TEMPERATURE ANALYSIS OF LIGHTWEIGHT AGGREGATE CONCRETE SLAB MEMBERS AT ELEVATED TEMPERATURES FOR PREDICTING FIRE RESISTANCE

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Abstract

This paper is focused on lightweight aggregate concrete with expanded clay and its issues according to fire resistance. The procedures and recommendations for the calculation of fire resistance of lightweight aggregate concrete structures are presented. These procedures are based on nowadays methods for normal-weight concrete structures. These methods are modified in order to cover specific parameters and properties of lightweight concrete structures.

Keywords: lightweight concrete, expanded clay, fire resistance, elevated temperatures, transient heat, specific heat, thermal conductivity

INTRODUCTION

Lightweight aggregate concrete (LWAC) has several advantages in comparison to normal-weight concrete (NWC). The most obvious one is lower bulk density and corresponding lower dead load of a construction. That can result in smaller cross-section of construction elements. In addition, cutting down transportation costs for precast elements is also a benefit. The lower bulk density corresponds with the lower thermal conductivity as well. This ability makes LWAC more suitable for heat insulating constructions as façade walls and precast panels. The most common use of in-situ pumping LWAC is for composite steel and concrete structures, especially for high-rise buildings when lesser loading for columns is needed.

These advantages are also disadvantages from another point of view. LWAC has higher porosity. It can result in higher absorbing capacity of water and lower compressive strength. Fire resistance of a structural member made of LWAC is mainly affected by parameters such as free water content, permeability, porosity of microstructure, coefficient of thermal expansion between cement paste and aggregate. Free water content accelerates pore pressure in concrete at elevated temperatures for instance. Together with low permeability, it can result in spalling phenomena0.

This paper presents a numerical model of transient heat transport. The model is based on elementary thermo-dynamics equations to predict temperature profile of cross-section of a slab element during fire. Temperature profile of concrete is influenced by these material characteristics: bulk density, thermal conductivity, specific heat. Data for these characteristics (Constitutive relations-Models of material characteristics) are based on the fire test of the LWAC precast panels, several cited papers, literature and standards (Euro codes, ACI, BS).

Fire resistance of LWAC panels is calculated with implementation of the assembled material models. Then comparison between the NWC and LWC is carried out.

1 FIRE RESISTANCE OF LWAC WITH EXPANDED CLAY AGGREGATE-STATE OF THE ART

There are several theories declaring fire resistance of LWAC is higher than NWC. These theories are based on the following three main statements.

- The first statement is that LWAC is less heat conductive than NWC. Therefore, gradient of temperature profile of cross-section is higher. This is caused by aggregate that is more porous.
- The second one is modul of elasticity. The modul of elasticity of expanded clay aggregates are similar to the modul of elasticity of hardened cement paste. That is a result of high temperature during manufacturing expanded clay aggregates that could exceed 1100°C. That temperature is similar to sintering temperature of cement. Therefore, LWAC with expanded clay aggregates is more compact under loading condition due to lower micro-cracking on the contact zone between lightweight aggregate and cement paste.
- The last statement is also derived from similar manufacturing temperature of cement and aggregate. Due to high temperature during manufacturing, expanded clay is more stable at elevated temperatures. Thus the coefficient of thermal expansion between a cement paste and aggregate is also similar.

2 FIRE TEST OF LWAC PRECAST PANELS

Many of further studies and assumptions are based on the fire tests of LWAC with expanded clay aggregate that were done in Czech Republic. The purpose of the fire test was to determine fire resistance of LWAC precast panels made of L25/28-D1,6 concrete (according to EN 1365-2:2000 and EN 1363-1:2000). The scheme of the test is in Fig. **1**.

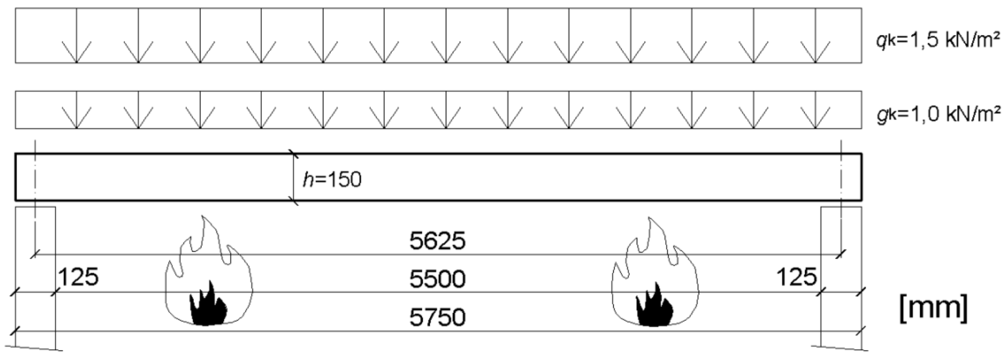

Fig. 1 Scheme of the fire test

Before the fire test was done, basic material characteristics had been measured (bulk density, moisture content, thermal conductivity). Those material characteristics are essential for further determination of material models at elevated temperatures and for simulation of behaviour LWAC panels at elevated temperatures. Temperatures on the unexposed side and deformation were measured during the fire test.

3 CONSTITUTIVE RELATIONS-MODELS OF MATERIAL CHARACTERISTICS

Generally, the temperature profile of cross-section of a construction is affected by three material characteristics: bulk density, specific heat and thermal conductivity. All of these characteristics are temperature and moisture dependent. Temperature is solved by numerical solution of transient heat. Development of moisture content during fire is indirectly implemented into material models. This approach brings simplification and there is no need to

solve a hydrothermal model of coupled temperature and moisture transport. In addition, less data of material characteristics are needed. Only data needed are the ones that have been measured on dry samples and samples with common temperature and common moisture content so that every laboratory could measure them.
Several models are assembled according to standards (EN 1992-1-2, EN 1994-1-2) or slightly modified. Other models are assembled in order to fit results obtained from the fire test. Empirical prediction of moisture content progress during fire loading is essential for all models.

4 NUMERICAL SOLUTION AND FIRE RESISTANCE CALCULATION

The numerical solution of temperature distribution is implemented into MATLAB program. Its workspace provides effective tools for matrix equations.
The 1-D transient heat transport model is used. The dimension of the numerical model was chosen as 1-D in order to cover only slab or wall elements. Moisture content must not be omitted hence is implemented into constitutive relations (Constitutive relations-Models of material characteristics).
Fire resistance of a structural member (panel, slab) is calculated according to temperature distribution. The calculation is done using EN 1992-1-2 standard.
Fire resistance of slab members is based on flexural strength in concrete member during fire condition. The equilibrium on a cross section is calculated in every 10s (time increment) and then the resisting bending moment is calculated and compared with the applied internal bending moment (Fig 2).

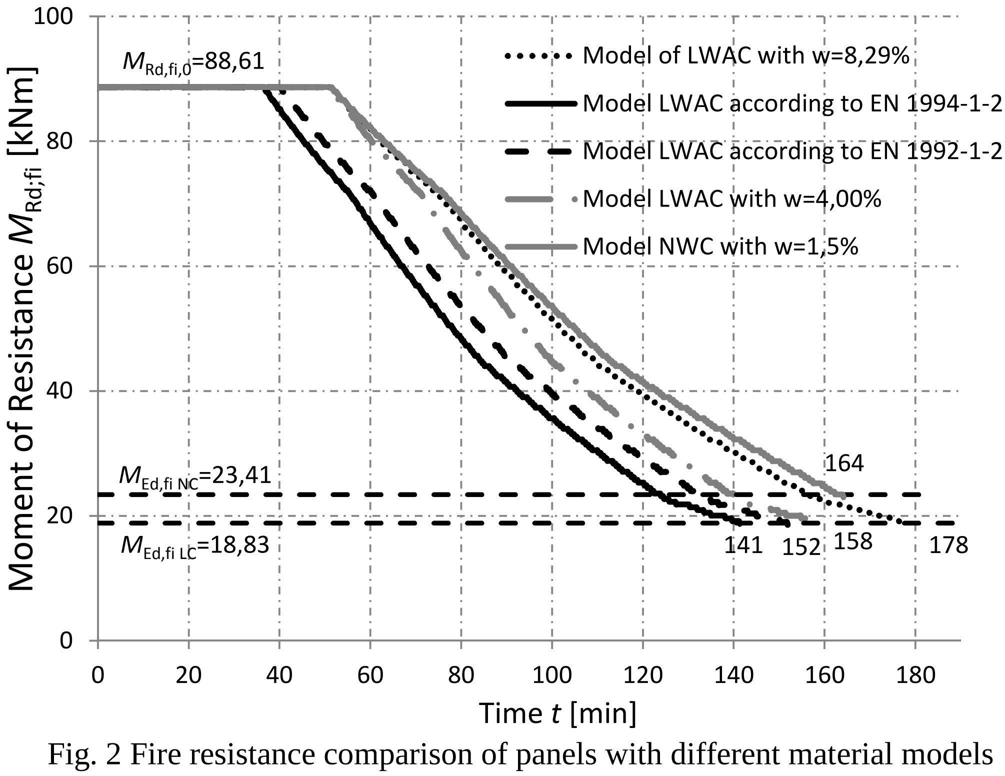

Fig. 2 Fire resistance comparison of panels with different material models

Apparently better fire resistance of LWAC panels is caused by lower dead load (lower bulk density) in case of heating the tensile side. The fact that LWAC has lower thermal conductivity is important for insulation on the unexposed side.Fire resistance in this case of fire(tensile side is heated) is determined by heating of reinforcement bars. So reduction coefficients of concrete at elevated temperatures are not used in this case because failure of reinforcement appears before. Every curve has different gradient of temperature as can be seen in Fig. 3. It is caused by different volumetric heat capacity (product of bulk density and specific heat). This value is higher for NWC (higher bulk density) thus more time is needed to heat NWC. However, higher thermal conductivity of NWC causes higher temperatures on the fire-unexposed side. Volumetric heat capacity is also influenced by moisture content.

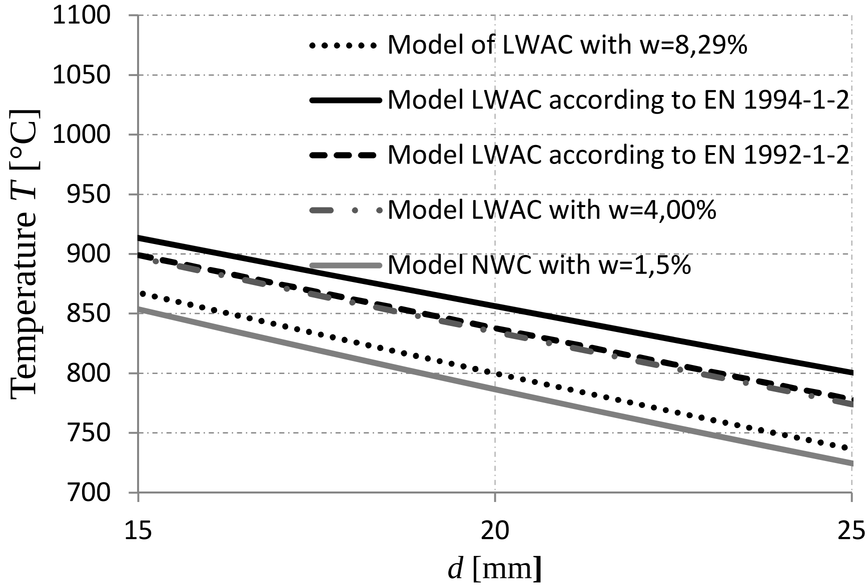

Fig. 3 Temperatures of reinforcement bars of panels with different material models

5 CONCLUSIONS

Fire resistance of slab member is highly influenced by location of fire, if it is on the tensile side or the side in compression. In condition of heating the tensile side of a member, fire resistance is determined by temperature of reinforcement bars. Slab member shows similar failure as in case of normal temperatures but with a few differences. The redistribution of internal forces is quicker and large deformations are observed.

Fire resistance of a slab member made of LWAC is mainly influenced by volumetric heat capacity. The higher volumetric heat capacity is, the lower temperatures of reinforcement bars are observed. Generally, materials with higher bulk density have higher volumetric heat capacity. Nevertheless, members made of LWAC has better insulating functions due to lower thermal conductivity.

5.1 Comparison between LWAC and NWC

The material models described in this paper were based on the fire test of LWAC with expanded clay and others materials with similar contain. All assumptions were made with neglecting explosive spalling.

Based on the results of this study, the following conclusions are written:

- Fire resistance of horizontal constructions (slabs, panels) made of LWAC with expanded clay aggregate is lower than NWC.
- Fire resistance of vertical constructions (columns) made of LWAC with expanded clay aggregate can be higher than NWC. It is caused by lower thermal conductivity results in lower temperatures in the centre of a member and higher values of the strength reduction coefficient (k_c) of concrete at elevated temperatures.
- Fire insulating function is higher at LWAC panel than NWC panel.
- The moisture content should be limited due to high risk of spalling. Especially expanded clay aggregate is more likely to absorb water.

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