

The use of EAF dust in cement composites: Assessment of environmental impact

Tina Šturm^a, Radmila Milačič^a, Simona Murko^a, Mitja Vahčič^a, Ana Mladenovič^b, Jerneja Strupi Šuput^b, Janez Ščančar^{a,*}

^a Department of Environmental Sciences, Jožef Stefan Institute, Jamova 39, 1000 Ljubljana, Slovenia

^b Slovenian National Building and Civil Engineering Institute, Dimičeva 12, 1000 Ljubljana, Slovenia

ARTICLE INFO

Article history:

Received 28 July 2008

Received in revised form 2 October 2008

Accepted 9 November 2008

Available online 17 November 2008

Keywords:

Cement composites

Cement composites with addition of EAF dust

Leachability

Cr(VI)

Metals

ABSTRACT

Electric arc filter dust (EAF dust) is a waste by-product which occurs in the production of steel. Instead of being disposed of, it can be used in cement composites for civil engineering, and for balances in washing machines. To estimate the environmental impact of the use of EAF dust in cement composites leachability tests based on diffusion were performed using water and salt water as leaching agents. Compact and ground cement composites, and cement composites with addition of 1.5% of EAF dust by mass were studied. The concentrations of total Cr and Cr(VI) were determined in leachates over a time period of 175 days. At the end of the experiment the concentrations of some other metals were also determined in leachates. The results indicated that Cr in leachates was present almost solely in its hexavalent form. No leaching of Cr(VI) was observed in aqueous leachates from compact cement composites and compact cement composites to which different quantities of EAF dust have been added. In ground cement composites and in ground cement composites with addition of EAF dust, Cr(VI) was leached with water in very low concentrations up to $5 \mu\text{g L}^{-1}$. Cr(VI) concentrations were higher in salt water leachates. In compact and ground cement composites with addition of EAF dust Cr(VI) concentrations were 40 and $100 \mu\text{g L}^{-1}$, respectively. It was experimentally found that addition of EAF dust had almost no influence on leaching of Cr(VI) from cement composites. Leaching of Cr(VI) originated primarily from cement. Leaching of other metals from composites investigated did not represent an environmental burden. From the physico-mechanical and environmental aspects EAF dust can be used as a component in cement mixtures.

© 2008 Elsevier B.V. All rights reserved.

1. Introduction

In the developed countries waste products like recycled building rubbles [1,2], waste glass [3], crumb rubber [4], quarry waste [5], shingle waste [6], sewage sludge [7], non-metallic automotive shredder residues [8] as well as industrial by-products such as steel slag [9–14], filter dust from steelworks [15], cement kiln dust [5,16], asphalt dust [5], coal fly ash [5,18], coal bottom ash [5] and municipal solid waste incinerator bottom ash [19] are widely used in civil engineering, especially for road construction. In the last decades these waste products are being exploited as alternative materials that successfully substitute natural raw materials. Re-use of recycled waste materials and industrial by-products leads to preservation of natural resources [11], substantial reduction of landfills load and protection of the terrestrial environment. The use of materials originating from industrial by-products is possible when such materials possess appropriate technical qualities [11,14]

and are environmentally acceptable [7,11,12,15,17]. Waste materials and industrial by-products that can be potentially re-used may contain different pollutants like metals and organic compounds. The toxicity of the pollutant depends not only on its total concentration, but also on the chemical form and its mobility in the environment. When waste materials and industrial by-products are re-used for road construction and in civil engineering, toxic substances may be successfully immobilised with asphalt [15] and cement [20,21]. Nevertheless, before the use, the environmental risk due to the potential release of contaminants from alternative aggregates should be critically evaluated [12,13,15,21–26]. The major potential hazard to terrestrial and aquatic environment is the leaching of toxic substances from such alternative materials [15,22–26]. In order to estimate the long-term environmental impact, leaching tests based on diffusion were proposed in the Netherland's NEN 7345 standard [27] and applied in the leaching protocol developed for concrete [28]. Similar leaching protocol was used also to evaluate the environmental acceptability of the asphalt composites with addition of filter dust [15].

In Slovenia, as by-products of the steel industry, about 200,000 tons of steel slag and 9000 tons of EAF dust from the

* Corresponding author. Tel.: +386 1 4773900; fax: +386 1 2519385.

E-mail address: janez.scancar@ijs.si (J. Ščančar).

electric arc furnaces are generated per year. For the time being EAF dust was disposed in landfills or recycled abroad. Disposal of EAF dust in landfills represented the environmental hazard due to its dusty nature and the presence of potentially toxic metals. Since landfills in Slovenia are overloaded and recycling is expensive, the alternatives for re-use of EAF dust were examined. EAF dust represents an appropriate material for incorporation into asphalt or cement. In our previous investigation the potential of the use of EAF dust in asphalt composites was critically evaluated [15]. It was demonstrated that from the physico-mechanical as well as from the environmental point of view, EAF dust can be used as an additive to asphalt for road construction.

The aim of the present investigation was to critically evaluate the potential use of EAF dust as additive to cement that may be used in civil engineering and for balances in washing machines. The physico-mechanical characteristics of cement composites with addition of EAF dust were evaluated and the long-term environmental impact investigated by the use of leachability tests based on diffusion. Water and salt water were applied as leaching agents. Compact and ground cement composites and cement composites with addition of 1.5% of EAF dust by mass were studied. The experiment was carried out over a time period of 175 days, following the concentrations of total Cr and Cr(VI) in leachates. Finally, the concentrations of some other metals were also determined in leachates at the end of the experiment.

2. Materials and methods

2.1. Apparatus

Total metal concentrations in leachates of cement composites and cement composites with addition of EAF dust were determined by flame atomic absorption spectrometry (FAAS) on a Varian (Mulgrave, Victoria, Australia) Spectra AA 110 atomic absorption spectrometer, and by electrothermal atomic absorption spectrometry (ETAAS) on a Hitachi (Tokyo, Japan) Z-8270 polarized Zeeman atomic absorption spectrometer equipped with an autosampler. The content of Cr(VI) in leachates of cement composites and cement composites with addition of EAF dust was determined by fast protein liquid chromatography with ETAAS detection (FPLC-ETAAS). The chromatographic system consisted of a Varian (Mulgrave, Victoria, Australia) Model 9010 HPLC inert Star Gradient Solvent Delivery System and a Rheodyne (Cotati, California, USA) Model 7161 injector using 0.5 mL loop. A strong anion-exchange FPLC column of Mono Q HR 5/5 (Amersham, Uppsala, Sweden) (column dimensions 5 mm × 50 mm, 10 μm beaded polyether resin, pH stability 2–12) was employed for the Cr(VI) separation. The separated Cr species were determined “off line” in 0.5 mL fractions by ETAAS.

A WTW (Weilheim, Germany) 330 pH meter was employed to determine the pH of leachates of cement composites and cement composites with addition of EAF dust.

2.2. Reagents

Merck (Darmstadt, Germany) suprapur acids and Milli-Q water (Direct-Q5 Ultrapure water system, Millipore Watertown, MA, USA) were used for the preparation of samples and standard solutions. All other reagents were of analytical reagent grade.

Stock standard solutions of metals ($1000 \pm 2 \text{ mg L}^{-1}$ in 5% HNO_3) were obtained from Merck. Fresh working standard solutions were prepared by dilution of an appropriate stock solution with water and used in determination of metal concentrations in leachates of cement composites and cement composites with the addition of EAF dust.

For the preparation of salt water, NaCl obtained from Carlo Erba (Milano, Italy) was used.

Sartorius (Goettingen, Germany) 0.45 μm cellulose nitrate membrane filters of 25 mm diameter were used in the filtration procedure.

The certified reference materials CRM 544, Cr(III), Cr(VI) species and total Cr in lyophilised solution obtained from the Community Bureau of Reference (BCR, Geel, Belgium) and SPS-SW1, Quality Control Material for Surface Water Analysis purchased from SPS Spectrapure Standards AS (Oslo, Norway) were used to check the accuracy of the analytical procedures.

2.3. Determination of Cr(VI) in leachates

Before analysis, leachates were filtered through 0.45 μm membrane filter. The same chromatographic procedure was applied as in the determination of Cr(VI) in the highly alkaline (pH 12) quicklime-treated sewage sludge extracts [29] and cement extracts [30]. 0.5 mL of sample was injected onto the column. Buffer A consisting of TRIS-HCl (0.005 mol L^{-1} , pH 8.0) and buffer B (buffer A plus 0.5 mol L^{-1} NaCl) were employed in linear gradient elution from 0 to 100% of buffer B for 15 min at a flow rate of 1.0 mL min^{-1} . Cr(VI) was eluted between 10.5 and 11.5 min with a maximal peak at 11.0 min. The column was regenerated with 2 mol L^{-1} NaCl for 5 min and equilibrated with buffer A in the following 10 min at a flow rate of 1.0 mL min^{-1} . The chromatographic run was completed in 30 min. The separated Cr species were determined “off line” by ETAAS in 0.5 mL fractions. In order to reduce the salt deposit and to obtain reproducible measurements, 5 μL of 32% HNO_3 was added to the graphite tube before each determination [31]. To overcome interference effects in ETAAS determinations, eluent-matched standard solutions of Cr(VI) were prepared in eluent solution of the same molarity that eluted Cr(VI) from the column (0.4 mol L^{-1} NaCl) [29,30]. All analyses were done in duplicate.

2.4. Determination of total Cr and other metals in leachates

Before determination of total metal concentrations sample leachates were filtered through 0.45 μm membrane filter. Total Cr, Mo, Co and V were determined by ETAAS under optimal measurement conditions. To reduce the salt deposit 5 μL of 32% HNO_3 was added to the graphite tube before each determination [31]. Concentrations of Cu, Zn, K, Cd and Pb were determined by FAAS in an air-acetylene flame, while Ni, Fe, Ca, Mg and Mn were determined by FAAS in a nitrous-oxide-acetylene flame.

2.5. EAF dust

EAF dust from electric arc furnaces is a waste by-product which occurs in the production of steel. In the present investigation EAF dust generated at the steelwork Štore Steel, Slovenia was used. It contains high total concentrations of metals, of which Zn (23–24%) and Fe (18–22%) are the major components. Other metals like Pb, Ca, Mg and Mn are present in concentrations below 4%, while Cr concentration is about 0.3%. Since metals in EAF dust are primarily present as sparingly soluble oxides the leaching of metals in water is in general negligible with exception of Cr(VI) that is to some extent leached with water. Concentration of Cr(VI) in aqueous leachate of filter dust (pH 7.0), determined according to the SIST EN 12457-4 procedure was found to be 0.8 mg kg^{-1} [15]. Other detailed characteristics of EAF dust were reported in our previous work [15].

2.6. Cement samples

The cement used for preparation of cement composites and cement composites with addition of EAF dust was CEM I, which

Table 1

The characteristics of the investigated cement pastes and mortars.

Parameters	CEM I	CEM I + 1% of EAF dust	CEM I + 1.5% of EAF dust	CEM I + 3% of EAF dust	CEM I + 5% of EAF dust
Standard consistence test (EN 196-3) [35]	28.7%	29.0%	29.4%	29.2%	29.4%
w/c paste	0.29	0.29	0.30	0.30	0.31
Initial setting time (EN 196-3)	125 min	225 min	200 min	>1440 min	>1440 min
Final setting time (EN 196-3)	180 min	280 min	265 min	–	–
Soundness test (EN 196-3)	0.6 mm	0.2 mm	0.7 mm	–	–
w/c mortar	0.50	0.51	0.51	–	–
Bending strength, 7 days (EN 196-1)	6.4 MPa	4.0 MPa	4.9 MPa	–	–
Compressive strength, 7 days (EN 196-1)	45.5 MPa	48.1 MPa	45.3 MPa	–	–
Shrinkage (EN 12617-4) [36] after					
7 days	–0.20‰	–0.23‰	–0.10‰	–	–
14 days	–0.33‰	–0.35‰	–0.17‰	–	–
21 days	–0.35‰	–0.35‰	–0.23‰	–	–
28 days	–0.40‰	–0.48‰	–0.35‰	–	–

is a common Portland cement, most widely used throughout the world in all fields of civil engineering. Concentration of water-soluble Cr(VI) in cement was determined according to SIST EN 196-10 procedure by the 1,5-diphenyl spectrophotometric method [32]. The cement used in experiments contained below 0.1 mg kg^{-1} of water-soluble Cr(VI). The pH of aqueous leachate of cement was 12. Slovenia adopted a European Directive 2003/53/EC [33] that has been implemented on 17 January 2005, introducing restriction on the use of cement and cement products, which contain, when hydrated, more than 2 mg kg^{-1} of soluble Cr(VI). To fulfill these requirements, cement samples are treated with reducing agents, e.g., ferrous(II) sulphate or ammonium ferrous(II) sulphate.

2.7. Experimental design

Since the effects which different quantities of added EAF dust might have on the properties of fresh cement pastes (cement + water) and hardened cement mortars (EN 196-1 [34]), it was decided that several different percentages of added EAF dust, amounting to 1, 1.5, 3 and 5% by mass, should be experimentally investigated (see Table 1). The total powder amount (5 by mass) was the same in each test. It was found that if only 1% of EAF dust is added none of the properties listed in Table 1 are affected, whereas if 1.5% of EAF dust is added there is no effect on the rheology of the fresh paste, and that shrinkage when the samples were exposed to drying was somewhat reduced, and a negligible reduction in their bending and compressive strengths occurs. If either 3 or 5% of EAF dust is added, then there is an effect on the properties of the fresh paste, and the drying time is extended by more than 1440 min. For this reason it was estimated that these two composites were unsuitable for use in civil engineering, and they were eliminated from the further test program.

From the above experimentally obtained results it therefore follows that the maximum amount of EAF dust which can be added to cement in order to ensure the latter's optimum physical–mechanical characteristics was 1.5% by mass of the cement composite. The leaching tests were performed on hardened mortar bars with dimensions: $16 \text{ cm} \times 4 \text{ cm} \times 4 \text{ cm}$. The volume of each composite was approximately 0.26 L and its mass 0.57 kg. Eight parallel cement composites without EAF dust and eight parallel cement composites with addition of 1.5% EAF dust were prepared. Four of eight parallel samples of each type of composite were ground to a particle size below 0.5 cm. The disc mill with grinding sets made from tungsten carbide has been used for preparation of ground composites. In order to assess the long-term environmental impact of cement and cement composites with addition of EAF dust, the leachability test was carried out in water and salt water (3.8% NaCl). Leachability was investigated in compact and ground composites. Ground composites simulated decomposition in the environment with time, while salt water as leaching solu-

tion simulated the sea water environment. In addition, salt water also simulated the potential environmental scenario that landfills in which cement composites are disposed are influenced by the salting of roads during the wintertime. Namely, cement composites that are used as balances in washing machines are at the end of their service life disposed in landfills. To perform the leachability test, NEN 7345 standard based on diffusion [27] and the leaching protocol that was developed for concrete [28] were adopted. In this leaching protocol the ratio between volume of a testing composite and the volume of added leaching solution was 1:5. Therefore, in our experiment, to each compact and/or ground composite 1.28 L of water or salt water were added. The experiments were carried out in duplicate. Compact and ground composites were transferred to 3 L polyethylene beakers. The leaching solution was added and the beakers were hermetically covered with plastic lids. The level of solution was marked at the start of the experiment. Blank samples (water and salt water) were prepared in polyethylene beakers and analysed together with samples during the course of the experiment. In order to investigate the leaching of Cr and Cr(VI) from cement composites and cement composites with addition of EAF dust the first samples were taken 3 h after the start of the experiment and the following after 1, 2, 4, 8, 14, 105 and 175 days. Before each sampling the solution was mixed with a glass rod. 15 mL of sample was then taken with a plastic syringe and filtered through a $0.45 \mu\text{m}$ membrane filter. After each sampling the same amount of leaching solution as taken for the analysis (15 mL) was added and the beakers were hermetically covered with plastic lids. In the leaching solution from the last sampling (175 days after the start of the experiment) Mo, Co, V, Cu, Zn, K, Cd, Pb, Ni, Fe, Ca, Mg and Mn were also determined.

3. Results and discussion

3.1. Quality control of analytical data

The accuracy of the determinations of total metal content in leachates was checked by the analysis of SPS-SW1, Quality Control Material for Surface Water Analysis. Results are presented in

Table 2Analysis of surface water Quality Control Material SPS-SW1 by FAAS* and ETAAS. Results represent the mean \pm variation of two parallel samples.

Element	Certified value ($\mu\text{g L}^{-1}$)	Determined value ($\mu\text{g L}^{-1}$)
Cd	0.50 ± 0.01	0.53 ± 0.03
Cu	20 ± 1	20.0 ± 0.1
Cr	2.00 ± 0.01	2.1 ± 0.1
Pb	5.0 ± 0.1	5.1 ± 0.1
Ni	10.0 ± 0.1	10.2 ± 0.2
Zn*	20 ± 1	21.2 ± 0.2
V	10.0 ± 0.1	10.5 ± 0.5

Table 3
pH values in aqueous and salt water leachates. Results represent average pH during the course of the experiment \pm deviation between individual measurements.

Sample	Leaching solution:water pH	Leaching solution:salt water pH
Blank sample (pH adjusted with NaOH/Na ₂ CO ₃ buffer)	12.0 \pm 0.1	13.0 \pm 0.1
Compact cement composite	11.0 \pm 0.1	12.0 \pm 0.1
Compact cement composite with addition of filter dust	11.0 \pm 0.1	12.0 \pm 0.1
Ground cement composite	12.0 \pm 0.1	13.0 \pm 0.1
Ground cement composite with addition of filter dust	12.0 \pm 0.1	13.0 \pm 0.1

Table 2. The data indicate good agreement between determined and certified values, confirming the accuracy of the analytical results.

The accuracy of the determination of total Cr and Cr(VI) was tested by the analysis of certified reference materials CRM 544, Cr(VI) in lyophilised solution. Total Cr was determined by ETAAS. The determined concentration $49.0 \pm 0.7 \mu\text{g L}^{-1}$ agreed well with the reported certified value for total Cr $49.4 \pm 0.9 \mu\text{g L}^{-1}$. Cr(VI) was determined by the anion-exchange FPLC-ETAAS procedure. The determined concentration of Cr(VI) $23.5 \pm 1.0 \mu\text{g L}^{-1}$ was in good agreement with the reported certified value $22.8 \pm 1.0 \mu\text{g L}^{-1}$. These results confirmed the accuracy of analytical results for the determination of Cr by ETAAS and Cr(VI) by FPLC-ETAAS.

3.2. Assessment of the environmental impact of the use of EAF dust in cement composites: leachability of Cr and Cr(VI)

In order to estimate the environmental consequences of the use of EAF dust as an additive to cement, cement composites and cement composites with addition of 1.5% of EAF dust by mass were investigated. The leachability of total Cr and Cr(VI) was studied in compact and ground composites in water and salt water as described in Section 2.7. The pH was determined in leachates throughout the experiment. It was experimentally found that pH in leachates was not changed during the course of the experiment. The results are presented in Table 3. The pH of blank samples of water and salt water was adjusted with NaOH/CaCO₃ buffer to 12

and 13, respectively. The pH of aqueous and salt water leachates of cement composites and cement composites with addition of EAF dust was, due to dissolved Ca(OH)₂ and CaCO₃, highly alkaline and ranged between 11 and 13. In ground composites the pH was for one unit higher than in compact composites due to higher specific surface and consequently higher leachability of Ca(OH)₂ and CaCO₃. In comparison to aqueous leachates, the pH was also for one unit higher in salt water composites. This indicates that due to the higher ionic strength of the leaching solution, the leachability of Ca(OH)₂ and CaCO₃ from cement composites is more efficient in salt water.

Data of the leaching test indicated that during the course of the experiment the total Cr and Cr(VI) were not leached with water in compact cement composites and compact cement composites with addition of EAF dust (concentrations were below the limit of detection of the analytical procedure applied $1.5 \mu\text{g L}^{-1}$ Cr(VI)). However, in ground cement composites and ground cement composites with addition of EAF dust (Fig. 1), total Cr and Cr(VI) were leached with water. Nevertheless, the concentrations were very low and did not exceed $5.5 \mu\text{g L}^{-1}$ of total Cr. As it can be seen from Fig. 1, Cr in aqueous leachates existed most exclusively in its hexavalent form. Data from Fig. 1 further indicate that leaching of Cr(VI) with water originated only from cement, since in ground cement composites with addition of EAF dust the same extent of leaching of Cr(VI) was observed as in ground cement composites. In Fig. 2 leaching from compact composites and in Fig. 3 leaching

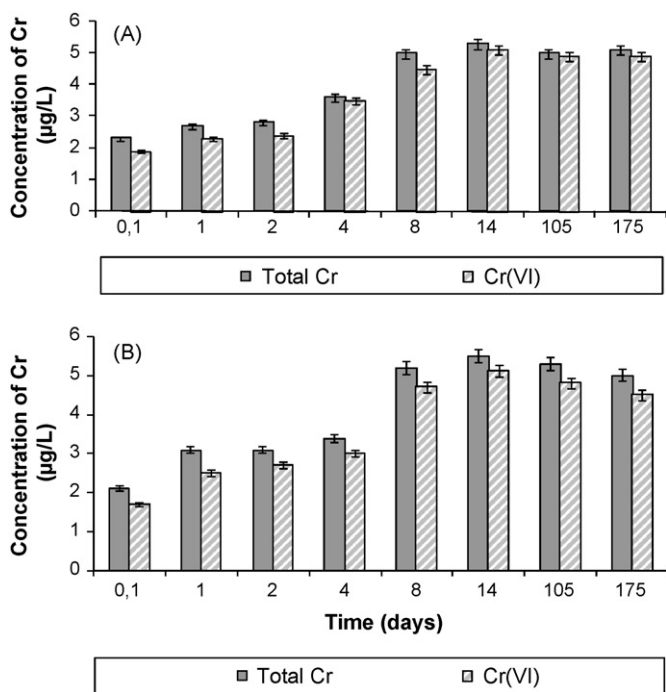


Fig. 1. Leaching of total Cr and Cr(VI) in water with time from ground cement composite (A) and ground cement composite with addition of filter dust (B). Results represent the average of two parallel samples. In each bar the two concentrations that characterize the mean value are indicated.

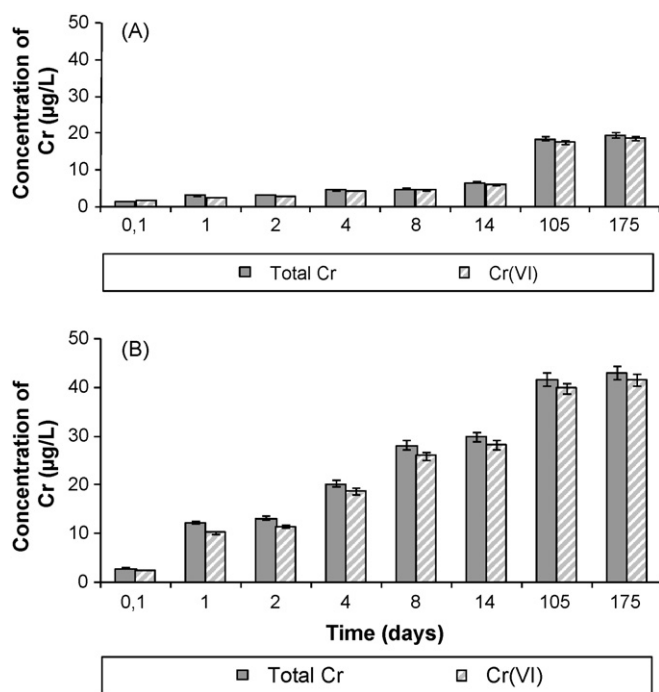


Fig. 2. Leaching of total Cr and Cr(VI) in salt water with time from compact cement composite (A) and compact cement composite with addition of filter dust (B). Results represent the average of two parallel samples. In each bar the two concentrations that characterize the mean value are indicated.

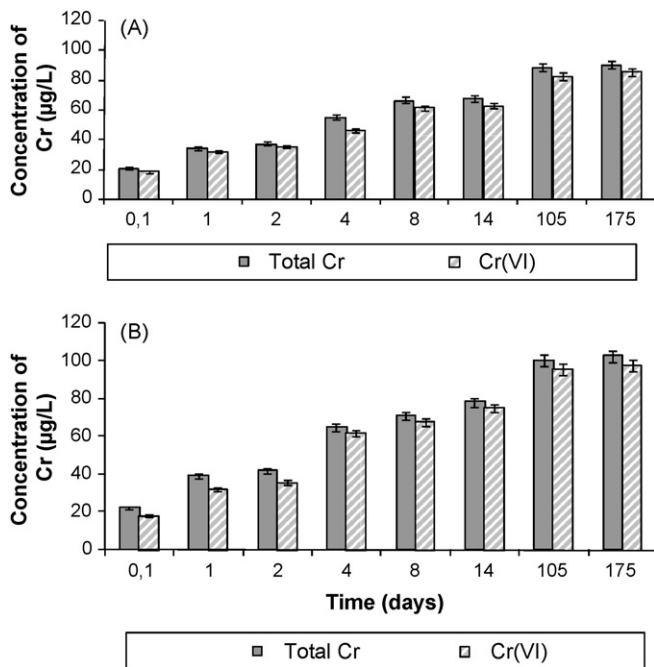


Fig. 3. Leaching of total Cr and Cr(VI) in salt water with time from ground cement composite (A) and ground cement composite with addition of filter dust (B). Results represent the average of two parallel samples. In each bar the two concentrations that characterize the mean value are indicated.

from ground composites in salt water is presented. The data from Figs. 2 and 3 indicate that more than 90% of total Cr in leachates is present in its hexavalent form. The extent of leaching of Cr(VI) in salt water is higher than in water. This effect is most probably related to higher ionic strength of salt water as leaching solution that causes more efficient leaching of $\text{Ca}(\text{OH})_2$ and CaCO_3 . As a consequence, the pH of leachate is risen for one unit (see data in Table 3), while higher pH values favour the existence of Cr(VI). Data from Figs. 2 and 3 further indicate that leaching of Cr(VI) in salt water from compact and ground cement composites and cement composites with addition of EAF dust gradually increases with time and tends toward constant values after approximately 100 days. During the course of the experiment the concentrations of Cr(VI) in leachates from compact cement composites in salt water did not exceed $20 \mu\text{g L}^{-1}$ and in leachates from compact cement composites with addition of EAF dust $40 \mu\text{g L}^{-1}$ (Fig. 2). The difference ($20 \mu\text{g L}^{-1}$ of Cr(VI)) corresponded to the leachability of Cr(VI) from EAF dust added to cement composite. More intensive leaching in salt water is observed from ground cement composites (up to $80 \mu\text{g L}^{-1}$ of Cr(VI)) and ground cement composites with addition of EAF dust (up to $100 \mu\text{g L}^{-1}$ of Cr(VI)) (Fig. 3). Again, the difference ($20 \mu\text{g L}^{-1}$ of Cr(VI)) corresponded to the leachability of Cr(VI) from EAF dust added to cement composite. Therefore, the main contribution to the leachability is represented by Cr(VI) that originates from cement. Namely, despite the presence of the reducing agents in cement [33], Cr is in highly alkaline solutions, that enable oxidation processes with atmospheric oxygen, to some extent oxidised to Cr(VI).

Table 4

Concentrations of elements in aqueous leachates from cement composites and compact cement with addition of filter dust 175 days after the start of the experiment. Concentrations of elements were determined by FAAS and ETAAS*. Results represent the mean \pm variation of two parallel samples.

Element	Concentration in aqueous leachate from compact cement composite (mg L^{-1})	Concentration in aqueous leachate from compact cement composite with addition of filter dust (mg L^{-1})	Concentration in aqueous leachate from ground cement composite (mg L^{-1})	Concentration in aqueous leachate from ground cement composite with addition of filter dust (mg L^{-1})
Ni	<0.1	<0.1	<0.1	<0.1
Cu	<0.01	<0.01	<0.01	<0.01
Zn	<0.005	<0.005	<0.005	<0.005
Fe	<0.05	<0.05	<0.05	<0.05
Ca	115 ± 4	117 ± 3	560 ± 15	500 ± 15
Mg	<0.005	<0.005	<0.005	<0.005
Mn	<0.05	<0.05	<0.05	<0.05
K	210 ± 6	245 ± 6	190 ± 6	185 ± 6
Mo*	<0.002	<0.002	0.069 ± 0.002	0.073 ± 0.002
Co*	<0.002	<0.002	<0.002	<0.002
V*	<0.002	<0.002	<0.002	<0.002
Cd	<0.01	<0.01	<0.01	<0.01
Pb	<0.08	<0.08	<0.08	<0.08

Table 5

Concentrations of elements in leachates of salt water from cement composites and cement composites with addition of filter dust 175 days after the start of the experiment. Concentrations of elements were determined by FAAS and ETAAS*. Results represent the mean \pm variation of two parallel samples.

Element	Concentration in leachate of salt water from compact cement composite (mg L^{-1})	Concentration in leachate of salt water from compact cement composite with addition of filter dust (mg L^{-1})	Concentration in leachate of salt water from ground cement composite (mg L^{-1})	Concentration in leachates of salt water from ground cement composite with addition of filter dust (mg L^{-1})
Ni	<0.1	<0.1	<0.1	<0.1
Cu	0.068 ± 0.002	0.054 ± 0.002	0.061 ± 0.002	0.057 ± 0.002
Zn	<0.005	<0.005	<0.005	<0.005
Fe	<0.05	<0.05	<0.05	<0.05
Ca	24 ± 1	58 ± 2	655 ± 15	600 ± 15
Mg	<0.005	<0.005	<0.005	<0.005
Mn	0.113 ± 0.003	0.110 ± 0.003	0.215 ± 0.005	0.215 ± 0.005
K	220 ± 6	208 ± 6	185 ± 5	180 ± 5
Mo*	<0.002	0.0142 ± 0.0004	0.083 ± 0.002	0.080 ± 0.002
Co*	0.0109 ± 0.0003	0.0145 ± 0.0004	0.0083 ± 0.0002	0.0128 ± 0.0004
V*	<0.002	<0.002	<0.002	<0.002
Cd	<0.01	<0.01	<0.01	<0.01
Pb	<0.08	<0.08	<0.08	<0.08

The highest Cr(VI) concentrations that were observed in salt water leachates from ground cement composite with addition of EAF dust did not exceed $100 \mu\text{g L}^{-1}$, that is according to the Slovenian legislation [37] the maximal allowed Cr(VI) concentration in leachates from disposals of inert waste. Based on our experimental data it may be concluded that considering Cr(VI) concentration, cement composites with addition of EAF dust do not represent an environmental hazard neither in the worst case scenario when the cement composite with addition of EAF dust is decomposed with time in the marine environment nor when it is disposed in an landfill which is influenced by the salting of roads.

3.3. Assessment of the environmental impact of the use of filter dust in cement composites: leachability of selected metals

To check the leaching of other metals from compact and ground cement composites and cement composites with addition of filter dust, concentrations of Ni, Cu, Zn, Fe, Ca, Mg, Mn, K, Mo, Co, V, Cd and Pb were also determined 175 days after the start of the experiment in aqueous and salt water leachates. The results are presented in Tables 4 and 5. The data from Tables 4 and 5 indicate that Ca and K are leached in significant concentrations that contribute to highly alkaline pH values of aqueous and salt water leachates. It is further evident that these two elements originate primarily from cement. The leaching of other metals: Ni, Cu, Zn, Fe, Mg, Mn, Mo, Co, V, Cd and Pb from compact and ground cement composites and cement composites with addition of EAF dust is negligible in water and salt water.

4. Conclusions

The potential of the use of EAF dust in cement composites in civil engineering and for balances in washing machines was critically evaluated. It was experimentally proven that the maximal amount of EAF dust added to cement that ensured the optimal physico-mechanical characteristics was 1.5% by mass of cement composite. To estimate the environmental impacts, leachability test based on diffusion was performed over a time period of 175 days in compact and ground cement composites and cement composites with addition of 1.5% of EAF dust. Water and salt water were used as leaching solutions. The results of the leaching test indicated that during the course of the experiment total Cr and Cr(VI) were not leached with water from compact cement composites and compact cement composites with addition of EAF dust. The leaching of total Cr and Cr(VI) from ground cement composites and ground cement composites with addition of EAF dust in water was low and did not exceed 5.5 and $5.0 \mu\text{g L}^{-1}$, respectively. The leaching of Cr and Cr(VI) in salt water was moderate. However, the concentrations of Cr(VI) in ground cement composites with addition of EAF dust did not exceed $100 \mu\text{g L}^{-1}$. Experimental data indicated that leaching of Cr originated primarily from cement and that more than 90% of total Cr existed in its hexavalent form. Of other metals Ca and K were leached from compact and ground composites in concentrations that contribute to highly alkaline pH values of aqueous and salt water leachates, while leaching of Ni, Cu, Zn, Fe, Mg, Mn, Mo, Co, V, Cd and Pb was negligible.

Based on the results of the present study it can be concluded that, from the point of view of their physico-mechanical properties, as well as from the environmental point of view, cement composites to which a maximum of 1.5% by mass of EAF dust has been added can be used in civil engineering for all purposes, including applications in the external environment. Cement composites with the addition of EAF dust can also be used as balances in washing machines which, at the end of their service life, are disposed in landfills.

Acknowledgement

This work was supported by the Ministry of Higher Education, Science and Technology of the Republic of Slovenia.

References

- [1] V. Corinaldesi, M. Giuggiolini, G. Moriconi, Use of rubble from building demolition in mortars, *Waste Manage.* 22 (2002) 893–899.
- [2] H.-J. Chen, T. Yen, K.-H. Chen, Use of building rubbles as recycled aggregates, *Cem. Concr. Res.* 33 (2003) 125–132.
- [3] A. Shayan, A. Xu, Value-added utilisation of waste glass in concrete, *Cem. Concr. Res.* 34 (2004) 81–89.
- [4] P. Sukontasukkul, C. Chaikaew, Properties of concrete pedestrian block mixed with crumb rubber, *Construct. Build. Mater.* 20 (2006) 450–457.
- [5] A. Katz, K. Kovler, Utilization of industrial by-products for the production of controlled low strength materials (CLSM), *Waste Manage.* 24 (2004) 501–512.
- [6] B. Sengoz, A. Topal, Use of asphalt roofing shingle waste in HMA, *Construct. Build. Mater.* 19 (2005) 337–346.
- [7] S. Valls, E. Vazquez, Leaching properties of stabilised/solidified cement-admixtures-sewage sludges systems, *Waste Manage.* 22 (2002) 37–45.
- [8] V.A. Rossetti, L. Di Palma, F. Medici, Production of aggregate from non-metallic automotive shredder residue, *J. Hazard. Mater.* B137 (2006) 1089–1095.
- [9] J. Geiseler, Use of steelwork slag in Europe, *Waste Manage.* 16 (1996) 59–63.
- [10] C. Shi, J. Qian, High Performance cementing materials from industrial slags—a review, *Res. Conserv. Recycle.* 29 (2000) 195–207.
- [11] H. Motz, J. Geiseler, Products of steel slags an opportunity to save natural resources, *Waste Manage.* 21 (2001) 285–293.
- [12] B.B. Lind, A.-M. Fallman, L.B. Larsson, Environmental impact of ferrochrome slag in road construction, *Waste Manage.* 21 (2001) 255–264.
- [13] P. Chaurand, J. Rose, V. Briois, L. Olivi, J.-L. Hazemann, O. Proux, J. Domas, J.-Y. Bottero, Environmental impacts of steel slag reused in road construction: a crystallographic and molecular (XANES) approach, *J. Hazard. Mater.* B139 (2007) 537–542.
- [14] L.-S. Piro, I.L. Piro, Reprocessing of metallurgical slag into materials for the building industry, *Waste Manage.* 24 (2004) 371–379.
- [15] M. Vahčić, R. Milačić, A. Mladenović, S. Murko, T. Zuliani, M. Zupančič, J. Ščančar, Leachability of Cr(VI) and other metals from asphalt composites with addition of filter dust, *Waste Manage.* (2008), doi:10.1016/j.wasman.2008.01.003.
- [16] R. Siddique, Utilization of cement kiln dust (CKD) in cement mortar and concrete—an overview, *Resour. Conserv. Recycl.* 48 (2006) 315–338.
- [17] U.S. Environmental Protection Agency, Guide for industrial waste management. <http://www.epa.gov/epaoswer/non-hw/industd/guide.htm> 2, 1–20.
- [18] R. Siddique, Performance characteristics of high-volume class F fly ash concrete, *Cem. Concr. Res.* 34 (2004) 487–493.
- [19] O. Hjelm, J. Holm, K. Crillesen, Utilisation of MSWI bottom ash as sub-base in road construction: first results from a large-scale test site, *J. Hazard. Mater.* A139 (2007) 47–480.
- [20] G. Laforest, J. Duchesne, Immobilization of chromium(VI) evaluated by binding isotherms for ground granulated blast furnace slag and ordinary Portland cement, *Cem. Concr. Res.* 35 (2005) 2322–2332.
- [21] B. Batchelor, Overview of waste stabilisation with cement, *Waste Manage.* 26 (2006) 689–698.
- [22] J. Hartlen, Environmental consequences of using residues, *Waste Manage.* 16 (1996) 1–6.
- [23] H.A. van der Sloot, Comparison of the characteristic leaching behavior of cements using standard (EN 196-1) cement mortar and an assessment of their long-term environmental behavior in construction products during service life and recycling, *Cem. Concr. Res.* 30 (2000) 1079–1096.
- [24] F. Sanchez, C. Geravis, A.C. Garrabrants, R. Barna, D.S. Kosson, Leaching of inorganic contaminants from cement-based waste materials as a result of carbonation during intermittent wetting, *Waste Manage.* 22 (2002) 249–260.
- [25] A.-M. Marion, M. De Laneve, A. De Grauw, Study of leaching behaviour of paving concretes: quantification of heavy metal content in leachates issued from tank test using demineralized water, *Cem. Concr. Res.* 35 (2005) 951–957.
- [26] P. Flyhammar, D. Bendz, Leaching of different elements from subbase layers of alternative aggregates in pavement constructions, *J. Hazard. Mater.* B137 (2006) 603–611.
- [27] NEN 7345, Leaching characteristics of solid earthy and stony building and waste materials. Leaching tests. Determination of the leaching inorganic components from buildings and monolithic waste materials with diffusion test, 1995.
- [28] I. Hohberg, G.J. de Groot, A.M.H. van der Veen, W. Wassing, Development of a leaching protocol for concrete, *Waste Manage.* 20 (2000) 177–184.
- [29] R. Milačić, J. Ščančar, Determination of hexavalent chromium in lime-treated sewage sludge by anion-exchange fast protein liquid chromatography with electrothermal atomic absorption spectrometry detection, *Analyst* 125 (2000) 1938–1942.
- [30] J. Ščančar, R. Milačić, F. Séby, O.F.X. Donard, Determination of chromium in cement by the use of HPLC-ICP-MS, FPLC-ETAAS, spectrophotometry and selective extraction techniques, *J. Anal. Atom. Spectr.* 20 (2005) 871–875.

- [31] J. Ščančar, R. Milačič, I. Falnoga, M. Čemažar, P. Bukovec, Use of nitric acid in sample pretreatment for determination of trace elements in various biological samples by ETAAS, *J. Pharm. Biomed. Anal.* 22 (2000) 993–1002.
- [32] SIST EN 196-10:2006 Methods of testing cement. Part 10. Determination of the water-soluble chromium(VI) content of cement.
- [33] Directive 2003/53/EC (the 26th amendment of the marketing and use of certain dangerous substances and preparations (nonylphenol, nonylphenol ethoxylate and cement).
- [34] EN 196-1:2005, Methods of testing cement. Part 1. Determination of strength.
- [35] EN 196-3:2005, Methods of testing cement. Part 3. Determination of setting times and soundness.
- [36] EN 12617-4:2002, Products and systems for the protection and repair of concrete structures—test methods. Part 4. Determination of shrinkage and expansion.
- [37] Official Gazzete of Republic of Slovenia, Regulation on waste disposal, 5 (2000) 511.