Monitoring of the Thermal Properties of Cement Composites with an Addition of Steel Slag

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Abstract This article presents the results of an experimental research dealing with the preparation of cement composites with an addition of steel slag, in order to verify the possibility of using ground steel slag as a suitable admixture into cement composites. The samples of the cement composites were prepared with the following types of cements: Portland cement CEM I 42.5 R, Portland mixed cement CEM II/B-S 32.5 R, blast furnace cement CEM III/A 32.5 N, and mixed cement CEM V/A (S-V) 32.5 R. We have tested the effect of ground steel slag as an

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A. Öchsner and H. Altenbach (eds.), *Improved Performance of Materials*,
Advanced Structured Materials 72, DOI 10.1007/978-3-319-59590-0_10

admixture, which had been dosed in the amount of 20% of the weight of the cement dose, on the strength parameters (tensile flexural strength and compressive strength) and the thermal properties (coefficient of thermal conductivity λ, specific heat capacity c, and coefficient of thermal diffusivity a). The results of this experimental research have shown that the use of ground steel slag as an admixture in an amount of 20% of the weight of cement in the cement composite will reduce the values of the coefficient of thermal conductivity λ in cements CEM I 42.5 R, CEM II/B-S 32.5 R, and CEM V/A (S-V) 32.5 R and, at the same time, it will not cause a decrease in compressive strength.

Keywords Cement · Admixture · Ground steel slag · Compressive strength · Tensile flexural strength · Thermal properties · Coefficient of thermal conductivity

1 Introduction

At present, heavy industry produces enormous amounts of wastes, thus causing environmental burden. One of the main representatives of this burden is the metallurgical industry, which belongs to the largest producers of wastes, whether it is in the form of emissions or production wastes. Metallurgical wastes are more and more frequently in the scope of interest of research teams constantly trying to come up with new possibilities of their use. These teams very often focus their attention on other industrial sectors consuming huge amounts of natural resources used in building production. A number of researches deal with the incorporation of metallurgical wastes into building mixtures. These researches are focused, for example, on the use of fly ash as a partial substitution of cement in the production of concretes, mortars and copolymers [1–4] or on the use of finely ground blast furnace slag together with fly ash and powder from electronic equipment as a substitution of cement in mortars in order to improve their properties [5, 6]. Other research projects deal with finely ground blast furnace slag as an effective substitute of cement, depending on its properties [7, 8], or a partial substitution of Portland cement with blast furnace slag, and concrete whose filler (natural aggregate) is partially replaced by steel slag [9, 10]. Researches focused on the thermal and technical properties of materials are becoming prominent, in order to reduce emissions and to protect the climate. There are results of researches dealing with the impact of the ratio of cement and ground iron ore used as filler on the final thermal conductivity of mortar [11], respectively dealing with the study of the thermal conductivity and strength of cement sealants containing fly ash, slag, and silica powder [12]. The experimental researches in this area are focused on the factors influencing the thermal conductivity of concrete, mortar, or cement pastes, such as the water-cement ratio, the types of admixtures, the density of fractions, the temperature and humidity [13]. We can also find results of numerical simulations of redevelopment material moisture based on cement composites [14] and the progress of the incorporation of moisture into a building with damaged waterproofing after the application of board insulation versus diffusion-open material based on calcium silicate [15, 16].

2 Materials and Methods

2.1 Composition of Cement Composite and Its Preparation

Cement. Four types of cement used for the production of cement composites have been tested to verify the possibility of the utilization of ground steel slag in the amount of 20% of the cement dose weight as an admixture: Portland cement CEM I 42.5 R and CEM V/A (S-V) 32.5 R from Cement Hranice, a.s. Company, as well as Portland mixed cement CEM II/B-S 32.5 R and blast furnace cement CEM III/A 32.5 N from Považské cementárny, a.s. All the tested cements meet the requirements of EN 197-1 [17].

Steel slag. It is an artificial aggregate which is produced during the metallurgical process, where active slag is used to separate adulterants. The basic components of steel slag are represented by the solutions of orthosilicates with the oxides of iron, manganese, aluminium and magnesium, which are chemically bound to calcium oxide. The chemical composition of the arising slag varies considerably, depending on the nature and the course of the technological process. The experimental research took advantage of converter slag fr. 0/8 from Třinecké železárny, a.s., which was ground to the specific surface area of 2356 cm^2/g according to Blaine. The grinding procedure consisted of the following steps:

1. 3 passages through a twin-cylinder mill (cylinder diameter of 300 mm), 1200/1070 rpm; 1st passage 3 mm slit (maximum refinement coefficient of 5); 2nd passage 1 mm slit (refinement coefficient of 3); 3rd passage 0.3 mm slit (minimum refinement coefficient of 3).
2. The material refined below 0.3 mm was subjected to grinding using a high speed twin-engine (1.5 + 1.5 kW) counter pin mill DESI11 with three rows of working bodies on the rotors with the diameter of 170 mm and the maximum velocity at the outer row of bodies of 210 m/s.

The chemical composition of steel slag is shown Table 1.

Table 1 Chemical composition of steel slag

Parameter	Na_2O	MgO	Al_2O_3	SiO_2	P_2O_5	SO_3	K_2O	CaO	TiO_2	MnO	Fe_2O_3
Weight %	0.42	11.4	2.40	15.3	0.95	0.40	<0.05	32.2	0.28	4.76	32.5
Parameter	V	Cr	Zn	Sr							
mg/kg	560	5450	–	–							

Table 2 Grain size composition of standardized sand

Sieve with square mesh (mm)	2.00	1.60	1.00	0.50	0.16	0.08
Total remains on the sieve (%)	0	7 ± 5	33 ± 5	67 ± 5	87 ± 5	99 ± 1

Sand. Sand standardized according to EN 196-1 was used for the production of the cement composites [17]. The grain size composition of the standardized sand is shown in Table 2. The total dose of sand for one mixture was 1350 g.

Water. Water from water mains was used for the preparation of the mortar and the subsequent production of the cement composites.

Mortar composition. Each mixture for the 3 test specimens (beams with the dimensions of 40 × 40 × 160 mm) contained 450 g of cement, 1350 g of sand and 225 g of water (comparative mixture). This comparative mixture also contained added ground steel slag in the amount of 20% of the cement dose weight, i.e. 90 g. This mortar composition was used for the testing of the above presented types of cements.

Mortar mixing. The mortar was mixed in a laboratory cement paste mixer BS-MI-CM5A from Beton Systém, s.r.o. The mixing procedure was as follows:

1. Water was poured into the mixing container and cement was dosed.
2. Mixing was automatically triggered immediately upon the contact of water and cement at low speed (rotation around the whisk axis of 140 ± 5 min^{-1}) and the mixing time was automatically measured at the same time. Sand was automatically and continuously added at equidistant time intervals of 30 s. After that, the mixing switched to high speed (rotations around the whisk axis of 285 ± 10 min^{-1}) and the mixing continued for additional 30 s.
3. The mixing was stopped automatically after 90 s. The mortar sticking to the walls and bottom of the container was scraped during the first 30 s with a rubber blade.
4. The mixing continued for additional 60 s at high speed (rotations around the whisk axis of 285 ± 10 min^{-1}).

Making of the test specimens. The test specimens in the shape of beams (composite cement), with the dimensions of 40 × 40 × 160 mm, were made immediately after the preparation of the mortar. The beam mould was always filled in two layers, while either of the layers was compacted with 60 surges on a compaction table ZSC 40. The excess mortar from the second layer was scraped off after the compaction using a metal ruler and the surface of the test specimens was horizontally smoothed out. The surface of each mould was covered with a glass plate and the mould was stored in a humid environment. After 24 h, the test specimens (beams) were demoulded and stored in water environment. The production process of the test specimens was in compliance with the procedure defined in the standard [17]. The test specimens produced in order to determine the thermal properties of the cement composite had the dimensions of 140 × 40 × 160 mm.

2.2 Methods

2.2.1 Determination of the Strength Characteristics

The strength properties of the cement composites (beams) were determined at the age of 28 days of the test specimens. The test specimens were tested for tensile flexural strength and compressive strength at the end of the beams according to a standardized procedure [17].

2.2.2 Determination of Thermal Properties

Effective thermal conductivity is significantly dependent not only on the chemical composition and structure of the material, but also on the effects of the external environment on the material, i.e. on moisture and temperature.

All the tested samples of the cement composites without and with the addition of ground steel slag were comparable in terms of the impact of humidity because they were measured in a dry state (steady-state weight). That is why their dependence on moisture was monitored.

The modelling of the thermal dependencies of the coefficients of thermal conductivity took advantage of conventional thermodynamic analytical relations (1, 2).

The coefficient of thermal conductivity λ in thermodynamics is generally defined by the Fourier's law

$$q = -\lambda \cdot grad\ t, \tag{1}$$

according to which the vector of the heat flow density q is directly proportional to the temperature gradient t and has the opposite direction.

In conventional thermodynamics, there is also a general physical rule that the higher material temperature increases the value of the coefficient of thermal conductivity approximately linearly in the narrow temperature interval, and quadratically in the wider temperature interval. The empirically verified dependence of the coefficient of thermal conductivity on temperature can be expressed analytically. The theoretical and practical thermodynamics uses the relation (2), especially for elementary temperature differences, such as the linear increase of material coefficient with temperature

$$\lambda = \lambda_0 \cdot [1 + \alpha_t \cdot (t - t_0)]\ , \tag{2}$$

where λ is the value of the coefficient of thermal conductivity of the examined material at the temperature t, λ_0 is the value of the coefficient of thermal conductivity of the examined material at the temperature of t_0, α_t is the linearized coefficient of the increase of the value of the coefficient of thermal conductivity with material temperature (using empirical and approximate evaluation for specific material).

The tested samples of the cement composites were well comparable in terms of their geometrical dimensions, they were also heated under the same operating conditions and measured using the same instruments, and the measurement results were evaluated by the same methodology.

ISOMET 2114 commercial device was used to measure the material parameters of the samples of the cement composites at a specific surface temperature. The measurements taking advantage of this device are based on an analysis of the course of the time dependence of the thermal response to pulses of heat flux into the analyzed material. The heat flux is created by scattered electric power in a probe resistor, which is thermally and conductively connected to the analyzed material. The temperature is sampled, and it is directly evaluated as a function of time by means of polynomial regression. The coefficients obtained by this regression are subsequently used to calculate the measured quantities.

The temperatures of opposite walls of the studied samples were measured using a prototype calorimetric computer-controlled chamber [18]. Excel spreadsheet processor was used to perform a graphical evaluation of the time development of the temperatures of the opposite walls of the examined samples, the evaluation of the temperature differences between the walls of the samples, the mean material core temperatures of the samples, and the coefficients of thermal conductivity of the samples, as well as graphical evaluations of the temperature development of the coefficients of thermal conductivity.

3 Measurement Results and Discussion

Figures 1 and 2 present the results of the strength characteristics of the cement composites.

The results of the strength parameter test clearly show that ground steel slag, which was used as an admixture in the production of cement composites and was dosed in the amount of 20% of the cement weight, does not significantly decrease the tensile flexural strength of the cement composites with various types of cements. When we compare the comparative samples and the samples with additions of ground steel slag, it is clearly visible that the change of the tensile flexural strength varies within the range of 0.06–0.51 MPa.

Figure 2 clearly shows that ground steel slag in the amount of 20% of the cement weight caused an increase in compressive strength of cement composites in cases where CEM II/B-S 32.5 R, CEM III/A 32.5 N and CEM V/A (S-V) 32.5 R cements were used. The highest increase (by about 5 MPa, app. 11%) was recorded in cement composites based on CEM II/B-S 32.5 R and CEM V/A (S-V) 32.5 R. On the other hand, the ground steel slag had no effects on the increase of the compressive strength of cement composites with CEM I 42.5 R.

Table 3 shows the results of the measurements of the thermal properties of the cement composites using commercial device ISOMET 2114.

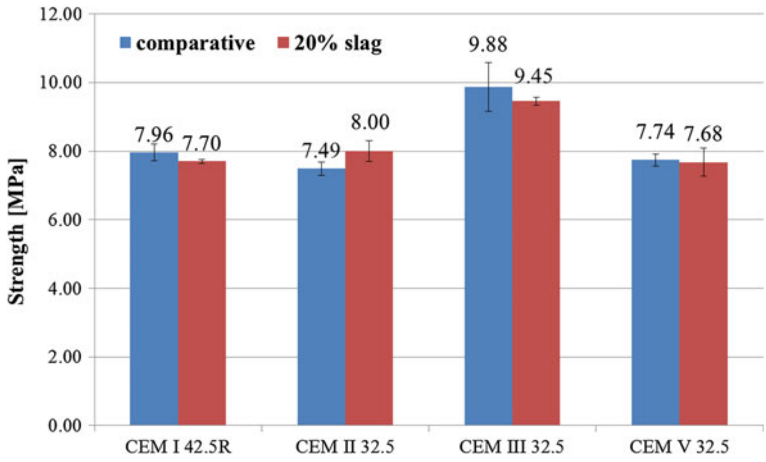

Fig. 1 Tensile flexural strength of cement composites after 28 days

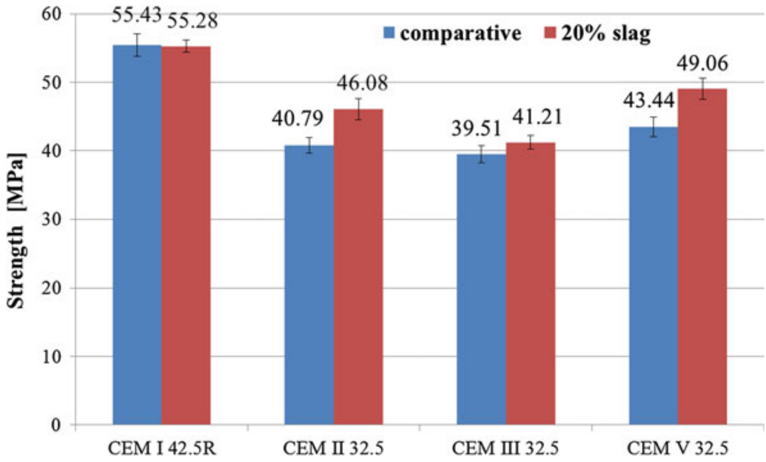

Fig. 2 Compressive strength of cement composites after 28 days

Table 3 shows that ground steel slag tested as an admixture in an amount of 20% of the cement weight is actively involved in the improvement of the thermal properties, especially in composites prepared from CEM I 42.5 R, CEM II/B-S 32.5 R and CEM V/A (S-V) 32.5 R.

Figures 3–6 present the results of the measurements of the thermal properties in a prototype calorimetric computer-controlled chamber within the temperature range of −5–50 °C. The measured results were used to model the dependencies of the coefficients of thermal conductivity λ on mean core temperature t_s of the examined samples.

Table 3 Thermal properties of cement composites measured using ISOMET 2114 device

Cement composite		Coefficient of thermal conductivity λ Ø (W/m K)	Volume-specific heat capacity $c \times 10^6$ Ø (J/m^3 K)	Coefficient of thermal diffusivity $a \times 10^{-6}$ Ø (m^2/s)
CEM I 42.5 R	Comparative	2.5218	1.8335	1.3754
	20% slag	2.4179	1.7815	1.3572
CEM II/B-S 32.5 R	Comparative	2.4941	1.8273	1.3650
	20% slag	2.3308	1.7367	1.3431
CEM III/A 32.5 N	Comparative	2.5046	1.8509	1.3532
	20% slag	2.5265	1.9056	1.3258
CEM V/A (S-V) 32.5 R	Comparative	2.6813	1.9231	1.3942
	20% slag	2.4602	1.8086	1.3603

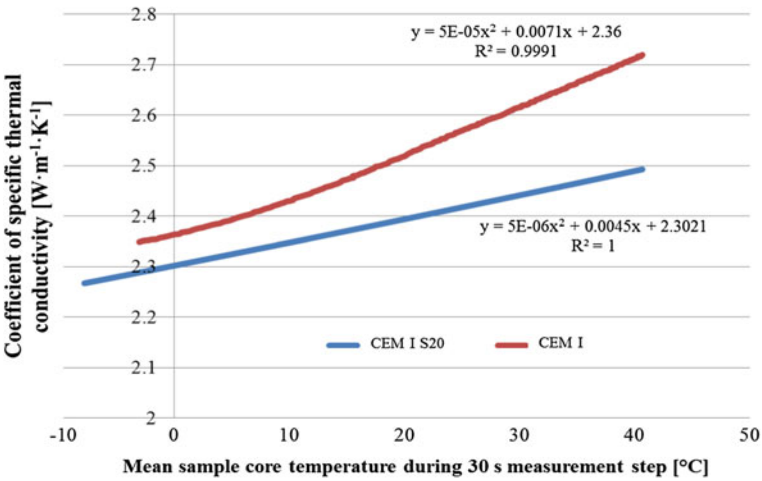

Fig. 3 Dependence of the coefficient of thermal conductivity λ on temperature for cement composite with CEM I 42.5 R

Direct measurements of the temperatures of opposite walls of the samples (250 sub-measurements of heating at temporally equidistant steps of 30 s) were performed during the experimental phase.

The evaluation phases involved indirect measurements, i.e. the measurement results were converted into an Excel spreadsheet processor. The evaluated factors included especially the mean material core temperatures t_s of the specimens during each sub-measurement in temporally equidistant steps of 30 s. The other modelled areas included the partial dependencies of $\lambda = \lambda\ (t_s)$ according to physical relations (1, 2) using an approximation and regression method (linear line, quadratic curve,

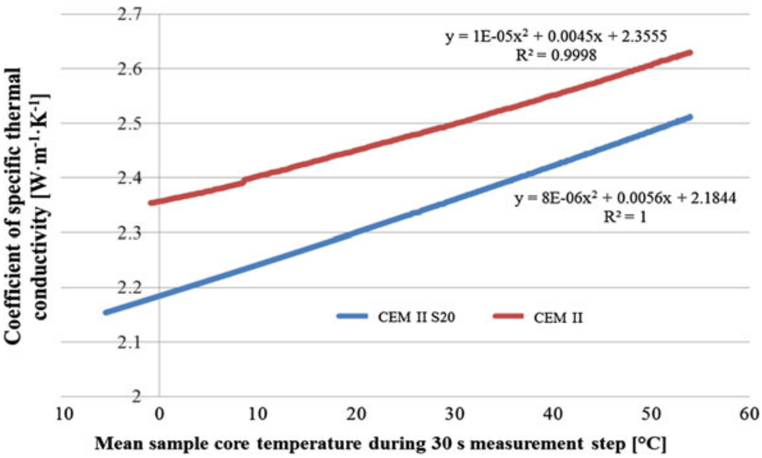

Fig. 4 Dependence of the coefficient of thermal conductivity λ on temperature for cement composite with CEM II/B-S 32.5 R

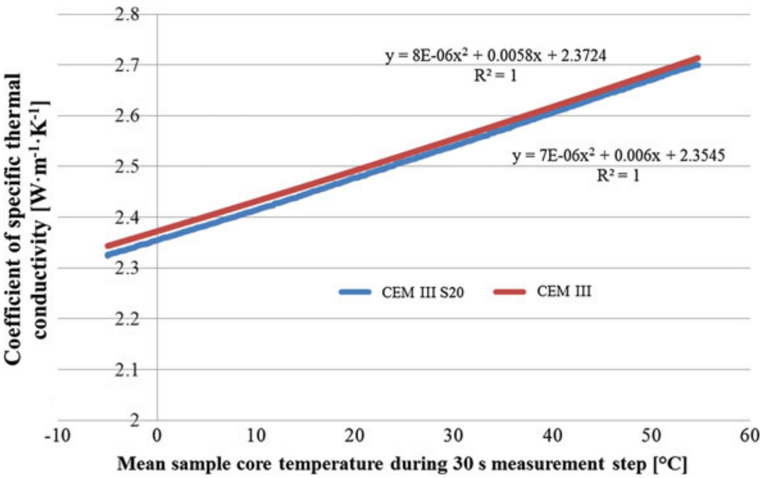

Fig. 5 Dependence of the coefficient of thermal conductivity λ on temperature for cement composite with CEM III/A 32.5 N

the courses were controlled by means of closeness of conformity). Finally, comparative charts of the dependencies of $\lambda = \lambda\ (t_s)$ of matching pairs of dependencies of the coefficients of thermal conductivity on mean sample material temperature with slag and the dependencies of the coefficients of thermal conductivity on the same mean material temperature without slag were performed for the purpose of the interpretation of the measurement results (see Figs. 3, 4, 5 and 6).

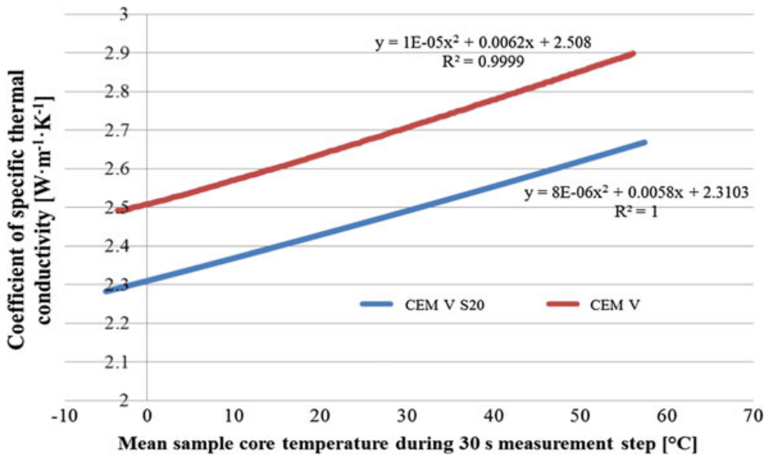

Fig. 6 Dependence of the coefficient of thermal conductivity λ on temperature for cement composite with CEM V/A (S-V) 32.5 R

It can be stated that in 2 presented cases of Portland cement CEM I 42.5 R and Portland mixed cement CEM II/B-S 32.5 R (Figs. 3 and 4), the dependencies of the coefficients of thermal conductivity on mean material core temperatures do not show entirely comparative development trends (in Fig. 3—the courses are slightly diverging, on the other hand, in Fig. 4—the courses are slightly converging). The admixture of slag is incorporated into the designed mixtures in such a way that the composites are not comparably "homogeneous" in their structure in comparison with the composites without the admixture of slag.

In 2 presented cases of blast furnace cement CEM III/A 32.5 N and mixed cement CEM V/A (S-V) 32.5 R (Figs. 5 and 6), it can be stated that the dependencies of the coefficients of thermal conductivity on the mean material core temperatures show well comparable development trends. The admixture of slag into the newly designed mixtures is incorporated in such a way that the composites are comparably "homogeneous" in their structure in comparison with the composites without the admixture of slag.

4 Conclusions

The results of the experimental research have confirmed that it is possible to use ground steel slag with a specific surface of 2350 cm^2/g according to Blaine as an admixture in an amount of 20% of the cement weight, without any significant decrease in the tensile flexural strength after 28 days in case of cement composites produced from CEM I 42.5 R, CEM II/B-S 32.5 R, CEM III/A 32.5 N and CEM V/A (S-V) 32.5 R.

Ground steel slag in an amount of 20% of the cement weight in all cases of the presented measurements:

- increases the compressive strength of the cement composites after 28 days (when using cement CEM I 42.5 R, CEM II/B-S 32.5 R and CEM V/A (S-V) 32.5 R);
- slightly decreases the value of the coefficient of thermal conductivity, i.e. the insulation thermal properties of the cement composites improve (when using cement CEM I 42.5 R, CEM II/B-S 32.5 R and CEM V/A (S-V) 32.5 R).

As far as the informative value of the measurement results is concerned, the designed and examined materials of the cement samples with an addition of ground steel slag have exactly declared properties under exactly specified laboratory conditions.

Acknowledgements Project Institute of Clean Technologies for Mining and Utilization of Raw Materials for Energy Use. Reg. No. LO1406. SP2016/35—The Use of Steel Slag as an Admixture for the Preparation of Cement Composites.

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