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Effect of thickness of the intumescent alkali aluminosilicate coating on temperature distribution in reinforced concrete

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ABSTRACT

The paper presents the results of investigations to determine the optimum thickness of intumescent aluminosilicate coating providing protection of concrete and reinforced concrete structures, in particular tunnels, in case of fire. It is shown that the developed intumescent aluminosilicate coating prevents heating of the surface structures of concrete and metal reinforcement of concrete to the limiting condition, i.e., to temperatures of 653 K and 773 K. The protective coating on the concrete surface, in thicknesses of 6 mm, can prevent concrete and reinforced concrete from brittle fracture and reinforcement from occurrence of plastic deformation for at least 2 h. The developed coatings were studied by heating the coated concrete surface using a spot fire (point source fire) for a period of 3 h, and temperatures beneath the coating and at a distance of 20 mm from the surface (embedded reinforcement) were measured. Measurements of pull-off adhesion of the coating were taken using an adhesion testing equipment before and after exposure of fire. Increasing the thickness of the protective coating reduces heating of the concrete in depth; the average temperature of the heating of the concrete at the depth of the metal reinforcement (20 mm) is 414.4 K, which is 1.9 times less than the limit of heating temperature of the metal fittings. The increase in thickness of the coating and time of fire exposure will result in even better heat insulating and fireproofing properties. Test results of the developed coating 6 mm in thickness suggested concluding that before exposure of fire type, its type of fracture – was A/B (concrete substrate/coating adhesion fracture) and its pull-off strength was 2.15 MPa. A mean value of adhesion (pull-off strength) of the developed coatings 12 and 18 mm in thickness was 1.55 MPa, type of fracture – B (cohesion fracture within the coating). After exposure of fire, not depending upon thickness of the coating, a mean value of adhesion (pull-off strength) was 0.85 MPa, type of fracture – B (cohesion fracture within the swollen porous coating).

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1. Introduction

Concrete is a versatile and the most widely spread construction material not only for general use, but also for restoration/reconstruction of historical concrete buildings and for so-called "responsible" structures like tunnels etc. In case of fire a concrete can be heated to temperatures of brittle fracture of concrete (653 K) during the first 10 min and reinforcement to temperatures of plastic deformation (773 K) during the next 50 min resulting in quick loss of integrity and load-bearing ability of the whole concrete structure. That is why a regular practice in the EU countries is to develop fire protection measures for each "responsible" application with consideration of various fire scenarios [1–5].

From the point of view of physico-chemical views on the processes of destruction under action of high temperatures (dehydration) of cement stone hydration products, these processes are accompanied by vapor mass transfer associated with crack opening and occurrence of so-called autogenous stresses. As a result, integrity of concrete lining is lost due to explosion.

In order to eliminate negative effect of fire on structural elements of concrete structures the passive fire protection measures should be used, among them the application of fire and heat resistant materials based on mineral binders [13], inclusive of geopolymers [6–12].

More advantageous is the application of intumescent coatings based on organic and mineral binders as active protection

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measures. These intumescent coatings when exposed to fire swell with formation of porous foam coke deposit, which prevents flow of heat across substrate material, and heating of concrete surface to critical temperatures.

However, intumescent organic binder-based coatings release some toxic matters into atmosphere and after swelling have low adhesion to protected concrete surfaces and even can be "washed out" under exposure of alternating heat fluxes.

The known-in-the-art intumescent sodium silicate-based coatings are rather effective ones in terms of their adhesion to concrete substrates, however, when applied to concrete with time they lose their ability to swell when heated.

An attempt to develop intumescent geopolymers-based coatings is described in Zénabou [14]. Swelling is provided by the use of gas formation agents. Disadvantage of this solution is that these agents can enter into reaction with the geopolymer matrix suppressing an ability of these coatings to swell. Adhesion of these coatings to concrete substrate is also a critical point.

An alternative to the above coatings could be the alkaline aluminosilicate binder-based coatings. The scientists of the V.D. Glukhovsky Scientific Research Institute have developed these coatings for Binders and Materials. An ability of these coatings to swell when heated is provide through a guided synthesis of hydration products of the zeolite structure (heulandite and ussingite) and hydromicas [15–18]. These materials start to swell when heated to temperatures higher than 373 K due to release of a chemically bound zeolitic water with the formation of an artificial stone with a lower density and with a well-developed pore structure. Despite these advantages, until now no studies have been held to reveal effect of thickness of coating to be applied to a concrete to protect concrete itself and reinforcement in it (in case of reinforced concrete) from action of fire.

The aim was to study effect of thickness of the intumescent alkali aluminosilicate coatings on prevention from being heated to critical temperatures when exposed to fire and adhesion of the coating before and after exposure of fire. The developed coatings were studied by heating the coated concrete surface using a spot fire (point source fire) for a period of 3 h and temperatures beneath the coating and at a distance of 20 mm from the surface (embedded reinforcement) were measured. Measurements of pull-off adhesion of the coating were taken using an adhesion testing equipment before and after exposure of fire.

2. Raw materials and examination techniques

2.1. Raw materials

The alkaline aluminosilicate dispersion of the $Na_2O \cdot Al_2O_3 \cdot 6SiO_2 \cdot 20H_2O$ composition was used as a binder, ratios of its structural oxides being as follows: $Na_2O/Al_2O_3=1$, $SiO_2/Al_2O_3=6$ and $H_2O/Al_2O_3=20$. Calculation of the ratios between oxides in the alkaline aluminosilicate binder that are required for synthesis of zeolites was carried out in accordance with Breck [20] and Krivenko [16].

Metakaolin (Trade name "KV 60", Keramost a.s., Czech Republic)

with a fineness measured as a specific surface area by Blaine of 300–350 m^2/kg was used as a solid phase component of the above dispersion. Its chemical composition is given in Table 1.

Sodium silicate solution with a silicate modulus $M_s=3.05$ and $\rho=1420 \pm 10$ kg/m^3 was used as an alkaline component.

Modification of the alkaline aluminosilicate binder was done by adding NaOH and a rotten-stone of the chemical composition shown in Table 1. A specific surface area of the ground rotten-stone was 250–280 m^2/kg (by Blaine).

Limestone of the chemical composition shown in Table 1 was used as an expanding agent and at the same time as a filler. It was ground until a specific surface area of 70–80 m^2/kg (by Blaine).

In addition, the alkaline aluminosilicate pellets of the $Na_2O \cdot Al_2O_3 \cdot 6SiO_2 \cdot 20H_2O$ composition (d=0.63–5.0 mm) were added as expanding agents and at the same time as fillers. These pellets were manufactured by granulation of the alkaline aluminosilicate binder in the $CaCl_2$-solution ($\rho=1350$ kg/m^3); these pellets are shown in Fig. 1.

2.2. Experimental

After mixing the alkaline aluminosilicate binder with expanding agents (fillers) in the required proportions the resulted coatings were applied in three thicknesses (6, 12 and 18 mm) manually with the help of a trowel to a vertical surface of concrete cubes (150 mm) [21–24]. Four thermocouples (TT-K-24-SLE type K, temperature range of 273–1523 K, accuracy ± 1.1 K, Czech Republic) were inserted into specially drilled holes in a plane in concrete specimens at a distance of 75 mm from the upper side of the concrete cube in order to determine temperature distribution across the concrete specimen in the points T_1–T_4: T_1 – on the surface of uncoated concrete or beneath the coating in case of coated concrete; T_2, T_3, T_4 – at distances of 37.5, 75 and 150 mm respectively from the side of concrete cube exposed to fire (Fig. 2). These thermocouples were connected to a multifunctional device KIMO HD 200 HT (France). An infrared pyrometer DT 8867H (Germany) was used to measure temperatures (T_s) on surface of the uncoated and coated concrete specimens. A gas fired torch (Rothenberger, Germany) with a flame temperature of 1373 K and heat flux of 100 kW/m^2 was used as a spot fire (point source fire) in fire test under the curve as that described in ISO 834-1:1999 [25] and Haugh (2007) (Fig. 2).

Fire tests of all uncoated and coated concrete specimens lasted until critical temperatures with regard of brittle fracture of concrete and plastic deformation of reinforcement would be reached, but not shorter than 2 h (Haugh, 2007). Temperature distribution across the concrete specimens was measured and recorded. Test specimens had no heat insulation because some part of heat flux was absorbed and dissipated by the coating.

Changes taking place in the coatings under study in the process of spot fire tests are shown in Fig. 3.

Adhesion of the coating to a concrete substrate was measured by a pull-off test in accordance with ISO 4624:2002 [26] using an adhesion testing equipment AKL 2230 Proceq (Switzerland).

Table 1
Chemical composition of constituent materials.

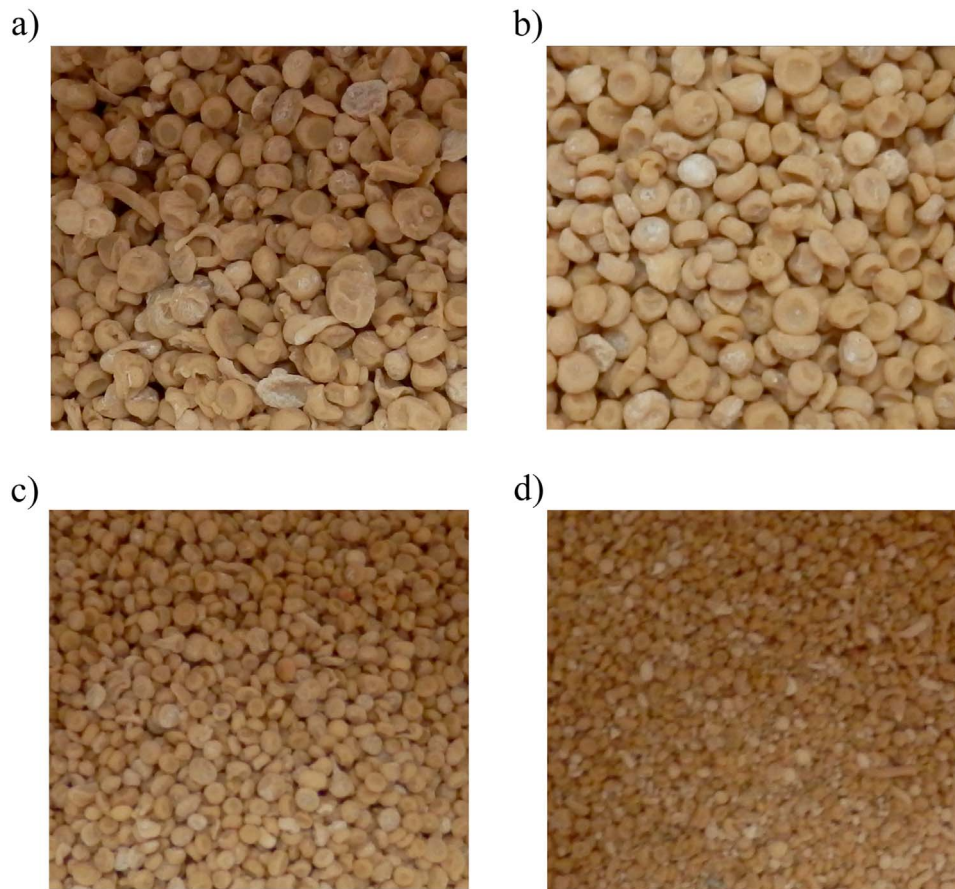| Component	Weight percent of oxides,%									
	SiO$_2$	Al$_2$O$_3$	Fe$_2$O$_3$	TiO$_2$	CaO	MgO	K$_2$O	Na$_2$O	Other	LOI
Metakaolin KV-60	53.67	43.61	0.77	0.74	0.52	traces	0.75	0.25	0.14	< 0.5
Rotten-stone	88.4	2.3	1.1	0.2	3.6	0.9	0.9	–	0.6	2.0
Limestone	7.6	2.92	2.64	0.22	44.15	2.89	1.18		–	39.71

a)

b)

c)

d)

Fig. 1. Pellets, size, mm: a – > d=5.0; b–d=2.5–5.0; c–d=1.25–2.5; d–d=0.63–1.25.
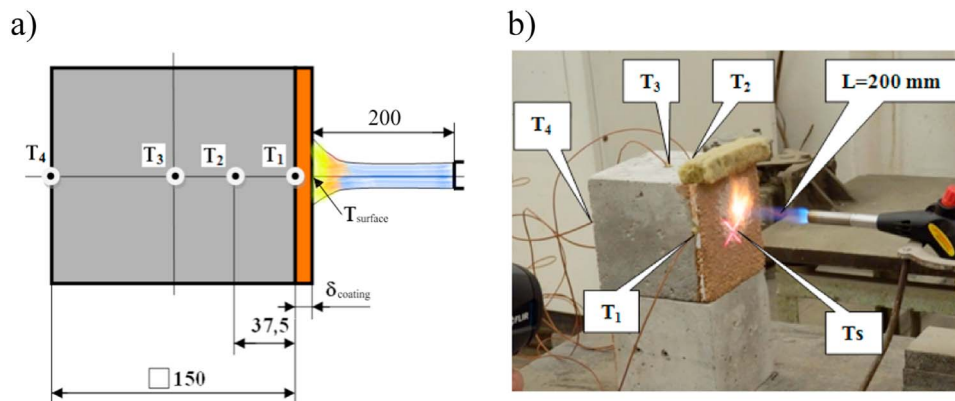
a)

b)

Fig. 2. Positioning of points of temperature measurement (a) and spot fire (point source fire) set-up (b).

3. Results

Analysis of temperature distribution in the concrete specimens under study showed that in case of the <u>uncoated</u> concrete specimen a temperature measured in point T_1(T_s) (point of contact of concrete surface with spot fire source) had exceeded a critical temperature (brittle fracture of concrete) (653 K) by 2.12 times even on the fifth minute of test (Fig. 4, a), resulting in concrete destruction. In points T_2–T_4 the <u>uncoated</u> concrete specimen was heated to temperatures of 540.9 K (T_2)–335.6 K (T_4) (Fig. 4a).

In case of the <u>coated</u> concrete specimens the temperatures measured in point T_1 (beneath the coating) did not exceed the above critical temperature for concrete and that with the increase in coating thickness the measured temperatures even tended to

decrease: at a thickness of 6 mm – 608.7 K; 12 mm – 558.6 K; 18 mm – 538.5 K (Fig. 4b–d). In Points T_2–T_4 the measured temperatures tended to decrease with the increase in coating thickness: at a thickness of 6 mm – from 397.5 K (T_2) down to 316.7 К (T_4); 12 mm – from 558.6 (T_2) down to 303.3 K (T_4); 18 mm – от 538.5 K (T_2) down to 309.7 K (T_4) (рис. 4, b, c, d), testifying to high heat insulation and fireproofing properties of the coatings under study.

A behavior of the <u>coated and uncoated reinforced</u> concrete specimens in case of fire was studied by appropriate calculations (interpolation) with account that a protective layer around reinforcement is 20 mm (Table 2).

The calculations made for the <u>uncoated reinforced</u> concrete specimens showed that in Point at a distance of 20 mm (possible
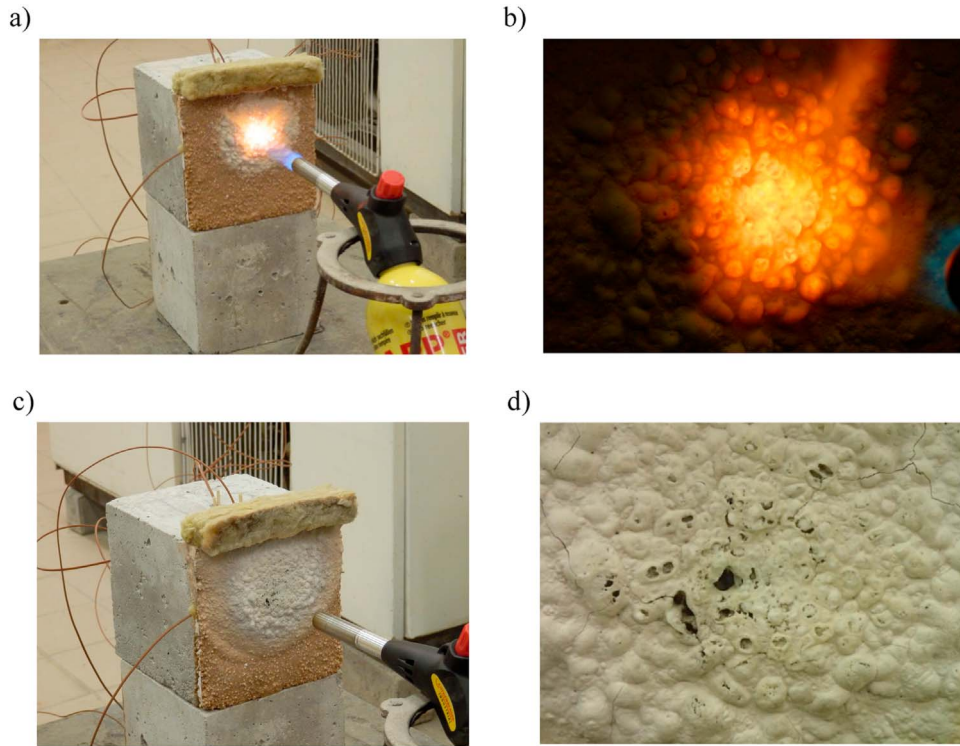
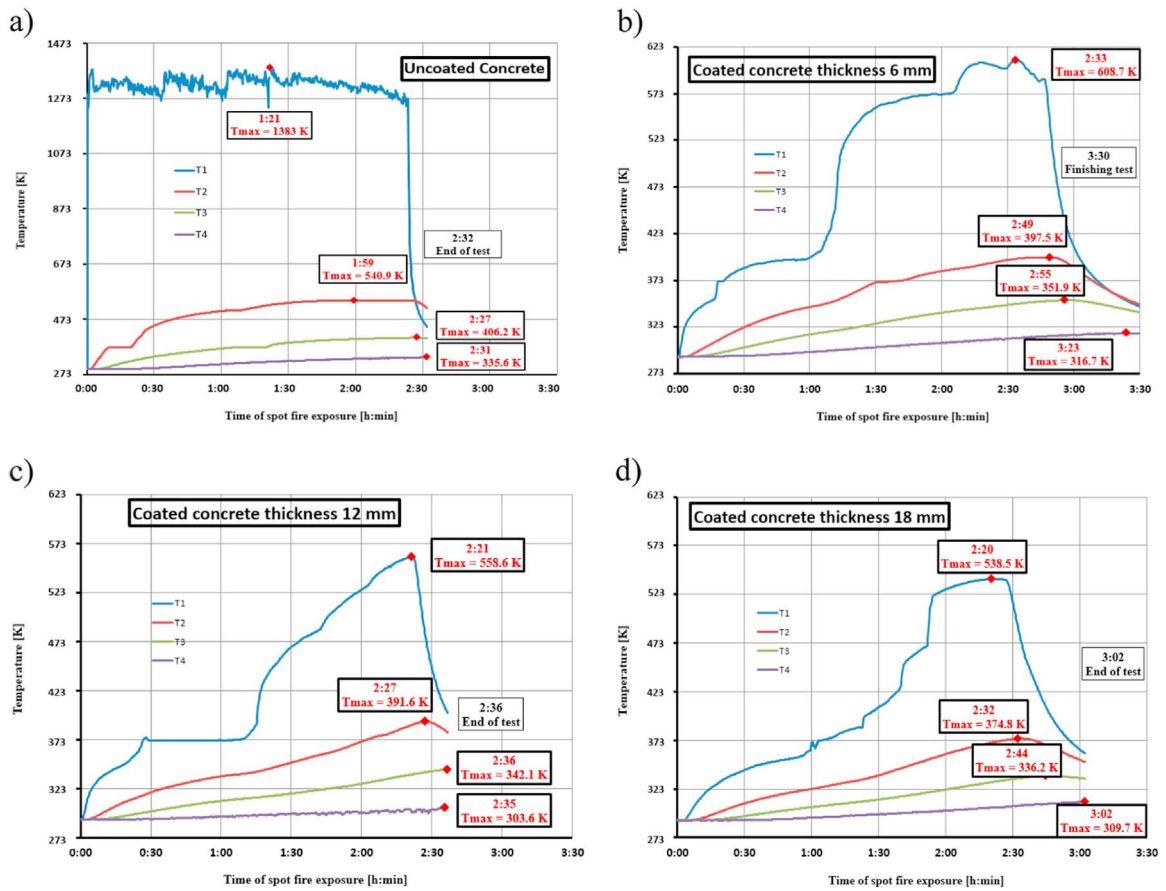**Fig. 3.** Changes in the coatings in the process of spot fire tests.

Fig. 4. Curves of temperature distribution across the uncoated (a) and coated concrete specimen (b, c, d) vs. time of spot fire exposure.

Table 2
Calculated temperatures for the uncoated and coated reinforced concrete specimens vs. time of spot fire exposure and thickness of coating (if applied).

Spot fire exposure time, h	Uncoated concrete specimen	Coated concrete specimen, thickness, mm		
		6	12	18
1	798 K	388 K	386 K	376 K
2	801 K	588 K	539 K	488 K
3	889 K	396 K	378 K	368 K

Table 3
Pull-off adhesion and type of fracture of the intumescent alkaline aluminosilicate-based coatings.

Coating thickness, mm	Pull-off strength of the coating, MPa/type of fracture	
	Before fire test	After fire test
6	2.15/ A/B	0.85/ B
12	1.56/ B	0.84/ B
18	1.54/ B	0.86/ B

reinforcement position) from the spot fire source a temperature of 798 K was reached after 1 h, being higher than a critical temperature for reinforcement (plastic deformation) (773 K).

In case of the coated reinforced concrete specimens, with increase in coating thickness from 6 to 18 mm and time of spot fire exposure from 1 to 3 h the temperatures to which the reinforcement could be heated did not reach critical values: at a thickness of 6 mm – from 388 K (1 h) up to 396 K (3 h); 12 mm – from 386 K (1 h) down to 378 K (3 h); 18 mm – from 376 K (1 h) down to 368 K (3 h). Above all, a conclusion was drawn that with the longer time of spot fire exposure the temperatures in critical points tended to decrease (Table 2).

This can be attributed to physico-mechanical processes taking place in the coatings under study in the process of swelling [16,19], namely: within a temperature range of 423–573 K due to removal of physical water from the developed intumescent coating and partial dehydration of ussingite and heulandites, a primary porous structure formation in the coating accompanied by its swelling; within a temperature range of 733–600 K due to transformation of the surface layer of the coating into a pyroclastic state a further porous structure formation takes place due to partial dehydration of $(NaAlSiO_4)_{12} \cdot 27H_2O$, faujasite-Na, chabazite and mordenite types; within a temperature range of 1023–1173 K – increase in thickness of porous layer of the coating due to complete dehydration of the zeolite-like phases (mentioned above) and dehydration of $CaCO_3$; at temperatures higher than 1323 K – porous microstructure formation of the layer of the coating with considerable increase associated with increase in thickness due to dehydration of the hydromicas of the aragonite and pyrophyllite types. Resistance to high temperatures is achieved due to synthesis in the resulted porous layer of the compounds like albite, jadeite, kyanite and α–tridymite.

Pull-off adhesion of the coatings from a concrete substrate and type of fracture are given in Table 3.

Visual examination of the detached surface as per ISO 4624:2002 [26] allowed establishing type of fracture (Table 3).

4. Conclusions

The results of study suggested drawing a conclusion that in case of spot fire exposure the intumescent alkaline aluminosilicate binder-based coatings applied to concrete and reinforced concrete surfaces in a thickness of only 6 mm could prevent concrete and reinforced concrete from brittle fracture and reinforcement from occurrence of plastic deformation for at least 2 h. The increase in thickness of the coating and time of fire exposure will result in even better heat insulating and fireproofing properties.

Test results of the developed coating 6 mm in thickness suggested concluding that before exposure of fire type, its type of fracture – was A/B (concrete substrate/coating adhesion fracture) and its pull-off strength was 2.15 MPa. A mean value of adhesion (pull-off strength) of the developed coatings 12 and 18 mm in thickness was 1.55 MPa, type of fracture – B (cohesion fracture within the coating). After exposure of fire, not depending upon thickness of the coating, a mean value of adhesion (pull-off strength) was 0.85 MPa, type of fracture – B (cohesion fracture within the swollen porous coating).

Acknowledgements

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