271
ASSESSMENT OF THE INFLUENCE OF THE VENTILATION IN ADVANCED FIRE MODELS <i>Iolanda Del Prete, Nicola Bianco, Emidio Nigro and Giuseppe Rotondo</i>	281
<b>MECHANICAL AND THERMAL PROPERTIES OF MATERIALS</b>	
STRESS REDISTRIBUTION ALONG POST-INSTALLED REBARS UNDER NON-UNIFORM TEMPERATURE LOADING <i>Nicolas Pinoteau, Sébastien Rémond, Pierre Pimienta and Thierry Guillet</i>	293

COMPRESSIVE STRENGTH OF FIBRE CONCRETES WITH ENHANCED FIRE BEHAVIOR <i>Hugo Caetano, João P.C. Rodrigues and Armando M. Junior</i>	303
DETERMINATION OF WOOD THERMAL CONDUCTIVITY <i>Eduardo Schneid, Carolina da Rosa and Poliana D. Moraes</i>	313
ULTRASONOGRAPHY APPLIED TO DETERMINE THE CONCRETE RESISTANCE UNDER A FIRE CONDITION <i>Armando L.M. Junior, Nádia S. Veiga, Carolina A.N. Alvim, André A. Garcia, Maria C.D. Relvas and Rafaela Montefusco</i>	321
FIRE BEHAVIOUR OF LIGHTWEIGHT CONCRETE UNITS BASED ON CORN COB AGGREGATE <i>Nuno Alves, Paulo Piloto, Elza Fonseca, Luísa Barreira, Débora Ferreira and Jorge Pinto</i>	331
THE RELATIONS BETWEEN THE ASSESSED DIAGNOSTIC PARAMETERS AND MECHANICAL PROPERTIES OF HEATED CONCRETES <i>Izabela Hager and Tomasz Tracz</i>	341
COMPRESSIVE BEHAVIOUR OF A TIRE RECYCLED STEEL AND TEXTILE FIBER CONCRETE SUBJECTED TO FIRE <i>Cristina C. Santos and João P. Rodrigues</i>	349
EXPERIMENTAL RESEARCH ON THE RESIDUAL MECHANICAL PROPERTIES OF AN ORDINARY CONCRETES AFTER FIRE <i>Cristina C. Santos and João P. Rodrigues</i>	359
COMPRESSIVE STRENGTH AT ELEVATED TEMPERATURES OF A CONCRETE WITH CHIPS OF POLYETHYLENE TEREPHTHALATE <i>Hugo Caetano, João P. Rodrigues and Pierre Pimienta</i>	369

## **FIRE CHEMISTRY, PHYSICS AND COMBUSTION**

A DESIGN FIRE MODEL FOR THE FULL PROCESS OF FIRE <i>Xia Zhang, Xiao Li and George Hadjisophocleous</i> .....	381
TOXIC GAS ANALYSIS FROM COMPARTMENT FIRES USING HEATED RAW GAS SAMPLING WITH HEATED FTIR 50+ SPECIES GAS ANALYSIS <i>Abdulaziz A. Alarifi, Herodotos N. Phylaktou and Gordon E. Andrews</i> .....	391
NUMERICAL SIMULATION OF VAPOUR CLOUD FIRES USING FLACS-FIRE <i>Deiveegan Muthusamy and Kees van Wingerden</i> .....	401
IMPACT OF WOOD FIRE LOAD ON TOXIC EMISSIONS IN VENTILATION CONTROLLED COMPARTMENT FIRES <i>Bintu G. Mustafa, Gordon E. Andrews, Herodotos N. Phylaktou, Ayesh AlShammri, Vishal Shah and Omar A.O. Aljumaiah</i> .....	411
THE EFFECT OF USING LIDS IN DIFFERENTIAL SCANNING CALORIMETER EXPERIMENTS FOR DETERMINING THE HEAT OF REACTION OF WOOD <i>Xiaoyun Wang, Charles Fleishmann and Michael Spearpoint</i> .....	421
INVERSE MODEL FOR DETERMINING HEAT RELEASE RATES <i>Qianru Guo, Alvaro Salinas and Ann E. Jeffers</i> .....	431
TOXIC GASES FROM COMPARTMENT FIRES WITH HANGING COTTON TOWELS AND LOW VENTILATION <i>Gordon E. Andrews, Paul Yeomans, Herodotos N. Phylaktou and Omar A. Aljumaiah</i> .....	441
ANALYSIS OF A NEW PLATE THERMOMETER - THE COPPER DISC PLATE THERMOMETER <i>Alexandra Byström, Oskar Lind, Erika Palmklint, Petter Jönsson and Ulf Wickström</i> .....	453

## **FIRE REACTION**

NUMERICAL INVESTIGATION ON WINDOW EJECTED FACADE FLAMES <i>M. Duny, D. Dhima, J.P. Garo, H.Y. Wang and B. Martinez-Ramirez</i> .....	463
BURNING OF POLYURETHANE FOAM CLOSE TO A WALL AND A CORNER DEPENDING ON SEPARATION DISTANCE <i>Junghoon Ji, Kazunori Harada, Yoshifumi Ohmiya, Masaki Noaki and Yichul Shin</i> .....	473
THE APPLICATION OF DIFFERENT COMPONENT SCHEMES TO PREDICT WOOD PYROLYSIS AND FIRE BEHAVIOUR <i>Xiaoyun Wang, Charles Fleishmann, Michael Spearpoint and Xinyan Huang</i> .....	483
BURNING OF POLYURETHANE FOAM BLOCK IN ISO ROOM COMPARTMENT <i>Kazunori Harada, Ken Matsuyama, Kazuhiko Ido, Masaaki Noaki, Sungchan Lee and Jaeyoung Lee</i> .....	493
NUMERICAL MODELING OF A VERTICAL WALL FIRE <i>M. Duny, D. Dhima, J.P. Garo and H.Y. Wang</i> .....	503
FIRE SPREAD RESULTED FROM BURNING A DOUBLE-SKIN FAÇADE DEMONSTRATION RIG <i>Nadia C.L. Chow</i> .....	513
TESTS ON INTUMESCENT PAINTS FOR FIRE PROTECTION OF EXISTING STEEL STRUCTURES <i>Antonio Bilotta, Donatella de Silva, Emidio Nigro and Luca Ponticelli</i> .....	521

## **SMOKE CONTROL**

ROAD TUNNEL - FIRE AND EVACUATION SCENARIO CASE STUDY <i>Dirceu Santos, João P. Rodrigues and Jorge Saraiva</i> .....	533
SCALE MODEL EXPERIMENTS ON SMOKE MOVEMENT IN A TILTED TUNNEL <i>S.I. Tsang, W.K. Chow and Gigi C.H. Lui</i> .....	543
FULL-SCALE TESTS AND CFD MODELLING TO INVESTIGATE THE EFFECT OF DIFFERENT MAKE-UP AIR VELOCITIES ON SMOKE LAYER HEIGHT IN ATRIUM FIRES <i>Amir Rafinazari and George Hadjisophocleous</i> .....	553
FULL-SIZE EXPERIMENTS OF AIR CURTAINS FOR SMOKE CONTROL IN CASE OF FIRE <i>João Carlos Viegas and Hildebrando Cruz</i> .....	561

## **FIRE RISK ASSESSMENT**

THE EFFECTS OF CONSTRUCTION TYPE AND ACTIVE FIRE PROTECTION SYSTEMS ON THE OVERALL BUILDING FIRE RISK <i>Xiao Li, Xia Zhang and George Hadjisophocleous</i> .....	575
SENSITIVITY ANALYSIS OF SIMULATION PARAMETERS FOR FIRE RISK ASSESSMENT <i>Damien Lamalle, Pierre Carlotti, Richard Perkins and Pietro Salizzoni</i> .....	585
FIRE RISK OF HORIZONTAL WOODEN STRUCTURES FULL SCALE VERIFICATION <i>Petr Hejtmánek, Luciano M. Bezerra and George C. B. Braga</i> .....	595
FIRE RISK ASSESSMENT OF INDUSTRIAL BUILDINGS – PARAMETERS THAT MAY HAVE INFLUENCE <i>Cecília Barra, João P. Rodrigues and Robert Fitzgerald</i> .....	605

## **EVACUATION AND FIREFIGHTING**

THE EFFECTIVENESS OF FIRE EXITS IN COMPLEX BUILDINGS – A WAYFINDING EXPERIMENT

*Rosaria Ono, Katia B.R. Moreira, Tomaz P. Leivas and Gilberto L. Camanho*  
.....615

METHODOLOGY TO VALIDATE THE ‘FASTER IS SLOWER’ CONCEPT

*César Martín-Gómez, Iker Zuriguel, Natalia Mambrilla, Ángel Garcimartín and Martín Pastor*  
.....623

PARAMETERS FOR BREATHING PROTECTION EQUIPMENT CONSUMPTION: CONTRIBUTION FROM AN EXPERIMENTAL PROTOCOL.

*Cristiano Corrêa, Anderson S. Castro, Aline Falcão, George C. Braga, José J.R. Silva and Tiago A.C. Pires*  
.....631

MULTICRITERIA EVALUATION OF EFFICIENCY IN THE URBAN FIREFIGHTING

*José P. Lopes, Carlos H. Antunes and João P. Rodrigues*  
.....641

## **FIRE REGULATIONS, STANDARDIZATION AND CONSTRUCTION TRENDS**

A FRAMEWORK FOR SYSTEMATIC DEVELOPMENT OF FIRE SCENARIOS AND QUANTIFIED DESIGN BASIS FIRES

*Ian Jutras, Brian Meacham and Beth Tubbs*  
.....653

EXPERIMENTAL PLAN FOR ASSESSING FIRE PERFORMANCE OF SELECT ‘GREEN’ BUILDING FEATURES AND TECHNOLOGIES

*Drew Martin, Brian Meacham and Nicholas Dembsey*  
.....663

RELIABILITY-BASED METHODOLOGY FOR DETERMINING AN EQUIVALENT STANDARD FIRE DURATION

*Ruben Van Coile, Robby Caspeepele and Luc Taerwe*  
.....673

IMPORTANCE OF ACCOUNTABILITY IN BUILDING CONTROL: A CASE STUDY <i>Amaya Osácar and Juan Echeverría</i> .....	683
RELIABILITY CENTERED MAINTENANCE APPROACH TO INSPECTION, TESTING, AND MAINTENANCE OF FIRE PROTECTION SYSTEMS AND EQUIPMENT <i>Lonny Simonian</i> .....	693
AN OVERVIEW OF CONCRETE MODULUS OF ELASTICITY EVOLUTION WITH TEMPERATURE AND COMMENTS TO EUROPEAN CODE PROVISIONS <i>Izabela Hager and Katarzyna Krzemień</i> .....	703

## **FIRE BEHAVIOUR OF LIGHTWEIGHT CONCRETE UNITS BASED ON CORN COB AGGREGATE**

**Nuno Alves**

Civil Engineer  
UTAD – Vila Real  
Portugal

**Paulo Piloto**

Professor  
IPB – Bragança  
Portugal

**Elza Fonseca\***

Professor  
IPB – Bragança  
Portugal

**Luísa Barreira**

Mechanical Engineer  
IPB – Bragança  
Portugal

**Débora Ferreira**

Professor  
IPB – Bragança  
Portugal

**Jorge Pinto**

Professor  
UTAD – Vila Real  
Portugal

### **ABSTRACT**

Recent research works have concluded that corn cob may have interesting material properties, in particular, lightness, and thermal and sound insulation abilities. In this research work, corn cob is proposed as an alternative sustainable aggregate for lightweight concrete masonry unit (CMU) manufacturing. The corn cob requires to be granulated previously in order to obtain adequate particle size grade. Subsequently, the particles are wrapped in a cement paste with the purpose of reducing their water absorption and adherent capacities. CMU are currently applied in the building of partition walls. The main goal of this research work consists on studying the fire behaviour of partition walls built with CMU of processed corn cob granulate (CMU-PCC).

**Keywords:** Lightweight concrete unit; corn cob aggregate, organic material; masonry; sustainable construction; fire.

### **1. INTRODUCTION**

The search for alternative environmental friendly building solutions has been the goal of the scientific and the technical communities. Affordable, low energy and good quality water consumptions, and small amount of CO<sub>2</sub> emission into the atmosphere are important attributes that these solutions have to fulfil. In general, applying organic products as raw building materials may be a step forward to achieve these attributes because they are likely of being abundant,

---

\* Corresponding author – e-mail: [efonseca@ipb.pt](mailto:efonseca@ipb.pt)

local and renewable. For instance, rice husk ash blended cement has been proposed as a partial substitute of cement in mortar production [1].

On the other hand, corn cob has also been proposed as an alternative aggregate for the manufacturing of lightweight concrete for non-structural applications [2]. In these cases, there is an additional advantage because these organic products are treated as agricultural waste [3].

In this research work, lightweight concrete unit based on processed granulate of corn cob (CMU-PCC) is proposed as an alternative building material. In this case, processed granulate of corn cob (PCC) works as a substitute of current applied lightweight aggregates such as expanded clay (EC).

For the manufacturing process of CMU-PCC it was adopted geometrical and size typologies, composition and manufacturing technology similar to the ones currently applied in CMU based on expanded clay (CMU-EC). Therefore, this type of unit (CMU-EC) was used as reference in this study.

Taking into account that partition walls are a potential building scenario in terms of the application of the CMU-PCC, the respective fire behaviour is fundamental to know. Thus, the main goal of this research work consists on giving a contribution in this context by performing an experimental and a numerical preliminary analysis of the proposed building material under specific fire conditions.

Samples of CMU-PCC and CMU-EC were tested under fire conditions related to the standard fire curve indicated in ISO 834 [4]. The obtained experimental results allow understanding the behaviour of the units under severe fire conditions. In addition, these results are also used to validate a numerical model of the fire behaviour of these units.

This paper is structured as follows: firstly, a brief description of the CMU-PCC is done; secondly, the adopted set-up of the fire test is explained; thirdly, the fire behaviour numerical analysis is introduced; fourthly, the main results are presented and discussed; finally, some conclusions are drafted.

## **2. LIGHTWEIGHT CONCRETE UNIT BASED ON PROCESSED GRANULATE OF CORN COB (CMU-PCC)**

Medium sand (MS; 0.0 – 4.0 mm), coarse sand (LS; 0.8 – 3.0 mm), gravel (G; 2.0 – 6.0 mm), Portland cement 32.5 N (C), lightweight aggregate (LWA) and water (W) were the adopted constituents of the manufactured CMU. CMU-PCC (which their LWA is PCC) and CMU-EC

(which their LWA is EC) were prepared according to the following proportion in terms of weight 1:1.02:1.22:2.04:0.76:0.88 (C/C:MS/C:LS/C:G/C:LWA/C:W/C) and 1:1.15:1.38:2.31:0.87:1 (C/C:MS/C:LS/C:G/C:LWA/C:W/C), respectively.

CMU were prepared considering the standard dimensions 500 mm × 200 mm × 200 mm (length (L) × width (W) × height (H)) with a +3/-5 mm dimensional tolerance.

After the manufacturing process, the dimensions, the dry mass ( $m_{dry,s}$ ) and the bulk density ( $\rho$ ) of CMU were assessed. The average (AVG), the standard deviation (SD) and the coefficient of variation (CoV) of these measures are presented in Table 1.

Table 1: Dimensions, dry mass and bulk density of the studied CMU

		L (mm)	W (mm)	H (mm)	$m_{dry,s}$ (kg)	$\rho$ (kg/m <sup>3</sup> )
CMU-EC	AVG	497	201	199	11.494	1364
	SD	1.19	1.03	1.16	0.716	41
	CoV (%)	0.24	0.51	0.58	6.23	3.0
CMU-PCC	AVG	496	200	197	14.081	1748
	SD	0.62	0.49	1.57	0.778	60
	CoV (%)	0.12	0.24	0.79	5.52	3.5

### 3. FIRE TEST

At this preliminary research stage, the reduced number of samples available CMU-EC and CMU-PCC was a testing limitation. Therefore, it was necessary to simplify the test set-up prescribed for masonries in EN 1364-1 [5]. Thus, in both cases (i.e. masonry wall of CMU-EC and masonry wall of CMU-PCC), it was only possible to build a masonry wall with two CMU. Figure 1.a shows the case of CMU-PCC masonry wall sample. Another adopted testing procedure simplification is related to the fact that the masonry wall samples were tested in the horizontal position. Only the upper surface of each masonry wall samples has to be exposed to fire. The other surfaces of the samples were protected with fibreglass panels, according to Figure 1.

Different types of thermocouples were applied in order to monitoring the thermal behaviour of each tested masonry wall. Therefore, ordinary thermocouples type K (T), disk thermocouples (TD) and plate thermocouples (TP) were used and placed as Figure 2 presents. Five TD (from TD1 to TD5) were placed on the underneath surface of the wall samples, Figure 2. In practise, these are the sensors which allow to evaluate the fire resistance of each tested wall. In addition, fourteen T (from T1 to T14, Figure 2) were inserted in the CMU. Plus, four TP (from TP1 to TP4,

Figure 2) were also placed at the intermediate hollows of the CMU. The temperatures measured by T and TP sensors will be used to validate the proposed numerical study (i.e. masonry wall of CMU-EC and masonry wall of CMU-PCC) in Section 4.

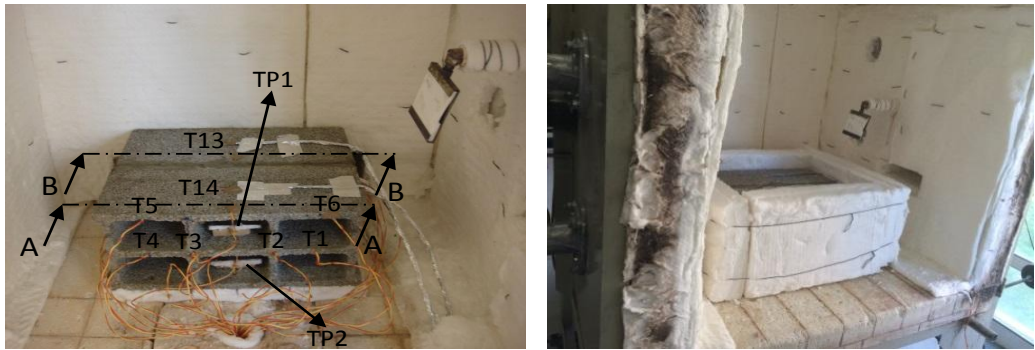


Figure 1: CMU-PCC masonry wall sample. Left: Thermocouple application, Right: Lateral fire protection

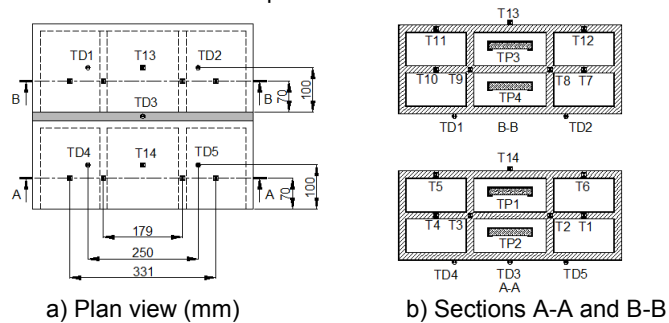


Figure 2: Schematic representation of the location of the thermocouple sensors

The fire tests were performed using a fire resistance furnace existing at Polytechnic Institute of Bragança (Bragança, Portugal), Figures 1 and 3. This equipment is able to carry out the ISO 834 standard fire curve test.



Figure 3: Fire test performance (Left: during test, Right: after testing)

In order to evaluate the fire insulation ability of a wall, the temperature evolution on the unexposed surface was assessed (TD sensors are used for this purpose). In that surface, two criteria are necessary to verify. The first criterion consists on guarantying that there is not an average temperature increasing of 140°C (related to the initial average temperature of that building element, TD0). Meanwhile, the second criterion consists on ensuring that an increasing of temperature up to 180°C (related to the initial average temperature of that building element, TD0) does not occur in any point of that surface of the wall.

TD0 is the average value of the temperatures measured by each TD sensor at the beginning of the test. In the cases of CMU-EC and CMU-PCC masonry wall samples, the quantified TD0 was 26°C and 22°C, respectively.

#### **4. NUMERICAL MODELING OF THE FIRE BEHAVIOUR OF CMU-EC AND CMU-PCC**

Taking into account the adopted standard geometry and size of the CMU under research (Table 1), a finite element mesh of the CMU masonry wall samples (built with 2 CMU) was defined considering SOLID70 (elements of 8 nodes, with 1 degree of freedom per node) of the Ansys computer programme [6], Figure 4.

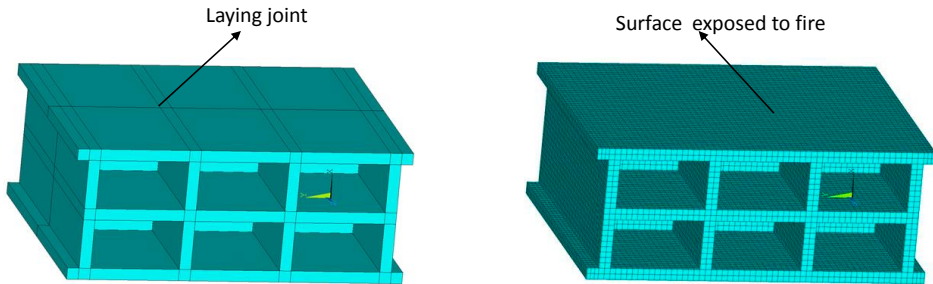


Figure 4: Finite element mesh of the CMU masonry wall samples (built with 2 CMU)

The temperature-dependent material properties of CMU under research are unknown. In particular, the thermal conductivity and the specific heat capacity of CMU-PCC. However, Eurocode 6 [7] presents data of these material properties for lightweight aggregate concrete units with a density range of 600 – 1000 kg/m<sup>3</sup>. Therefore, based on several numerical simulations and based on the experimental data (in particular, TP temperature measuring), it was possible to estimate the temperature-dependent material properties of CMU under research (CMU-EC and CMU-PCC). These material properties are indicated in Figure 5. In addition, the considered emissivity value was 0.87 which is related to cement based mortars.

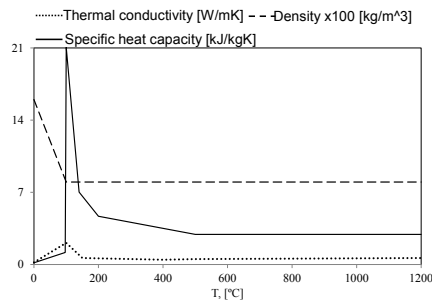


Figure 5: Temperature-dependent material properties of CMU-EC and CMU-PCC

The considered boundary conditions were convection and radiation in the exposed surface to fire and in the hollows, respectively, [8]. It was numerically assumed that the temperature evolution of the surface of the wall exposed to fire was similar to the respective curve of ISO 834. On the other hand, in the hollows of the CMU, the respective temperature evolution was based on the experimental measurements of TP (from TP1 to TP4, Figure 2.b). It was also adopted a convection coefficient equal to 25 W/m<sup>2</sup>K and a fire emissivity equal to 1.

## 5. RESULTS PRESENTATION AND DISCUSSION

In both cases (CMU-EC and CMU-PCC masonry wall fire tests), there was acceptable concordance between experimental and ISO 834 fire curves (“Real forno” and ISO 834 curves in Figure 6) and according to [9]. At the same time, the temperature measurements by TP are also presented in Figure 6 (curves TP\_e). These TP\_e curves allow us understanding the temperature evolution of the walls during the fire test performance and also the fire behaviour of each element. As expected, in both cases, the upper part of the wall (related to TP1 and TP3, Figure 2.b) presented higher temperature than the lower part of the wall (related to TP2 and TP4, Figure 2.b). There was also a good agreement between TP1\_e and TP3\_e curves in both cases, Figures 6.a and 6.b. In contrast, there was a certain discrepancy between the measurements of TP2\_e and TP4\_e (Figure 6.a and 6.b). This fact may be justified considering the adopted simplified fire insulation of the wall.

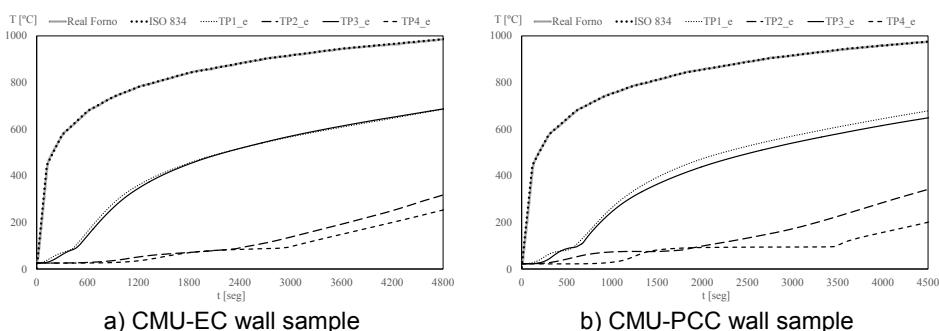
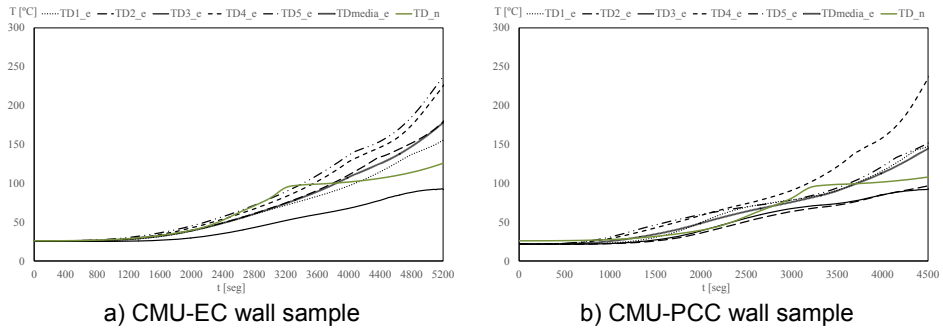


Figure 6: Real and ISO 834 fire curves. TP curves (Note: “e” means experimental; “Real forno” means real furnace; “seg” means second)

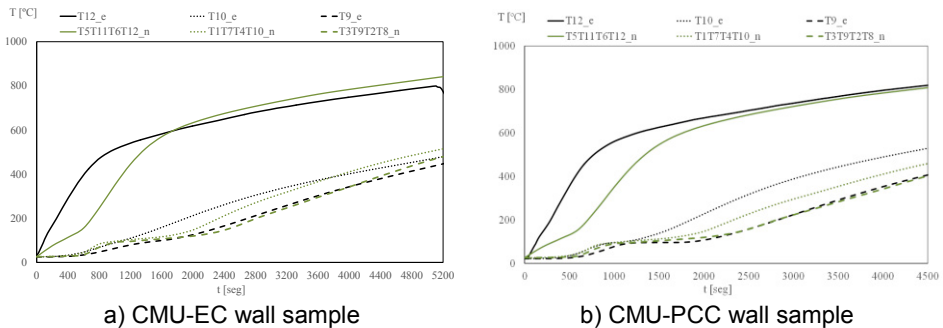
In order to complement the above information, Figures 7.a and 7.b present the temperature curves (TD\_e) related to the measurements of the five TD placed on the surface unexposed to fire (Figure 2.a) of the CMU-EC and the CMU-PCC wall samples, respectively. For each case, the average temperature curve (TDmedia\_e) and the numerical temperature curve (TD\_n) are also plotted in Figure 7.

In both cases, the second criterion has failed. As a result, CMU-EC and CMU-PCC masonry wall samples have shown a fire resistance of 83 minutes and 72 minutes, respectively. At the same time, in both cases, the wall samples also kept their structural integrity during the fire test. Therefore, both building elements have shown similar fire resistance behaviour which let us concluding that the standard CMU-EC and the alternative CMU-PCC may be adequate for partition walls concerning fire resistance ability.



a) CMU-EC wall sample  
 b) CMU-PCC wall sample  
 Figure 7: Temperature evolution of the surface unexposed to fire. Experimental (e) and numerical (n) values. (Note: TDmedia\_e corresponds to the average value of the measurements of TD; “seg” means second)

The verified acceptable concordance between TDmedia\_e and TD\_n curves for CMU-EC and CMU\_PCC walls (Figures 7.a and 7.b, respectively) may allow us validating the proposed numerical model of the fire behaviour of each wall under research. The data presented in Figure 8 also give strength for this validation.



a) CMU-EC wall sample  
 b) CMU-PCC wall sample  
 Figure 8: Temperature in certain parts of the wall (experimental (e) and numerical (n))

## 6. FINAL REMARKS

The fire resistance of CMU-PCC was evaluated in this research work. At each stage of this study, CMU-PCC was compared to CMU-EC which is a current applied lightweight concrete masonry unit for partition walls.

In both cases, similar fire behaviour was verified. That fire behaviour was adequate and the materials have shown appropriate fire resistance after being under the exposure of the ISO 834

fire curve during 60 minutes. This fact, may indicate that the application of processed granulate of corn cob as a lightweight aggregate may be promising.

A fire behaviour numerical model of CMU was also defined and proposed in this research work. The concordance between experimental and numerical values was acceptable. This numerical model has shown appropriate for both CMU-EC and CMU-PCC. The thermal-dependent material properties of these CMU were adjusted by this numerical model. In addition, the proposed numerical model may be useful for studying the fire behaviour of other standard geometrical solutions of CMU.

It is worth to emphasize that this work corresponds to a preliminary stage. A more representative amount of CMU-EC and CMU-PCC wall samples, real size wall samples and testing the wall samples in the vertical position are some technical aspects that require to be considered in further research to be done in this context.

## REFERENCES

- [1] Ganesan, K., Rajagopal, K. & Thangavel, K. - *Rice husk ash blended cement: Assessment of optimal level of replacement for strength and permeability properties of concrete*, *Construction and Building Materials*, vol. 22, 2008, p.1675-1683.
- [2] Pinto *et al.* - *Corn cob lightweight concrete for non-structural applications – Construction and Building Materials*, vol. 34, 2012, p. 346-351.
- [3] Pinto et al (2011). *Corn`s cob as a potential ecological thermal insulation material*. *Energy and Buildings*. vol. 43, Issue 8, 2011, p. 1985-1990.
- [4] ISO 834-1. "Fire-resistance tests - Elements of building construction – Part 1: general requirements". 1999.
- [5] EN1364-1 – Ensayos de Resistencia al fuego de elementos no portantes – Parte 1: Paredes, 1999.
- [6] ANSYS Teaching Introductory, Release 15.0, Help System, ANSYS, Inc.
- [7] EN1996-1-2: 2005. Eurocode 6: Design of masonry structures - Part 1-2: General rules – structural fire design. CEN – European Committee for Standardization
- [8] EN 1991-1-2: 2002. Eurocode 1: Actions on structures. - Part 1-2: General actions – actions on structures exposed to fire. CEN – European Committee for Standardization, 2002.
- [9] EN1363-1 - Fire resistance tests - Part 1: General requirements. CEN – European Committee for Standardization, 1999.



**International Council  
for Research and Innovation in  
Building and Construction**



**Hot Disk®**



**University of Coimbra**



**albrasci**  
Luso-Brazilian Association  
for Fire Safety



**Institute for Sustainability and Innovation in  
Structural Engineering**



**OE**



**OET**



**OA**



**ANPC**

ISSN 2412-2629



9 789899 184355 4

