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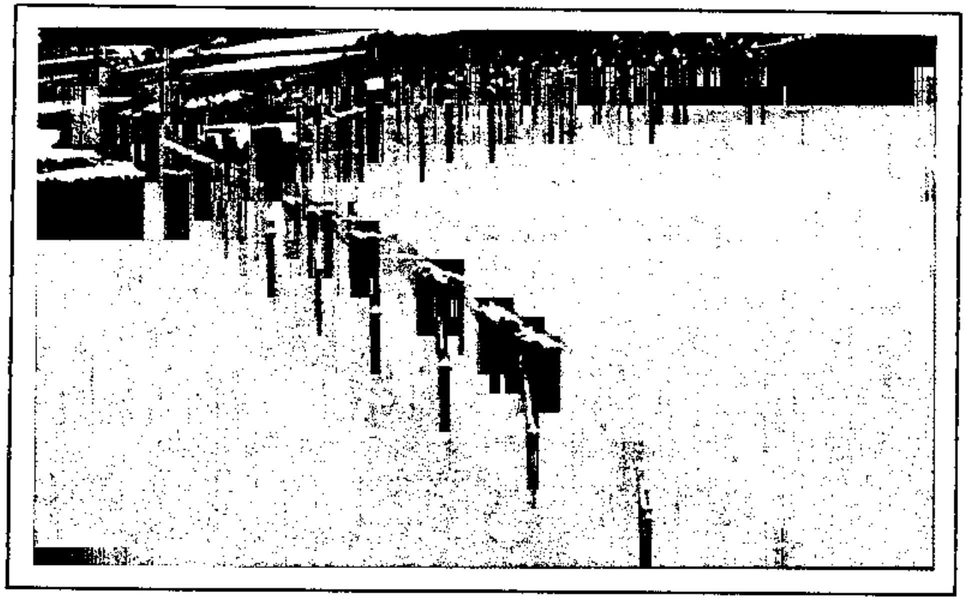

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Editor

ENVIRONMENTAL COMPATIBILITY OF CEMENT-BASED BUILDING MATERIALS

by P. Schiessl and I. Hohberg

Synopsis: Emissions of environmentally relevant substances from cement-based materials and their impact on the environment have become an increasingly important issue. The use of secondary raw materials/wastes should be further stimulated from the point of view of the conservation of resources and energy. This requires a guarantee on the technical properties and the environmental compatibility of the construction products. Concepts are presented on the basis of actual research and development work on how the environmental compatibility of cement-based building materials can be assessed in the future. The main emphasis is laid on the leaching of environmentally relevant substances and the emission of radiation.

Realistic leaching tests were carried out with specimen from mortar mixtures with and without the addition of fly ash. The results show, that only a very small fraction of the total element content is leached in realistic leaching tests. Decisive in the leaching process are the availability of the substances considered and the resistance to diffusion of the matrix. Cement-based materials with usual (standardized) ingredients do not show significant leaching of heavy metals and are therefore not hazardous to soil and groundwater in this respect.

Furthermore, investigations were carried out concerning the gamma radiation exposures and radon exhalation rates caused by cement-based materials. Concretes with and without the application of industrial by-products were included in the testing programme. The results confirm that the radiation from concrete with and without the application of industrial by-products is at the same level as and often lower than the radiation from natural building materials.

Keywords: Blast-furnace slag cement, concrete, environmental compatibility, fly ash, heavy metals, leaching test, radiation, radon exhalation, portland cement.

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INTRODUCTION

Growing scarcity of natural resources and declining landfill space are necessarily leading to the use of industrial by-products in construction materials, partly in order to conserve natural resources and partly in order to minimize ultimate waste disposal and save energy costs. In Germany, the use of secondary raw materials like bituminous coal fly ashes as concrete addition and blast-furnace slag in cement production have a long tradition. These materials contribute positively to the technical properties of the cement-based materials, due to a reaction similar to that of the cement. More and more, other industrial by-products (e. g. metal slag and incineration ashes) will be applied in the production of cement-based building materials.

For regulatory purposes, the protection of the environment (quality of air, water and soil) and of human health is a prime concern. This requires an assessment of environmental effects when using waste materials. A valid method for the prediction of the emissions from building materials into the environment and systematical knowledge on this subject are still lacking.

For an objective assessment of the environmental compatibility of a new building material before its use, the dominant mechanisms of the emission and/or the immobilization of environmentally relevant substances have to be clarified, in order to obtain models for the evaluation of emissions from real building parts under real conditions. Suitable test methods whose results are reproducible and, above all, practically relevant are needed for this purpose. Finally, assessment criteria and limit values that are not oriented to what can be measured analytically, but adequately project the potential danger, have to be set.

The following aspects are often discussed in connection with the environmental compatibility of cement-based building materials:

- leaching of mainly inorganic substances, as e.g. heavy metals, (pollution of groundwater and soil)
- the emission of fugitive constituents (mainly of organic origin; pollution of air)
- emission of radiation/radon (increase in the natural radiation exposure)

In this contribution, concepts are presented on the basis of actual research and development work, how the environmental compatibility of cement-based building materials can be assessed in the future. The main emphasis is laid on the leaching of environmentally relevant substances and the emission of radiation. Up till now, only a few investigation results exist regarding the emission of fugitive constituents of organic origin. Generally, concrete from standardized raw materials does not contribute to measurable changes in the air due to gaseous emissions /1, 2/. This aspect will not be considered in this paper any more.

LEACHING OF ENVIRONMENTALLY RELEVANT SUBSTANCES

GENERAL

For cement-based materials, the main aspect in respect to leaching is the release of inorganic compounds (e.g. heavy metal salts) due to the contact with water e.g. rain or groundwater. The leaching of organic substances is not of great importance for conventional concrete /3/. Therefore, this chapter deals only with the leaching of inorganic compounds from cement-based building materials.

Generally, the leaching behaviour of cement-based materials needs to be considered during their overall life cycle: from production, via the period of use, until demolition and reuse or disposal (see Fig. 1). In this paper we deal mainly with concrete/cement-based materials during use. Therefore the leaching mechanisms are discussed for hardened cement paste.

TEST METHODS

Knowledge of the time-dependent leaching behaviour of cement-based building materials under the given and/or under the expected conditions in the building or building part is necessary to evaluate the potential danger due to the leaching of environmentally relevant substances. In the laboratory, this information can be obtained from leaching tests. In leaching tests, an effort is made to create defined border conditions and to simulate specific influencing parameters. To achieve this, a uniform test method, commonly accepted and acknowledged, has to be developed.

Three general test methods can be differentiated (a detailed description of the various leaching methods is given in /1, 5/):

(a) determination of the total content of environmentally relevant substances,
(b) determination of the availability (mobility),
(c) realistic leaching tests (release under real conditions).

The total amounts of environmentally relevant substances yielded are largely independent of their solubility and the actual bonding relations for test methods according to (a).

The fraction of the total content that is available (mobile) under the given leaching conditions is determined in the test methods according to (b). This fraction is necessary for the prediction of leaching rates (calculation of effective diffusion coefficients). Generally, the available fraction is much smaller than the total content. Up till now, such a method for investigating cement-based building materials is not available although there is an agreement on the necessity of such a method. At the moment, test methods are being applied for which very extreme test conditions (finely ground samples, low pH values) are chosen. No predictions as to the time at which these amounts are actually leached are possible with these methods. The results obtained only represent an additional characterization of the material.

Results that describe the time-dependent leaching under practical leaching conditions can be achieved solely with the leaching tests according to (c). In this case, test specimen similar to those used in practice can be considered. The dominant leaching mechanism and the leaching rates can then be determined from the test results. The results enable the determination of the chemical and physical retention capacity of the matrix. Examples for these tests are tank tests. In tank tests, mortar or concrete specimen are placed in a container in such a way that they are surrounded on all sides by the leachant. The leachant is renewed and analysed in defined time intervals (details see /1, 5/).

Fig. 2 shows the results from different leaching methods for chromium and zinc from the investigation of a mortar specimen. The results demonstrate that only a part of the total element content is leachable /6/. This fraction is relatively high under extreme conditions (low pH value, finely ground test samples), whereas much lower amounts are leached in realistic test methods (tank tests). Furthermore, the presentation confirms how different the results from the various methods are.

MECHANISMS AND PARAMETERS

The time-dependent leaching of environmentally relevant substances (e.g. heavy metals) from cement-based building materials is controlled by various influencing factors and processes. The immobilization of the heavy metals in the cement matrix and/or in the aggregates and additions used is decisive, as well as the transport mechanism of the heavy metal ions from the building material into the leaching fluid, the leachant. The immobilization of heavy metals in the cement matrix and the transport mechanisms can be influenced by physical and chemical parameters/processes. The physical parameters are e.g. the permeability, the porosity as well as the tortuosity. Chemical parameters/processes are e. g. changes in pH-value (since the solubility of metal ions strongly depends on the pH-value), incorporation (fixation) of heavy metals ions in mineral or glassy phases and adsorption and desorption processes. These parameters and processes are represented in Fig. 3.

Basically, the following mechanism may occur when a material is brought into contact with a leachant /7/:

- Soluble salts, adsorbed at the surface of the sample, are dissolved at the first contact with the leachant (so-called „wash-off-effect"). This process ends already after a short period of leaching.
- If a major component of the matrix is soluble in the leachant, a continuous dissolution occurs, from the surface to the inside. This may become a dominant mechanism during the leaching of concrete, if aggressive leachants are applied.
- Diffusion can take place from the solid into the leachant, or vice versa (from the leachant into the solid), depending on the concentration of elements in the pore solution and in the contact solution. Diffusion in the cement matrix takes place mainly in the capillary pores.

In addition to this precipitation or dissolution of salts in the matrix may occur, due to changes in the pH-value (see above). Adsorption and absorption processes can take place at the surface.

The results of a tank leach test allow a deduction of the prevailing leaching mechanism if the leaching rate J ($\mathrm{mmol \cdot s^{-1} \cdot m^{-2}}$) is plotted against the time t (s) in a log/log-scale /6, 8/. Lines with different gradients m are obtained in the graph (see Fig. 4). The dominant leaching mechanism can be recognized from the value of the gradient m. If a horizontal line ($m = 0$) is obtained, then a continuous dissolution of the matrix has taken place. A gradient $m = -1$ indicates a wash-off of the surface ("wash-off effect"). If the dominant leaching mechanism is diffusion, then a line with the gradient $m = -1/2$ results. The various mechanisms can also superimpose one another.

Fig. 5 shows the tank leaching results from the investigation of a mortar specimen (example zinc) /8/. A line with a gradient of -0.51 results in the lgJ-lgt graph. The gradients determined from the lgJ-lgt graphs for other elements (chromium, copper, lead, e.t.c.) also lie at around -0.5 /8/. These results confirm that the leaching of cement-based building materials is dominated mainly by diffusion processes. Diffusion and/or transport coefficients, can thus be determined from the test results, enabling a modelling and evaluation of leaching rates (details see /1, 6/).

RESULTS FROM LEACHING TESTS

Materials and methods

The investigations described here were carried out in order to determine the leaching behaviour of heavy metals from cement-based materials with and without application of industrial by-products.

A normal portland cement (PC) and a blast-furnace slag cement (BFSC) containing 46 mass.% of slag in compliance with the requirements of German cement standard DIN 1164 were selected for the investigations. Four bituminous coal fly ashes (FA) with different heavy metal contents were chosen as concrete addition. The fly ashes met the requirements of European standard EN 450. The heavy metal contents of these raw materials are summarized in Table 1.

For the investigations mortar mixtures with and without addition of FA were prepared according to European standard EN 196-1 using standard 0.08/2 mm sand. The fly ash content (f) in the mixtures with FA was 20 mass.% in relation to total binder content (c+0.5f). The water-binder ratio (w/(c+0.5f)) was 0.5 for all mixtures. The heavy metal contents of the different mortars are given in Table 2.

Specimen (40 mm by 40 mm by 160 mm) were prepared from the mortar mixtures. After one day in the mould, the specimen were cured up to an age of 28 days in a climate chamber at 20 °C and 95 % relative humidity.

Tank leaching tests with a duration of 56 days and 8 leachant renewals (leachant: demineralized water) were performed with the mortar specimen. The results of the tank tests can be taken from Table 3. In Fig. 6, 7, the time-dependent leaching behaviour for zinc and chromium is shown in comparison to the total element contents. The total element content was each divided into the fractions from the aggregate, the cement and the fly ash that were calculated based on the composition and the contents of the ingredients.

The results show that the leaching of zinc and chromium (as well as that from the other elements, see Tables 2, 3) from mortars with and without the use of fly ash, is dependent on neither the total element content nor on the element contents of the additions used. Generally, the amounts of heavy metals leached are very low, often near the detection limits, due to the immobilization of the heavy metals in the highly alkaline, dense cement matrix. The addition of fly ashes with relatively high contents of heavy metals (in relation to the cement) does not result in higher emissions. The emissions from mortars with fly ash are often lower than for the mortar without fly ash addition due to the pozzolanic reaction and the filler effect of the fly ashes (especially for zinc).

As can be taken from the presented results, only a very small fraction of the total element content is leached in realistic leaching tests /6/. Decisive in the leaching process are the availability (mobility) of the substances considered and the resistance to diffusion of the matrix. These parameters determine the size of the effective diffusion coefficients in the cement matrix which can be calculated from the results of tank leaching tests /1, 5/. Cement-based materials with usual (standardized) ingredients do not show significant leaching of heavy metals and therefore are not hazardous to soil and groundwater in this respect /1, 2/.

NATURAL RADIATION FROM CEMENT-BASED BUILDING MATERIALS

GENERAL

In Germany, the radiation exposure of the population outdoors and in dwellings was intensively investigated. Of particular interest were the gamma ray dose due to the concentrations of naturally radioactive substances in building materials and the inhalations dose due to decay products of radon-222 and radon-220, which emanate from building materials and soil into room air.

In Fig. 8 the mean annual radiation doses for Germany from different sources are summarized. The total mean annual radiation dose amounts to about 4 mSv/a. A large part of the total radiation dose of the population is attributed to the residence in houses (1.2 mSv/a). The mean annual radiation from artificial sources is roughly 1.6 mSv/a and can almost exclusively be attributed to medical diagnostics (radio diagnostics). The unchangeable natural radiation dose (cosmic/terrestrial radiation and the radiation dose due to the incorporation of radio nuclides) contributes just as much to the total radiation exposure (1.2 mSv/a) and is, in contrast to residing in buildings and to use of radio diagnostics, practically impossible to influence /9/. The single components of radiation exposure due to residing in buildings are represented in the right part of Fig. 8. It can be taken from this that the greater part of radiation exposure in houses results from the inhalation of the radioactive noble gases radon-222 and radon-220 and/or their decay products.

Caused by enrichment processes, industrial by-products (like coal fly ashes and metal slags) often contain higher contents of radioactive substances than other (natural) building materials. With this background, the employment of such industrial by-products in cement-based building materials is often discussed. Investigations are presented in this paper, addressed at the evaluation of concrete with the application of industrial by-products with respect to gamma radiation and radon exhalation.

EVALUATION OF RADIATION DOSE

In Germany, the radiation dose of building materials is often assessed by the determination of the specific activities of the radio nuclides Potassium-40, Radium-226 and Thorium-232. Although the naturally radioactive substances in building materials contribute only negligibly to the radiation exposure of the population due to their direct gamma radiation, building materials are, up till now, often still assessed from the determination of the specific activity of the radioactive nuclides. The following formula (Leningrad criterion) is used in the assessment /10/:

$$\frac{a\,{}^{40}\mathrm{K}}{4810}+\frac{a\,{}^{226}\mathrm{Ra}}{370}+\frac{a\,{}^{232}\mathrm{Th}}{260}\leq 1 \qquad (1)$$

The Leningrad model, leading to this formula, assumes that the whole room (walls, ceiling, floor of infinite thickness) is from the material considered. By the application of this formula the radiation dose originating from a building material, is overrated, since the real thickness of the walls, ceiling and floor is not taken into account. On the other hand, the summation formula does not take into consideration the radiation dose due to the inhalation of radon-222 and/or radon-220. This summation formula is only useful to compare building materials, not to evaluate the radiation dose of inhabitants. Table 4 shows the specific activities (content of radio nuclide per kilogram of the considered material) for some concrete components, as well as the summation value, which results from the summation formula (equation 1).

A possible model for the evaluation of the radiation dose from building materials due to γ-radiation and radon exhalation is described in /12/. This room model considers walls of definite thickness, ventilation rates, as well as geometric relations of the room. In Table 5, the equations and parameters for the evaluation of building materials are summarized. Examples for the application of this evaluation are shown later in this paper for different concretes with and without the application of industrial by-products. More details on the determination of equilibrium factors and dose conversion factors can be found in /13, 14, 15/.

In Germany, numerous radon measurements were carried out in dwellings and outdoors /9, 16/. According to these measurements, the mean value of the radon concentration in dwellings lies at 50 $\mathrm{Bq/m^3}$ and outdoors at around 14 $\mathrm{Bq/m^3}$. Radon concentrations in the room air of up to 80,000 $\mathrm{Bq/m^3}$ were ascertained in some special regions (see Fig. 9). The radon fraction that originates from the building materials itself lies at a maximum of 30 $\mathrm{Bq/m^3}$. The fraction from concrete normally lies at 1-10 $\mathrm{Bq/m^3}$. Therefore high radon concentrations in room air cannot be attributed to the radon exhalated from building materials (this fraction is negligible). Most of the radon originates from the ground (depending on the geological conditions up to 90%) /9/. This shows, that, at the moment, the radon exhalation is not a problem of the building materials, rather it is determined by the question of how houses can be shielded from the ground.

INVESTIGATIONS

Experiments on concretes with and without the application of industrial by-products were carried out, in order to estimate the radiation dose resulting from concrete /11/.

For the investigation a Portland Cement (PC) and a blast-furnace slag cement (BFSC) in compliance with the requirements of German cement standard DIN 1164 were selected. Two fly ashes with different radium activities (FA1: radium activity = 70 Bq/kg and FA2: radium activity = 130 Bq/kg)) were used as concrete additions. The fly ashes met the requirements of European standard EN 450. The concretes contained 20 mass.% fly ash relative to the total binder content (c+0.5f). The grain size distribution of the concrete aggregates corresponded to grading curve A/B 16 in accordance with German standard DIN 1045. For one concrete mixture 50 vol.% of the aggregate was replaced by a metal slag (not certified). The water/binder-ratio was 0.5 for all concretes. From the concrete mixtures specimen (0.2 m by 0.2 m by 0.12 m) were prepared in order to measure the radon exhalation rates. After one day in the mould, the specimen were cured seven days under water and after that up to an age of 90 days in a climate chamber at 20 °C and 65 % relative humidity.

The specific activities as well as the radon exhalation rates were determined for all concretes (analysis method see /11/). The radon room air concentrations are calculated from the exhalation rates (see Table 5). The results of the measurements and the calculations are summarized in Table 6. The exhalation rates for the concretes are presented in dependence on the specific radium-226 activity in Fig. 10. The results from Table 6 and Fig. 10 confirm the independence of the radon exhalation rates from the radium-226 activities of the raw materials applied. Inspite of the double radium-226 activity of FA1 in relation to FA2, the concrete with FA2 shows a lower radon exhalation rate than the concrete with FA1. This effect is due firstly to the glassy matrix of the fly ash, resulting in a low exhalation and secondly to the pore blocking effect of the fly ashes, which results in a hindering of the diffusion of the radon gas. The concrete from blast-furnace slag cement has distinctly lower exhalations rates than the concrete from Portland cement. The lower exhalation rates can be explained by the molten surface of the applicated blast-furnace slag and by the influence of the blast-furnace slag on the pore system of the cement matrix. The addition of fly ash results in a reduced radon exhalation rate also for the concrete with blast-furnace slag cement. Surprisingly, the concrete with metal slag has only very low radon exhalation, in spite of its very high radium-226 activity. This could also be attributed to the molten surface of the slag /11/. The radon room air concentrations calculated (1-7 $\mathrm{Bq/m^3}$, see Table 6) are below the mean value for building materials (30 $\mathrm{Bq/m^3}$), thus the contribution of concretes in raising radon air concentrations could be assumed as negligible.

The total radiation dose (γ-radiation exposure and radon inhalation) resulting from the concretes examined were calculated on the basis of the equations and parameters from Table 5. The results of the calculations show an additional radiation dose of 0.10-0.27 mSv/a (without concrete with metal slag) due the investigated concretes (see Fig. 11.). This value lies far below the mean radiation dose from residing in a house (roughly 1.2 mSv/a). The values determined lie in the region of the results from other experiments on concretes in /1, 12/.

The results represented here show that the radiation from concrete with and without the application of industrial by-products is at the same level as and often lower than the radiation from natural building materials.

ASSESSMENT OF THE ENVIRONMENTAL COMPATIBILITY

Setting absolute limit values for the environmental compatibility (the effect on soil, air, water and human health) for the emission of environmentally relevant substances of building materials is neither possible nor does it make sense, because of the large ranges in the contents of environmentally relevant substances in cement-based building materials and the difficulty in the transfer of the results of laboratory tests into practice, as well as the lack of knowledge of the actual effects on organisms. There is, nevertheless, a need to act on the development of a material class and an application-class related evaluation scheme for cement-based building materials because of the increasing pressure expected in the future to recover waste materials.

One possibility to overcome the problem of discussing absolute values for allowable limits of emissions is to establish a system based on well proven and accepted applications in practice (see Fig. 12). For example, a scheme can be set up classifying concretes with certain compositions (classification of materials) for certain applications (classification of environments or applications). For these well established, well known and tried materials, the relevant material parameters can be determined using the established test methods, leading to a "emission behaviour classification of materials" and a correlation to an environmental classification.

SUMMARY

Emissions of environmentally relevant substances from cement-based materials and their impact on the environment have become an increasingly important issue. The use of secondary raw materials/wastes should be further stimulated from the point of view of the conservation of resources and energy. This requires a guarantee on the technical properties and the environmental compatibility of the construction products.

The considerations have shown how complex the topic of the environmental compatibility of cement-based materials is. A basic test scheme and harmonized test methods for the separate aspects have to be worked out for this area.

There is a need to act on the development of a material-class related and an application-class related evaluation scheme for construction materials, regarding their environmental compatibility, because of the increasing pressure expected in the future to recover waste materials. New waste materials can be assessed or ruled out as possible raw materials for construction materials through such a scheme that is oriented to the release rates of common concretes. The research is not yet complete especially in the field of harmful organic substances.

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TABLE 1--HEAVY METAL CONTENTS OF THE CEMENTS AND FLY ASHES USED /1, 6, 8/

sample		PC	BFSC	FA1	FA2	FA3	FA4
element		content in mg/kg					
Antimony,	Sb	2	5	19	37	20	16
Arsenic,	As	7	2	247	321	56	67
Barium,	Ba	280	420	1316	787	1453	910
Cadmium,	Cd	< 0.5	< 0.5	7	7	2	< 2
Chromium,	Cr	68	46	248	250	360	203
Cobalt,	Co	6	4	65	74	99	42
Copper,	Cu	96	18	189	307	442	183
Lead,	Pb	21	14	817	482	377	359
Mercury,	Hg	< 0.1	< 0.1	< 0.1	< 0.1	n. d.	n. d.
Nickel,	Ni	36	23	158	181	301	218
Thallium,	Tl	0.2	0.5	2	3	1	n. d.
Zinc,	Zn	309,	245	1177	560	720	455

PC: normal portland cement

FA: fly ash

BFSC: blast-furnace slag cement

n. d.: not determined

TABLE 2--HEAVY METAL CONTENTS OF DIFFERENT MORTARS

mortar	M1	M2	M3	M4	M5	M6	M7	M8
cement	PC					BFSC		
addition	-	FA1	FA2	FA3	FA4	-	FA1	FA2
w/(c+0.5f)	0.50							
element	content in mg/kg							
Antimony, Sb	1	1	n. d.	2	n. d.	7	4	5
Arsenic, As	9	21	18	10	4	6	29	6
Barium, Ba	194	259	212	106	201	226	310	368
Cadmium, Cd	< 0.5	1	1	0,4	< 1	< 0,5	1	< 1
Chromium, Cr	42	53	45	49	42	22	19	35
Cobalt, Co	30	35	51	32	38	34	49	54
Copper, Cu	5	17	16	25	44	4	22	20
Lead, Pb	11	69	29	18	47	13	87	37
Mercury, Hg	< 0.1	< 0,1	< 0.1	< 0.1	< 0,1	< 0.1	0.1	< 0.1
Nickel, Ni	10	18	15	17	12	10	21	27
Thallium, Tl	< 0.1	0.3	0.3	0.5	0.2	0.1	0.6	0.4
Zinc, Zn	79	185	86	145	110	106	206	135

PC: normal portland cement

FA: fly ash

BFSC: blast-furnace slag cement

n. d.: not determined

TABLE 3--RESULTS FROM TANK TESTS WITH MORTAR SPECIMEN; LEACHED AMOUNTS IN DEPENDENCE ON CEMENT AND FLY ASH ADDITION /1, 6, 8/

mortar	M1	M2	M3	M4	M5	M6	M7	M8
cement	PC					BFSC		
addition	-	FA1	FA2	FA3	FA4	-	FA1	FA2
w/(c+0.5f)	0.50							
element	amount leached in mg/kg[1)]							
Arsenic, As	< 0.01							
Chromium, Cr	0.09	0.15	0.03	0.03	0.07	0.08	0.09	0.10
Copper, Cu	< 0.02	< 0.02	0.02	0.02	0.01	< 0.02	< 0.02	< 0.02
Lead, Pb	0.01	0.03	< 0.01	0.02	0.02	0.03	< 0.02	< 0.02
Zinc, Zn	0.18	0.09	0.07	0.09	0.11	0.02	0.02	< 0.02

1) leached amounts after 56 days and 8 leachant renewals

PC: Portland cement

FA: fly ash

BFSC: Blast-furnace slag cement

TABLE 4--SPECIFIC ACTIVITY CONCENTRATIONS OF ^{40}K, ^{226}RA AND ^{232}TH IN CONCRETE COMPONENTS AND SUMMATION VALUES /11, 16/

component	number of samples	specific activity ^{40}K	^{226}Ra	^{232}Th	summation value[1)]
		Bq/kg			
normal portland cement (PC)	14	222	< 26	< 19	< 0.19
blast-furnace slag cement (BFSC)	3	148	59	85	0.52
gravel/sand (quartz)	50	259	< 15	< 19	< 0.16
limestone	20	37	< 19	< 19	< 0.13
coal fly ash (FA)	21	921	143	105	1.00
blast-furnace slag (BFS)	1	200	64	70	0.48
metal slag (MS)[2)]	1	880	650	55	2.15
water	-	1	0	0	< 0.01

1) according to the Leningrad criterion (mean values) /1, 17/

2) not certified

TABLE 5-- EQUATIONS AND PARAMETERS FOR THE EVALUATION OF THE RADIATION DOSE FROM BUILDING MATERIALS

parameter	unit	evaluation
gamma radiation dose, H_γ	mSv/a	$H_\gamma(^{226}Ra) = 1.3 \cdot 10^{-3} \cdot a_{^{226}Ra}$, $H_\gamma(^{232}Th) = 1.6 \cdot 10^{-3} \cdot a_{^{232}Th}$
inhalation dose for radon-222, H_e		$H_e = D_e \cdot e \cdot f \cdot F \cdot V^{-1} \cdot L^{-1}$
radon concentration in room air, c_i	Bq/m^3	$c_i = e \cdot F \cdot V^{-1} \cdot v^{-1}$
exhalation rate, e	Bq/(m^2·h)	1)
doses conversion factor, D_e	mSv m^3/(Bq·a)	0.061
equilibrium factor, f	-	0.3
thickness of the wall, d	m	0.2
ventilation rate, v	h^{-1}	0.4
surface/volume ratio of the room, $F \cdot V^{-1}$	m^{-1}	1.7

1) to be determined by analysis or calculation /12/

TABLE 6-- SPECIFIC ACTIVITIES AND RADON-222 EXHALATION RATES FROM CONCRETE WITH AND WITHOUT THE APPLICATION OF INDUSTRIAL BY-PRODUCTS AS WELL AS RADON ROOM AIR CONCENTRATIONS /11/

concrete	cement	addition/ aggregate	w/b$^{1)}$	specific activity			e	c_i
				^{40}K	^{226}Ra	^{232}Th		
				Bq/kg			Bq/(m^2·h)	Bq/m^3
C1	PC	-	0,5	238	17	15	1.9	7
C2		FA1		270	19	16	0.8	3
C3		FA2		263	19	19	0.6	3
C4		MS		520	33	302	0.3	1
C5	BFSC	-		230	19	19	1.2	5
C6		FA2		256	23	23	1.0	4

1) w/b-ratio: water-binder ratio: (w/(c+0.5f), f = fly ash content

PC: normal portland cement

FA: fly ash

MS: aggregate partly (50 vol.%) replaced by metal slag

e: exhalation rate; normalized to a thickness of 0.20 m

c_i: radon room air concentration; calculated according to Table 5

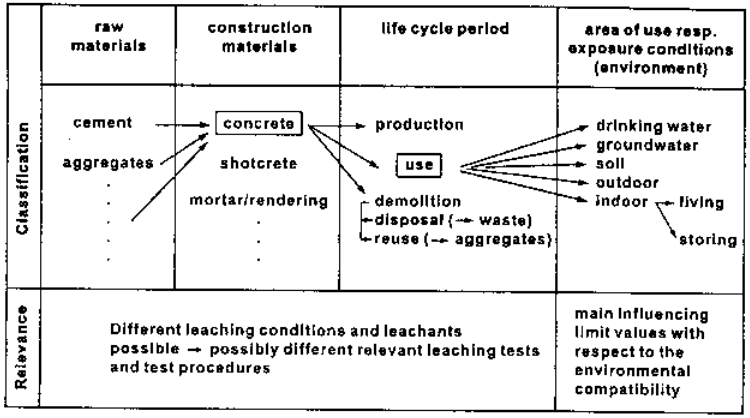


Fig. 1. Environmental compatibility of cement-based materials; basic scheme.

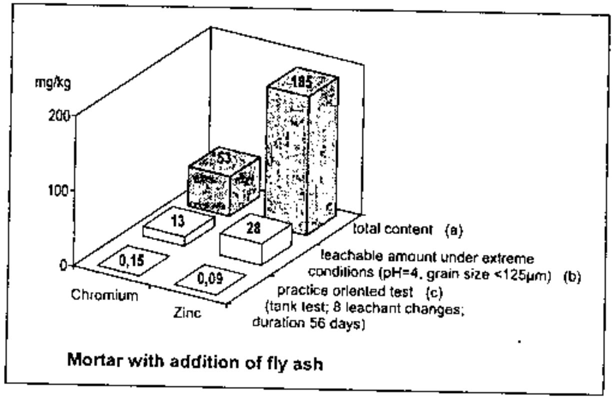


Fig. 2. Investigation of a specimen from a mortar with the addition of fly ash; comparison of different leaching methods /6/.

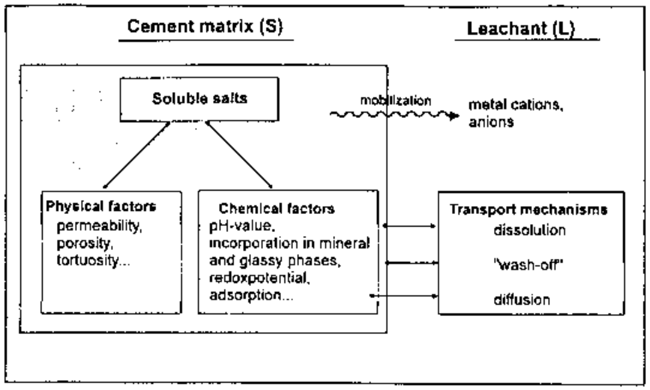


Fig. 3. Leaching processes; immobilization of heavy metals and transport mechanisms /4/.

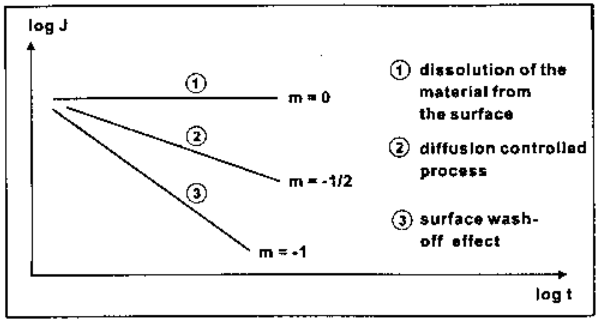


Fig. 4. Evaluation of the results of tank leaching tests - prevailing leaching mechanisms /6/.

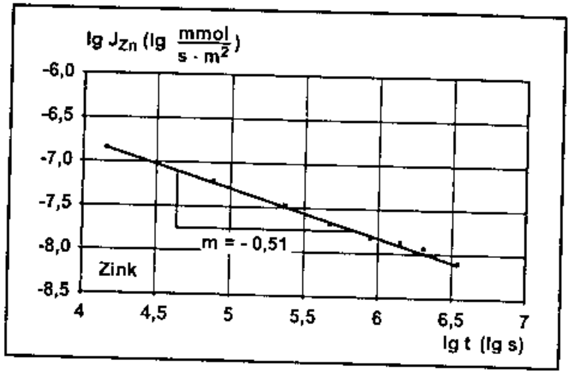


Fig. 5. Leaching results from the investigation of a mortar specimen (example zinc) /8/.

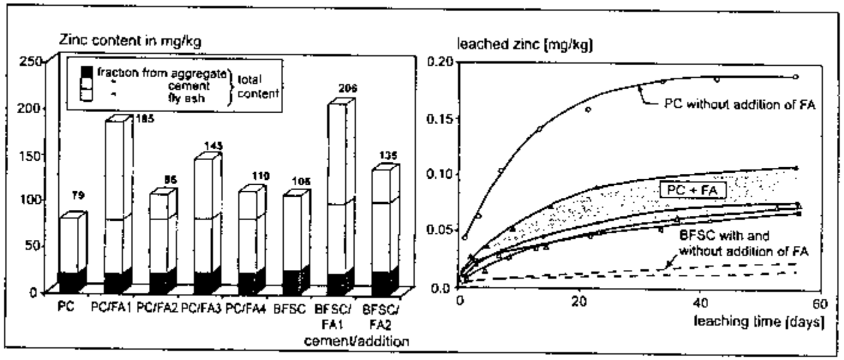


Fig. 6. Tank leaching test results in relation to total zinc contents for different mortars in dependence on cement and addition (PC: normal portland cement; FA: fly ash; BFSC: blast-furnace slag cement; w/b=0.5 for all mortars).

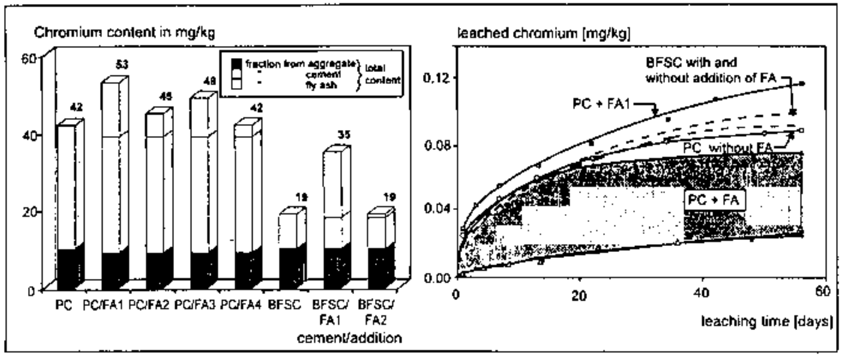


Fig. 7. Tank leaching test results in relation to total chromium contents for different mortars in dependence on cement and addition (PC: normal portland cement; FA: fly ash; BFSC: blast-furnace slag cement; w/b=0.5 for all mortars).

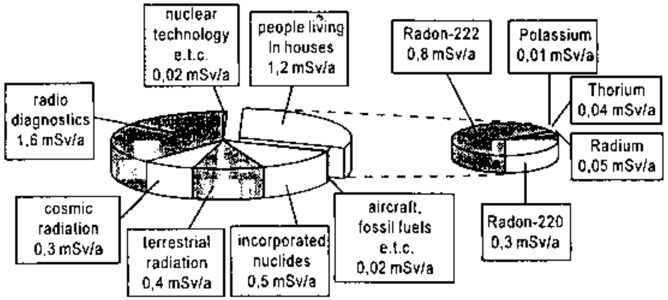
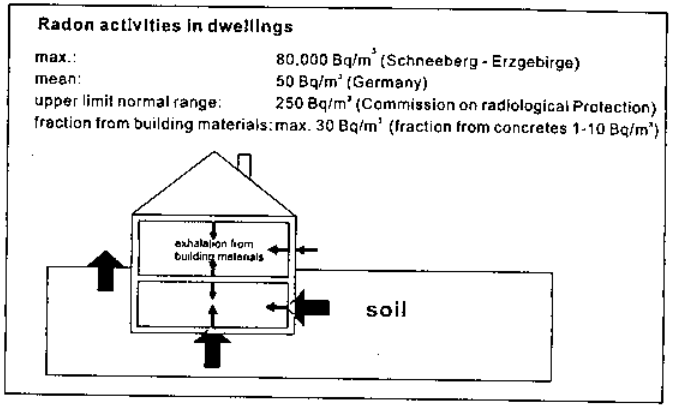


Fig. 8. Mean annual effective radiation dose of the population in Germany /9/.



max.: 80.000 Bq/m³ (Schneeberg - Erzgebirge)
mean: 50 Bq/m³ (Germany)
upper limit normal range: 250 Bq/m³ (Commission on radiological Protection)
fraction from building materials: max. 30 Bq/m³ (fraction from concretes 1-10 Bq/m³)

Fig. 9. Measured and recommended radon room air concentrations; values according to /9/.

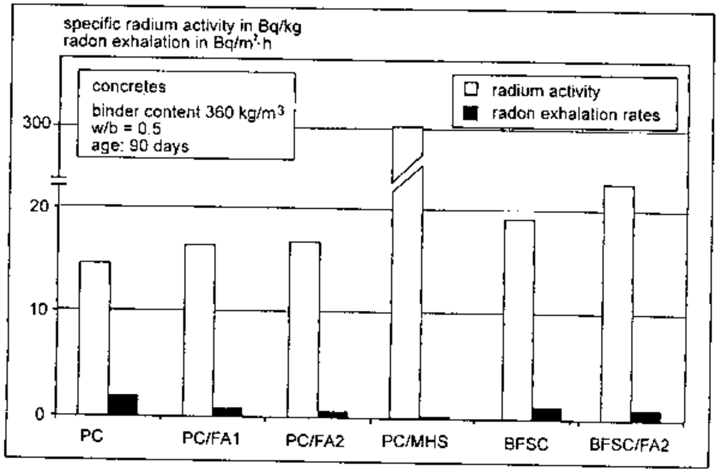


Fig. 10. Radon exhalation rates from concrete; dependence on the cement and addition/aggregate as well as on the specific radium activity (PC: normal portland cement; BFSC: blast-furnace slag cement; FA: fly ash; MHS: metal slag) /11/.

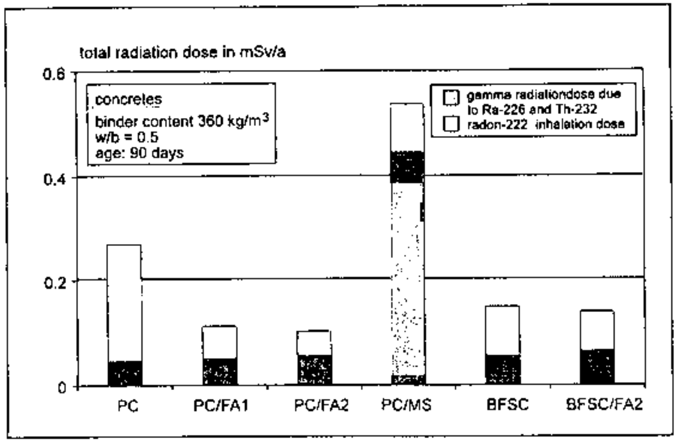


Fig. 11. Calculated radiation doses from the investigated concretes (PC: normal portland cement; BFSC: blast-furnace slag cement; FA: fly ash; MS: metal slag (not certified)) /11/.

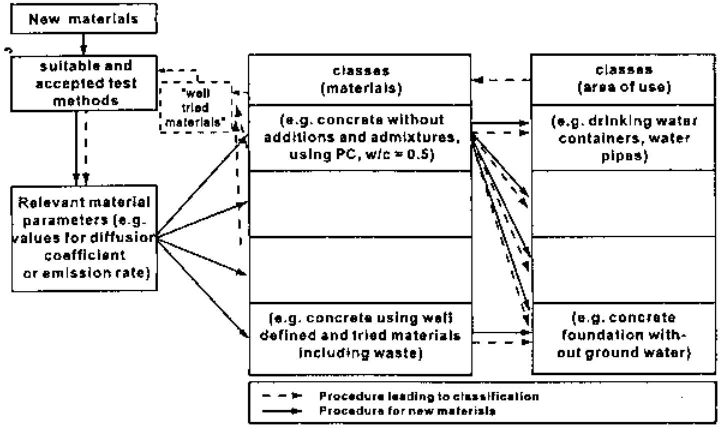


Fig. 12. Classification scheme for cement-based building materials.