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EQUIVALENT THERMAL DIFFUSIVITY OF NATURAL AND RECYCLED AGGREGATE CONCRETE AT TEMPERATURE UP TO 350 °C

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Abstract.

The paper presents the evolution of equivalent thermal diffusivity with temperature of concretes with natural coarse aggregates and recycled concrete aggregates. Thermal diffusivity was evaluated based on the temperature measurements made on cylindrical samples using so-called "inverse technique". Thermal diffusivity parameter was estimated for concretes manufactured with different replacement ratios of natural by recycled coarse aggregate (0, 50 and 100 %) produced by crushing the worn-out concrete pavement that was dismounted after exploitation period. The diffusivity of concrete was tested up to 350 °C. The progressive decrease of thermal diffusivity was observed, and the lowest D values were obtained for higher recycled concrete aggregates content. The results were presented against the background of other authors results and referred to the D values proposed in EUROCODE 2.

Keywords: Fire, recycled concrete aggregates, temperature, thermal diffusion.

1. Introduction

By volume,construction and demolition waste (CDW) are one of the largest streams of waste in Europe with 850 million tons that are produced per year [1]. The waste separation process enables to obtain good quality aggregates and their use in concrete is economically, environmentally and technically feasible with the respect of all technical standards. The progressive replacement of natural aggregates by recycled concrete aggregates contributes to the implementation of the strategy for sustainable development of the field of construction through the successful implementation of sustainable building materials with a reduced carbon footprint. The concrete industry scepticism based on concern about poor-quality recycled products needs to change with the research projects showing successful application of recycled concrete aggregates RCA without compromising on quality and contribute to the decrease environmental impact. The detailed recommendations concerning assessing the properties of recycled aggregates are given in [2], however the imitation concerning their replacement of natural aggregate in the concrete mix is imposed [3].

In the present research the properties of concrete with recycled aggregates were investigated in the view of study their behaviour in fire. The fire behaviour of concrete with natural aggregate is well documented in the literature [4–6]. Well known cases of fires in engineering facilities like Channel (1996); Mont Blanc (1999); Gotthard (2001) tunnels has drew attention to one of the disadvantages of concrete that is concrete spalling in a fire. The sudden loss of concrete cover and concrete element cross-section reduction may jeopardise the overall load-bearing capacity of the structural element [7]. It has been confirmed that the composition of concrete, as well as boundary conditions, affects the concrete propensity to spall in a fire. One of the main parameters governing concrete spalling is permeability. In denser and less permeable concrete, the spalling risk is higher [8]. Concrete permeability is a derivative of the type of aggregate used, transport properties of the cement paste and the permeability of interfacial transition zone ITZ between the cement paste and the aggregate. The permeability of recycled concrete aggregate differs from natural aggregate, thus transport properties of those concretes may be higher than in traditional concretes [9], thus lowering the risk of spalling behaviour. In view of studying the RCA concrete behaviour in the fire the first step that was undertaking was the observation of thermal properties evolution presented in this paper.

The aim of this project is to examine the impact of concrete composition, in particular the recycled concrete aggregate amount RCA on the thermal properties of concrete. As the heat transfer in concrete plays a crucial role in fire resistance evaluation, the

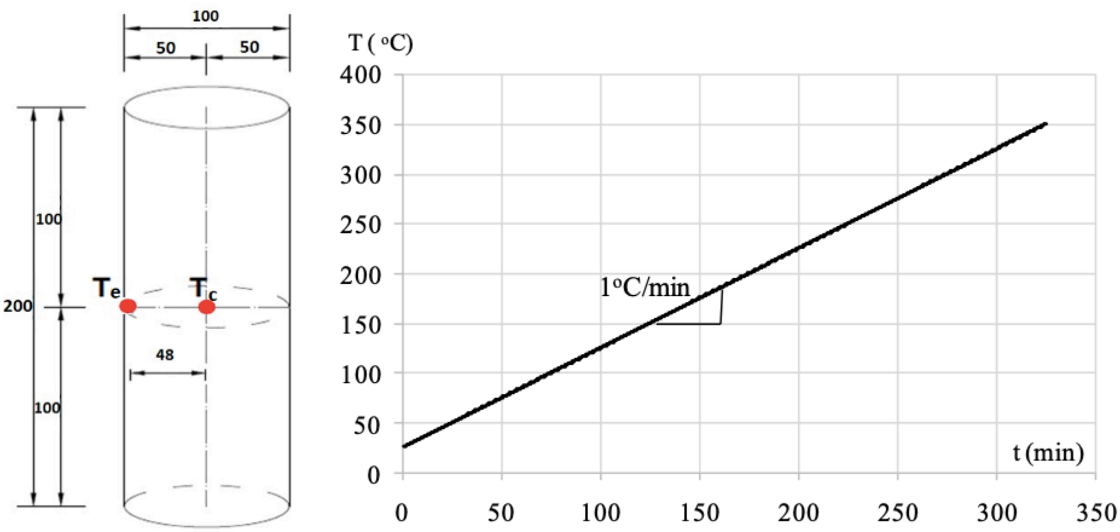

Figure 1. Thermocouples arrangement in the concrete cylinder, and the furnace heating rate.

thermal properties that change with the temperature are essential and need to be provided to the calculation model. Thermal diffusivity (D) is a specific property of the material and allows you to determine how quickly a given material reacts to temperature changes. This is a property that measures the rate of heat transfer from the exposed surface of the material to the inner layers. The higher the value of thermal diffusivity, the faster the temperature increase at a certain depth. To predict the behaviour of concrete during a fire and carry out simulations determining the temperature development in a heated element, one need to know the value of thermal diffusivity. Thermal diffusivity can be evaluated directly from its definition or its evaluation can be based on the temperature measurements made on cylindrical samples, called an "inverse technique".

2. Experimental method

The thermal diffusivity (D) of concrete depends on its thermal conductivity (λ), density (ρ) and specific heat of the material (c_p). Thermal diffusivity can be determined (Eq. 1) by directly determining these physical properties by experimental methods or by using an inverse method leading to the determination of D. The unit of thermal diffusivity is [J/kgK], but [mm^2/s] or [m^2/s] are also used in the literature.

$$D = \frac{\lambda}{\rho \, c_p} \quad \left[\frac{\mathrm{m}^2}{\mathrm{s}}\right] \tag{1}$$

The method determining the equivalent thermal diffusivity of concrete was recently described by Felicetti [10, 11] showing good compliance with experimental results from standard fire tests. The main advantage of the "inverse technique" is the determination of thermal diffusivity without the need for cumbersome measurements of thermal conductivity and specific heat values as well as density change evaluation, knowing that all those values vary with temperature increase.

The inverse method is quite sensitive to moisture presence in concrete and other physicochemical processes that occur when the material is exposed to high temperature. It consists in heating the cylindrical sample (diameter 100 mm; height 200 mm) in the electric furnace and measuring temperature increase in the centre of the sample (T_c - centre) and on 2 mm from cylinder lateral surface (T_e - exterior) using K-type thermocouples, Figure 1. The temperature differences are measured on the central cross-section where the field of temperature is considered dependant only to distance from the cylinder centre. The temperature increases with the constant heating rate 1 °C/min up to 350 °C. The test result is the temperature difference $T_e - T_c$ in function of time.

during the test. In the determination of thermal diffusivity by the inverse method, the initial assumptions is adopted that the cylinder is axis-symmetric and infinitely long, so the analyse is related to a differential equation for transient heat conduction. To determine the diffusivity that characterises the transient process of heat exchange inside a constant mass we use Fourier's Law (Eq. 2):

$$\rho \, c_p \frac{\partial T}{\partial t} + \mathrm{div}\,(q) = 0 \tag{2}$$

Assuming a cylindrical coordinate system (θ, r, z) (Eq. 3):

$$\frac{\partial T}{\partial t} = D \left[\frac{\mathrm{d}^2 T}{\mathrm{d}r^2} + \frac{1}{r}\frac{\partial T}{\partial t}\right] \tag{3}$$

and using Laplace transformation, we get a formula for the temperature difference between the edge and the centre of the sample (Eq. 4):

Component	Units	OC	RAC 50%	RAC 100%
CEM I 42.5 R	kg/m^3	414.2	414.2	414.2
water	kg/m^3	186.4	186.4	186.4
w/c	–	0.45	0.45	0.45
river sand 0/4 mm Dwudniaki	kg/m^3	615.1	280.6	569.2
coarse agg. 2/8 mm Dwudniaki	kg/m^3	579.9	280.6	–
coarse agg. 8/16 mm Dwudniaki	kg/m^3	562.3	264.1	–
recycled concrete agg. 4/16 mm	kg/m^3	–	825.3	1057.2
plasticizer BASF BV 18	% mc	0.9	0.9	0.9
Basf Glenium SKY 591	% mc	1.4	1.4	1.4
cement paste content	dm^3/m^3	320	320	320
mortar content	dm^3/m^3	542	511	540
density	kg/m^3	2248.5	2236.8	2221.3
water content	%	5.2	5.8	6.7
water absorption	%	6.9	7.3	7.8
28 days compressive strength	MPa	46.1	56.8	54.5
28 days tensile splitting strength	MPa	3.3	3.6	3.4

Table 1. Mix design and properties.

$$T(r,t) = R\left[t - \frac{a^2 - r^2}{4D}\right] \quad (4)$$

From here we get the formula for D - equivalent thermal diffusivity (Eq. 5):

$$D = \frac{Ra^2}{4\Delta T} \quad (5)$$

where:

- R - heating rate [°C/min],
- a - sample radius [m],
- ΔT - temperature gradient [°C/cm],
- D -thermal diffusivity [mm^2/s].

3. Materials

The measurements were carried out for concrete made of CEM I 42.5 cement, riverbed coarse aggregate Dwudniaki from Dunajec River southern Poland (grain size 2/8 mm and 8/16 mm) and crushed concrete from the worn-out concrete pavement with grain size - 4/16 mm. Before being crushed the mechanical properties of concrete from the pavement was determined on drills. The compressive strength of 66.8 MPa, modulus of elasticity 41.2 GPa and apparent density of 2290 kg/m^3 characterised the recycled concrete.

For all 3 concretes the same water-cement ratio (w/c) and cement paste volume was maintained. Additionally, a plasticiser was used to obtain good workability and water content reduction. The mix composition of the concretes is shown in Table 1. The concretes were labelled: the reference ordinary concrete (OC) made of natural riverbed aggregates; RAC 50% is concrete made of recycled pavement aggregate with 50% of natural coarse aggregate replacement with recycled one; RAC 100% recycled aggregate concrete made of recycled concrete coarse aggregates. In all concretes - OC, RAC 50% and RAC 100% riverbed quartz sand was used.

The concretes specimens were cast and stored in plastic cubic or cylindrical moulds for the first 24 hours. After preliminary curing, water evaporation was prevented by covering them with plastic lids for 7 days. During the next 28 days, they were stored in natural air-drying conditions at the temperature of 20 ± 5 °C and relative humidity of 50 ± 5 %. The compressive strength and splitting tensile strength of concretes after 28 days were determined on 10 cm^3 cubes. All basic physical (density, water content, water absorption) and mechanical (compressive and splitting tensile strength) performances are summarised in Table 1.

4. Results and observations

The temperature evolution in time measured with type K thermocouples was presented in Figure 2. The solid line is showing the heating programme. The presented results were used to determine effective thermal diffusivity as a function of temperature, obtained from the Eq. 5 and expressed in [mm^2/s]. The results are shown in Figure 3.

Due to thermal gradient value close to zero at the beginning of the test, when the furnace starts to heat, the effective thermal diffusivity values are very high. This phenomenon was previously observed by [10], and the correction factor was proposed to reduce this unwanted effect so that the suggestion to compute the instantaneous heating rate was proposed [11]. The equivalent thermal diffusivity decreases with increasing temperature in the range up to 350 °C. In heated

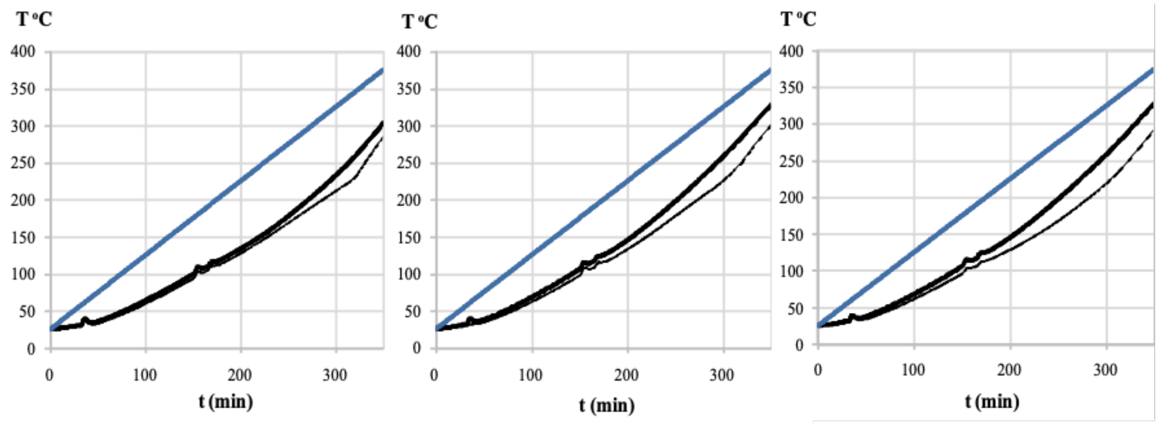

FIGURE 2. Time - temperature curves for OC, RAC 50% and RAC 100%.

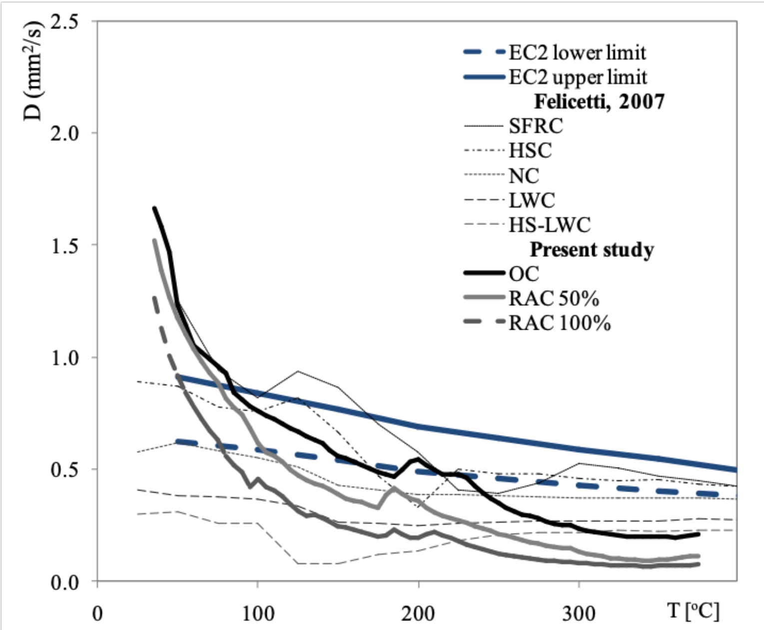

FIGURE 3. Equivalent thermal diffusivity for OC, RAC 50% and RAC 100%compared with the results of Felicetti [11] and EC 2 proposed values.

with 1 °C/min cylinders the values of equivalent thermal diffusivity reaches at 100 °C 0.76 mm^2/s, 0.61 mm^2/s and 0.45 mm^2/s respectively for OC, RAC 50% and RAC 100%. The highest value obtained for OC results from the density of this material. With an increasing proportion of recycled concrete aggregates, the D values are reduced. The similar tendencies are observed at 200 °C and 300 °C.

From the graph, we can see the water migration effect occurring in the lower temperature in case of concretes with recycled concrete aggregates. It confirms that those materials enable faster water migration due to their higher permeability. The observed water migration perturbance on Figure 3 is linked with specific heat significant peak at a temperature close to 200 °C.

The comparison with the D range proposed by EUROCODE 2 (EC2) [12] for both samples with recycled aggregates RAC 50% and RAC 100% shows thatthe thermal diffusivity values are mostly below both the upper and lower limits given in EC2. The results remain similar to the experimental results of Felicetti [10, 11].

5. CONCLUSIONS

Determination of thermal diffusivity is a vital parameter for the correct modelling of heat flow through heated concrete. Thanks to the inverse method, we determine diffusivity for much higher temperatures than other stationary and non-stationary methods. Non-stationary transient temperature methods, despite their broad application, require the use of specialised and often costly measuring equipment complex in mathematical and numerical terms. In the inverse method, we can use widely available and easy-to-use laboratory equipment to perform the tests. Although the technique does not allow for specific parameters to established: ρ, c_p and λ but their ratio expressed in diffusivity definition $D = \lambda/\rho$ cpis assessed.

Acknowledgements

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