CrossMark

ORIGINAL ARTICLE

Leaching behavior of some demolition wastes

N. Saca[1] · Al. Dimache[2] · L. R. Radu[1] · I. Iancu[2]

Abstract Demolition wastes may be used in different civil engineering applications as road constructions, concrete, and embankments or landfill. Regardless its application, leaching tests of the waste should be carried out to assess concentrations of pollutants. Concrete, brick and mixture of concrete, bricks, tiles and ceramics wastes were subject to percolation test—CEN/TS 14405, and batch test—SR EN 12457. The leachates were analyzed with respect to concentration of inorganic elements—arsenic, barium, cadmium, chromium, copper, mercury, molybdenum, nickel, lead, selenium, zinc, fluoride, chloride and sulfate, and organic compounds (phenol index). The concentrations of elements in leachates were compared with the limit values of European regulation for the acceptance of inert wastes at landfills. Generally, the releases of inorganic species in leachates were below limits values. Some waste leachates obtained by percolation and batch test had high values for phenol index.

Keywords Waste · Demolition · Leaching test · Concretes · Bricks

Introduction

The valorization of industrial wastes and by-products in construction applications is an important research area. In addition, Directive 2008/98/CE of the European Parliament on waste is pressing to "reducing the use of resources, and favoring the practical application of the waste hierarchy" and suggested that "by 2020, the preparing for reuse, recycling and other material recovery of non-hazardous construction and demolition waste shall be increased to a minimum of 70 % by weight" [1]. Construction and demolition wastes (CDW) are a major part of total solid waste production in the world, e.g., Western Europe produces from 175 to 250 million tons [2]. Central and Eastern Europe is behind Western Europe in implementing necessary changes to improve its waste management sector. In Romania, sewerage operators' reports annually on the amounts of municipal wastes and construction and demolition wastes collected. The quantity of CDW increased in 2003–2008, correlated with the fast development of the construction field (from 474350 tons in 2006 to 531780 tons in 2011 [3]). After 2009, the quantity of CDW decreased due to the real estate market setback and economic crisis.

CDW is generated from the construction, renovation, repair, and demolition of different structures. The composition of wastes varies for different activities and structures [2, 4]. Demolition wastes are composed mainly of concrete, wood products, asphalt, drywall, and masonry. Other components present in significant quantities are metals, plastics, soil, insulation, and paper. The selective demolition process facilitates the removal of gypsum, clay, organic particle and lightweight particle. In these conditions, the quality of demolition waste can be enhanced and the waste complies with the limit values for chemical compounds [5].

✉ N. Saca
nastasiasaca@gmail.com

1   Roads, Railways and Building Materials Department, Technical University of Civil Engineering, Bucharest, Romania

2   Hydraulics and Environmental Protection Department, Technical University of Civil Engineering, Bucharest, Romania

The majority of demolition wastes are inert. A small fraction of these solid wastes contains different chemicals which are hazardous to environment and human health. The hazardous wastes list is available as per the European Regulation [6–9]. Inert CDW can be processed and made suitable for use in road construction, e.g., [10–14]. Other research studies have clearly suggested the possibility of properly treating and reusing such waste as aggregate in new concrete (especially lower level applications) [15–25].

To landfilling or reuse, it is necessary to assess the environmental risk of demolition wastes with respect to the release of potential pollutants. The test procedures described in SR EN 12457 [26, 27] and CEN/TS 14405 [28] reflect possible scenarios under natural deposition conditions.

The aim of this article is to assess the leaching behavior of demolition wastes obtained from steel plant demolition. The main objective is to find which pollutants can be transported in soil and ground water and how large are the concentration of pollutants compared to the threshold values for the acceptance of inert waste at landfills.

Materials and methods

Materials

The demolition wastes (DW) source is a steel plant. Sampling was carried out during daytime at an atmospheric temperature of 10 °C. For each waste was taken samples from the edge, top and inside (1 m depth) of the waste pile. The samples with age under 1 week (C1, B1 and M1) and age under 1 year (C2, B2 and M2) from the demolition site were stored in closed packages and kept under optimal conditions to minimize alteration of the waste materials. The samples were reduced to the size necessary for testing by quartering method.

Types of materials are concretes, bricks and mixture of concrete, bricks, tiles and ceramics. The main physical characteristics of the DW are summarized in Table 1.

Experimental methods

The demolition wastes were examined by batch test (liquid/solid ratio of 2 and 10) and column percolation test (L/S ratio of 0.1).

Batch test was performed according to SR EN 12457, a compliance test by which a granular recycled material is analyzed to verify whether complies with EU regulation. Batch test was performed by agitating the solid waste and demineralized water for 24 h in an end-over-end tumbler followed by sample preparation consisting of settling and filtration through 0.45 μm membrane filter (Fig. 1). Wastes leach at their natural pH value.

Up-flow percolation test was performed with glass columns of 100 mm internal diameter [28]. The column filling height was about 35 cm. On the top and bottom section of the column was placed a thin layer of fine quartz sand to ensure proper water flow over the width of the column. The waste was slightly compacted. The columns were saturated with demineralized water (conductivity of maximum of 0.1 mS/m). The saturated materials were left for 3 days to equilibrate the system. After this period, the pump was started; the linear velocity was 15 cm/day. The flow rate, ϕ, in mL/h, was calculated according to Eq. 1:

$$\phi = v_L \times \pi \times d^2 \times 0.0104 \tag{1}$$

where v_L is the linear velocity of the leaching through the empty column (cm/day); d diameter of the column (cm).

Water is percolated through a column of waste and collected as a function of liquid/solid (L/S) ratio.

The metal concentrations in the leachates were determined by inductively coupled plasma optical emission spectrometry (ICP-OES) and atomic absorption spectrometry (AAS). Phenol index was determined by UV/VIS molecular absorption spectrometry.

Chlorides were done by titration with silver nitrate using chromate as indicator. Fluorides were determined by titration with thorium nitrate, in the presence of sodium alizarin sulfate. Sulfates were determined by gravimetric method (precipitation with aqueous barium chloride).

Table 1 Physical properties of demolition wastes

Type of material	Code of material	Humidity (%)	Loose bulk density (kg/m^3)
Concrete	C1	6.4	1245
Concrete	C2	7.5	1210
Bricks	B1	2.0	1147
Bricks	B2	6.4	1280
Mixture of concrete, bricks, tiles and ceramics	M1	7.5	1257
Mixture of concrete, bricks, tiles and ceramics	M2	12.4	982
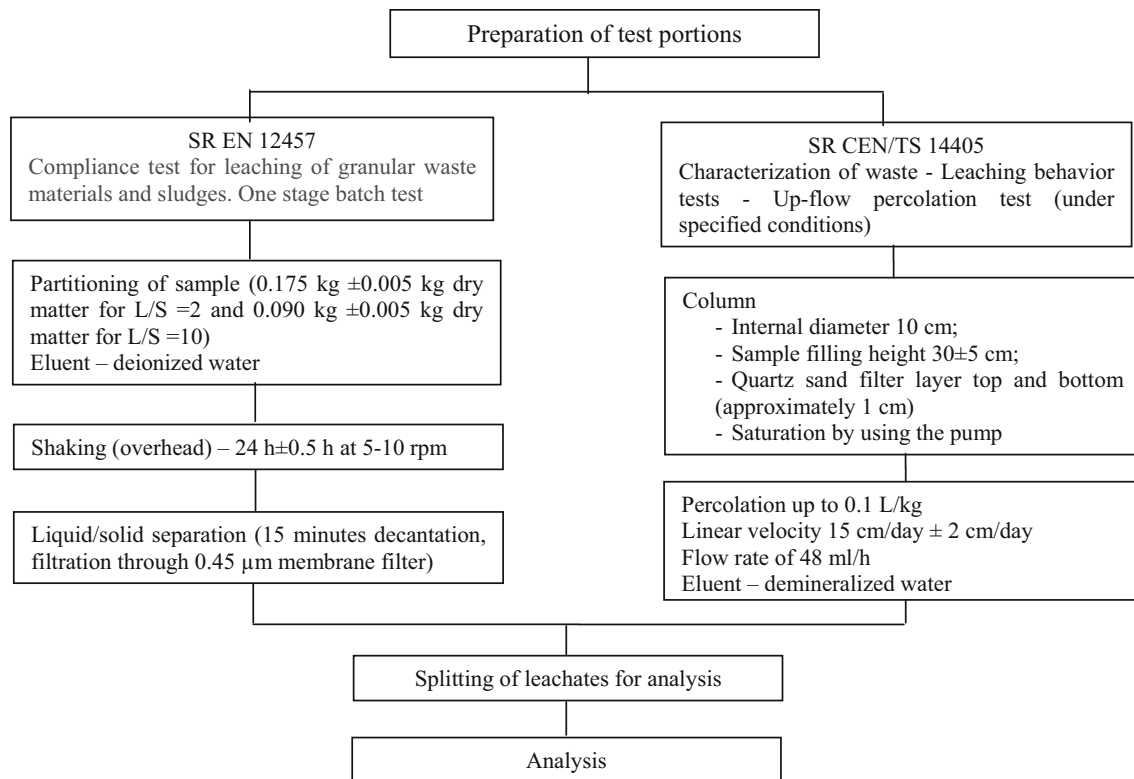
Fig. 1 Leaching test procedures

Table 2 Limit values for inert waste landfill

Parameter	As	Ba	Cd	Cr total	Cu	Hg	Mo	Ni
$L/S = 2$ (mg/kg)	0.1	7	0.03	0.2	0.9	0.003	0.3	0.2
$L/S = 10$ (mg/kg)	0.5	20	0.04	0.5	2	0.01	0.5	0.4
$L/S = 0.1$ (mg/L)	0.06	4	0.02	0.1	0.6	0.002	0.2	0.12

Parameter	Pb	Se	Zn	Fluoride	Chloride	Sulfate	Phenol index
$L/S = 2$ (mg/kg)	0.2	0.06	2	4	550	560	0.5
$L/S = 10$ (mg/kg)	0.5	0.1	4	10	800	1000	1
$L/S = 0.1$ (mg/L)	0.15	0.04	1.2	2.5	460	1500	0.3

Results expressed as leachate concentrations (mg/L and μg/L) allow the transformation of measured concentrations into release units (mg/kg of dry matter), A, according to Eq. (2):

$$A = C \times \left[\left(\frac{L}{MD} \right) + \left(\frac{MC}{100} \right) \right] \quad (2)$$

where C is the concentration of element in the leachate, mg/L; L volume of the demineralized water added, L; MC is the humidity of the sample; %wt dry matter; MD is the dry weight of the sample, kg.

The analyzed elements were: arsenic, barium, cadmium, chromium, copper, mercury, molybdenum, nickel, lead, selenium, zinc, fluoride, chloride, sulfate and phenol index. For every element analyzed, the results are expressed in mg/kg in relation to liquid/solid ratio ($L/S = 2$ and $L/S = 10$). For $L/S = 0.1$ the results are in mg/L.

These values were compared to the limits of leaching values for the acceptance of waste at landfills for inert wastes according to 2003/33/EC transposed into national legislation by Ministerial Order no. 95/2005 (Table 2).

Results and discussion

Batch test

pH values

The leachates obtained in the batch test were generally alkaline (Table 3). The pH of concrete samples ranged

Table 3 The pH values of leachates

Code	C1	C2	B1	B2	M1	M2
$L/S = 2$	11.82	8.45	8.28	8.04	11.87	10.49
$L/S = 10$	11.64	8.53	8.48	8.18	12.02	10.24

from 8.45 to 11.82. Typical range for the pH is between the fresh concrete pH (>12.5) and the pH of fully carbonated concrete which can be defined as the pH where the phenolphthalein color change occurs (<10). The pH values vary with the service life exposure of the original concrete structure [29, 30]. According to Butera et al. [31] carbonation influences the leaching process by decreased pH and component releases.

The pH values of the leachates brick wastes were neutral or slightly alkaline. The leachates from M1 and M2 wastes are alkaline. The largest difference between pH was obtained for samples C1 and C2; an accentuated carbonation of C2 waste samples corroborated with its age may be assumed.

Inorganic species

Table 4 presents the concentration of arsenic, barium, cadmium, chromium, copper, mercury, molybdenum, nickel, lead, selenium and zinc for concrete demolition wastes, brick demolition wastes and mixtures in leachates from the batch test.

According to the obtained data, the releases of the elements As, Ba, Cu, Mo, Ni, Pb, Sb, Se, and Zn were inferior to the threshold values indicated by EU Landfill Directive. For chromium, releases from two samples were close to the limit values (0.2 mg/kg for $L/S = 2$ and 0.5 mg/kg for $L/S = 10$), namely C1 and M1. Chromium, copper, zinc, molybdenum concentrations are subject to exhaustion in time. This decrease can be due to the depletion of the elements within the porous structure; if the leaching tests continue long enough the total available content of pollutant would be released.

The cadmium and mercury releases were far below limit values for all wastes; the cadmium releases were below 0.01 mg/kg regardless L/S ratio; mercury releases vary from 0.0001 to 0.00068 mg/kg. According to Wahlstrom et al. 2000, the leaching of those elements is low in pH static test [32].

Generally, the releases of analyzed elements were higher in leachates from C1, B1 and M1 wastes than C2, B2 and M2. The data presented in Table 4 show that the concentrations of cations were higher in $L/S = 10$ leachates than in the case of $L/S = 2$. The concentration of elements Cu, Ni, Cd, Mo, Cr and Se is higher in C1 sample than C2.

Table 4 The releases of elements (mg/kg) for concrete, bricks and mixture wastes from batch test

Code	Limit value		C1		C2		B1		B2		M1		M2	
	$L/S = 2$	$L/S = 10$	$L/S = 2$	$L/S = 10$	$L/S = 2$	$L/S = 10$	$L/S = 2$	$L/S = 10$	$L/S = 2$	$L/S = 10$	$L/S = 2$	$L/S = 10$	$L/S = 2$	$L/S = 10$
As	0.1	0.5	0.06	0.02	0.01	0.05	0.05	0.16	0.01	0.08	0.01	<0.01	0.03	0.16
Ba	7	20	0.06	0.25	0.06	0.17	0.06	0.11	0.07	0.30	0.114	0.45	0.052	0.2
Cd	0.03	0.04	0.002	<0.01	<0.002	<0.01	<0.002	<0.01	<0.002	<0.01	<0.002	<0.01	<0.002	0.01
Cr total	0.2	0.5	0.2	0.3	0.004	0.04	0.01	0.03	0.01	0.07	0.20	0.48	0.11	0.2
Cu	0.9	2	0.4	1.0	0.1	0.7	0.19	0.75	0.27	0.78	0.198	0.95	0.20	0.57
Hg	0.03	0.01	0.0001	<0.0005	<0.0001	<0.0005	<0.0001	<0.0005	<0.0001	<0.0005	0.00068	0.00002	<0.0001	0.0005
Mo	0.3	0.5	0.07	0.14	0.04	0.05	0.04	0.08	0.03	0.05	0.05	0.12	0.09	0.12
Ni	0.2	0.4	0.04	0.08	0.01	0.03	0.03	0.05	0.01	0.03	0.068	0.08	0.02	0.04
Pb	0.2	0.5	0.004	0.04	0.006	0.02	0.01	0.03	0.01	0.06	0.016	0.02	0.008	0.05
Se	0.06	0.1	0.006	<0.01	<0.002	<0.01	0.01	0.02	<0.002	<0.01	0.014	<0.01	0.008	0.01
Zn	2	4	0.06	0.26	0.05	0.34	0.06	0.21	0.08	0.52	0.104	0.39	0.09	0.56

Table 5 Chloride, sulfate and fluoride releases—batch test

Releases (mg/kg)	Code	Limit value	C1	C2	B1	B2	M1	M2
Fluoride	$L/S = 2$	4	0.2	2.0	2.1	2.4	0.7	3.6
	$L/S = 10$	10	1.0	5.9	3.7	5.9	1.0	9.9
Chloride	$L/S = 2$	550	4.2	4.2	85.2	27	7	1
	$L/S = 10$	800	5	14	85	5	5	14
Sulfate	$L/S = 2$	560	344	454	190	462	142	593
	$L/S = 10$	1000	626	543	255	517	375	612

The sulfate and chloride contents are a limiting factor in using construction and demolition wastes in different civil engineering applications. Chloride can lead to corrosion of steel reinforcement. The chloride releases are presented in Table 5. Chloride releases were lower than the limit value for both $L/S = 2$ and $L/S = 10$. Generally, the chloride releases increased with L/S ratio, except B2 waste whose release decreases with L/S. The highest values were obtained for bricks wastes, namely B1, whose chloride release was nearly constant regardless L/S ratio.

Sulfate-based products, such as gypsum ($CaSO_4 2H_2O$) from stucco, plaster, cardboard-plaster panels, are common contaminants in construction and demolition waste. The usual limits for soluble sulfates are derived from a structural motivation. Sulfate in concrete can lead to loss of strengths and dimensional instability. For this reason, recycled aggregates with less than 4.4 % of gypsum and less than 30 % of ceramic particles could be used in non-structural civil applications without potential risk to the environment [33]. The results of batch leaching test showed releases below limit values for both L/S ratio, except M2 waste whose release for $L/S = 2$ was higher.

Sulfate content in concrete waste leachates was from 344 to 454 mg/kg for $L/S = 2$, from 543 to 626 mg/kg for $L/S = 10$; the highest values were obtained for concrete C2 (Table 5).

Sulfate contents in brick wastes were 190 mg/kg (B1) and 462 mg/kg (B2) for $L/S = 2$, and 255 mg/kg (B1) and 517 mg/kg (B2) for $L/S = 10$. The content of sulfate in mixture waste leachates for $L/S = 2$ was 142 mg/kg for M1 and 593 mg/kg for M2. For $L/S = 10$ the sulfate content was 375 mg/kg for M1 and 612 mg/kg for M2. Sulfate releases were higher in leachates from wastes C2, B2 and M2. For all leachates, the sulfate releases were lower than the legal limit values for waste acceptance at landfills for inert wastes, excepting M2 sample.

Fluoride releases were below threshold values for almost all wastes, excepting M2 whose releases were almost equal to the legal limit values (Table 5).

Organic species

Phenol index was analyzed in the leachates. For $L/S = 2$, phenol index had the same order of magnitude for wastes

Table 6 Phenol index—batch test

Code	Limit value	C1	C2	B1	B2	M1	M2
$L/S = 2$	0.5	2.2	0.1	0.2	0.2	0.7	1.1
$L/S = 10$	1	3.7	1	1.5	1	7.3	5.9

C2, B1 and B2 (from 0.1 to 0.2), values below legal limit. For C1 the index value was much higher (2.2) than limit value, while for M1 was slightly exceeded (0.7).

For $L/S = 10$, phenol index values were approximately equal or much higher than the limit values. The limit value was significantly exceeded in M1 and M2 waste leachates (Table 6).

Column percolation test

While the eluent is in constant contact with the waste in the batch tests, the elution agent is renewed in the column test. Batch test has the advantage of simple design and shorter periods of time. Column testing provides a closer approximation to leaching processes under field conditions.

pH values

The leachates obtained in the column leaching test (for $L/S = 0.1$) were slightly alkaline—10.84 and 8.00 for C1 and C2 concrete samples. The leachates of mixture waste (concrete, bricks, tiles and ceramics)—M1 had high alkaline pH value (12.34) unlike M2 sample that had lower pH value (10.18). The results have the same order of magnitude as leachates obtained in the batch test. The lower pH values denote a high degree of carbonation of concrete (C1 and C2 wastes). The lower values of pH for M2 sample can be explained by the presence of high amount of bricks, tiles and ceramics in the waste or high carbonation degree of concrete. Leachates of brick wastes were neutral (Table 7).

Table 7 pH values of leachates—column leaching test ($L/S = 0.1$)

Code	C1	C2	B1	B2	M1	M2
pH	10.84	8.00	7.45	7.18	12.34	10.18

Table 8 The concentrations of elements (mg/l) for waste leachates—column leaching test ($L/S = 0.1$)

Parameter	Limit value	C1	C2	B1	B2	M1	M2
As	0.06	0.01	0.01	0.02	0.01	0.005	0.013
Ba	4	0.03	0.11	0.17	0.07	0.059	0.059
Cd	0.02	<0.001	<0.001	<0.001	0.001	<0.001	<0.001
Cr total	0.1	0.1	0.01	0.003	0.004	0.09	0.1
Cu	0.6	0.3	0.2	0.07	0.19	0.157	0.085
Hg	0.002	0.00005	0.00045	0.00005	<0.00005	0.00032	0.00005
Mo	0.2	0.03	0.04	0.05	0.05	0.027	0.065
Ni	0.12	0.03	0.01	0.01	0.02	0.028	0.012
Pb	0.15	0.005	0.007	0.003	0.01	0.005	0.005
Se	0.04	0.006	0.005	0.01	0.01	0.006	0.009
Zn	1.2	0.03	0.05	0.05	0.04	0.039	0.030
Chloride	460	4.25	4.96	42.25	13.47	3.55	3.55
Fluoride	2.5	<0.1	<0.1	<0.1	0.37	1.25	0.37
Sulfate	1500	123.46	575.3	486.44	723.00	49.38	303.00
Phenol index	0.3	1.2	<0.1	<0.1	<0.1	0.31	<0.1

Inorganic species leaching

The mobilization of the inorganic components was high in this initial stage of the elution (Table 8). In this stage of leaching, the dissolution and surface wash-off processes play a predominant role. The concentration of Cr total reached the limit values for C1 and M2 samples. The content of Ba, Cd, Hg was at least 5 times lower than the threshold values. The concentrations were below limit values for all elements (Table 8).

The concentration of chloride and fluoride was below the limit values (Table 8). The highest values for sulfate concentration were obtained in brick wastes leachates, 486 mg/L for B1 sample and 723 mg/L for B2 sample, but these were lower than the threshold values for the waste acceptance at landfills for inert wastes.

Phenol index

Phenols were found in all leachates but the limit value (0.3) was exceeded for C1 and M1 leachate wastes. For example, phenol index in the leachate of C1 waste was about 3.8 times higher than the legal limit value. The phenol index in the leachate from brick wastes was 0.1 as in concrete C2 and mixture M2 (Table 8).

The high phenol content may be correlated with the origin of the wastes—steel plant. Probably, original concretes were contaminated with phenolic compounds. According to Harber [34] and Ghose [35], phenols are among the main potential contaminants associated with steel production. Phenols are associated with coke making process and foundries.

Conclusions

Demolition wastes—concretes, bricks, mixture of concrete, bricks, tiles and ceramics—were subject to column leaching test and batch test to determine which of the analyzed wastes can release pollutant in environment. The leachates were analyzed with respect to their concentration of arsenic, barium, cadmium, chromium, copper, mercury, molybdenum, nickel, lead, selenium, zinc, fluoride, chloride, sulfate and phenol index.

Comparing the results with legal limit values led to the following conclusions:

– The concentration and releases of the inorganic species in the leachates were generally below the threshold values indicated by EU Landfill Directive, regardless the type of the leaching test;
– Significant concentrations of phenols were observed in the some leachates from column percolation test and batch test for $L/S = 2$, namely C1 and M1. The analysis of leachates corresponding to batch test—liquid/solid ratio of 10—reveals a phenol index higher than the legal limit value for almost all analyzed samples (C1, B1, M1 and M2). The high level of phenol index in leachates is probably due contamination of construction located in the area of coke making process or foundries. In addition, the contaminants may be spread more widely by demolition and site clearance.

Better sorting of wastes will limit the dispersion of pollutant in the environment and will lead to more waste to be reused.

References

1. Directive 2008/98/EC (2008) Directive 2008/98/EC of the European Parliament and of the Council of 19 November 2008 on waste and repealing certain Directives. In: Off J Eur Union L312/3

2. Roussat N, Mehu J, Abdelghafour M, Brula P (2008) Leaching behavior of hazardous demolition waste. Waste Manag 28:2032–2040. doi:10.1016/j.wasman.2007.10.019

3. The National Environmental Protection Agency (2013) National Report on the state of environment. http://www.anpm.ro/upload/116008_RSM-2012.pdf. Accessed 14 Dec 2015

4. Krueger R, Ham RK, Boyle WC (1989) The variability of ferrous foundry waste leaching characteristics and comparison to landfill unsaturated zone leachate quality. 43rd Purdue University industrial waste conference proceedings. 605–616

5. Pacheco-Torgal F, Tam V, Labrincha J, Ding Y, de Brito J (eds) (2013) Handbook of recycled concrete and demolition waste. Elsevier, Amsterdam

6. European list of waste (2000) Commission Decision replacing Decision 94/3/EC establishing a list of wastes pursuant to Article 1(a) of Council Directive 75/442/EEC on waste and Council Decision 94/904/EC establishing a list of hazardous waste pursuant to Article 1(4) of Council Directive 91/689/EEC on hazardous waste

7. Jang YC, Townsend TG (2001) Occurrence of organic pollutants in recovered soil fines from construction and demolition waste. Waste Manag 21:703–715. doi:10.1016/S0956-053X(01)00007-1

8. Sheridan SK, Townsend TG, Price JL, Connell JT (2000) Policy options for hazardous-building-component removal before demolition. Pract Period Hazard Toxic Radioact Waste Manag 4:111–117. doi:10.1061/(ASCE)1090-025X(2000)4:3(111)

9. Weber JW, Jang YC, Townsend TG, Laux S (2002) Leachate from land disposed residential construction waste. J Environ Eng 128:237–245. doi:10.1061/(ASCE)0733-9372(2002)128:3(237)

10. Behiry AEAEM (2013) Utilization of cement treated recycled concrete aggregates as base or subbase layer in Egypt. Ain Shams Eng J 4:661–673. doi:10.1016/j.asej.2013.02.005

11. Jimenez J, Ayuso J, Galvin A, Lopez M, Agrela F (2012) Use of mixed recycled aggregates with a low embodied energy from non-selected CDW in unpaved rural roads. Constr Build Mater 34:34–43. doi:10.1016/j.conbuildmat.2012.02.042

12. Jankovic K, Nikolic D, Bojovic D (2012) Concrete paving blocks and flags made with crushed brick as aggregate. Constr Build Mater 28:659–663. doi:10.1016/j.conbuildmat.2011.10.036

13. Hendricks CF, Janssen GMT (2001) Reuse of construction and demolition waste in the Netherlands for road constructions. Heron J 46:109–117. http://heronjournal.nl/46-2/4.pdf. Accessed 11 Dec 2015

14. Aljassar AH, Al-Fadala KB, Ali AM (2005) Recycling building demolition waste in hot-mix asphalt concrete: a case study in Kuwait. J Mater Cycles Waste Manage 7:112–115. doi:10.1007/s10163-005-0135-4

15. Silva RV, de Brito J, Dhir RK (2014) Properties and composition of recycled aggregates from construction and demolition waste suitable for concrete production. Constr Build Mater 65:201–217. doi:10.1016/j.conbuildmat.2014.04.117

16. Cabral AEB (2013) Chapter concrete with construction and demolition wastes, eco-efficient concrete, civil and structural engineering. Woodhead Publishing Limited, India

17. Evangelista L, De Brito J (2010) Durability performance of concrete made with fine recycled concrete aggregates. Cem Concr Compos 32:9–14. doi:10.1016/j.cemconcomp.2009.09.005

18. Chakradhara Rao M, Bhattacharyya S.K, Barai SV (2010) Recycled aggregate concrete: a sustainable built environment. International conference on sustainable built environment, Kandy, 227–232

19. Safiuddin M, Johnson Alengaram U, Abdus Salam Md, Zamin Jumaat M, Fadhli Jaafar F, Binti Saad H (2011) Properties of high-workability concrete with recycled concrete aggregate. Mater Res 14:248–255. doi:10.1590/S1516-14392011005000039

20. Sagoe C, Brown T, Taylor A (2001) Performance of concrete made with commercially produced coarse recycled concrete aggregate. Cem Concr Res 31:707–712. doi:10.1016/S0008-8846(00)00476-2

21. Tam V, Wang K, Tamb CM (2008) Assessing relationships among properties of demolished concrete, recycled aggregate and recycled aggregate concrete using regression analysis. J Hazard Mater 152:703–714. doi:10.1016/j.jhazmat.2007.07.061

22. Evangelista L, de Brito J (2014) Concrete with fine recycled aggregates: a review. Eur J Environ Civil Eng 18:129–172. doi:10.1080/19648189.2013.851038

23. Tam V, Gao XF, Tam CM (2005) Microstructural analysis of recycled aggregate concrete produced from two-stage mixing approach. Cem Concr Res 35:1195–1203. doi:10.1016/j.cemconres.2004.10.025

24. Herbudiman B, Saptaji AM (2013) Self-compacting concrete with recycled traditional roof tile powder. Procedia Eng 54:805–816. doi:10.1016/j.proeng.2013.03.074

25. De Brito J, Pereira AS, Correia JR (2005) Mechanical behavior of non-structural concrete made, with recycled ceramic aggregates. Cem Concr Compos 27:429–433. doi:10.1016/j.cemconcomp.2004.07.005

26. SR EN 12457-1 (2003). Characterization of waste—leaching—compliance test for leaching of granular waste materials and sludges—Part 1: one stage batch test at a liquid to solid ratio of 2 l/kg for materials with high solid content and with particle size below 4 mm (without or with size reduction)

27. SR EN 12457-2 (2003). Characterization of waste—leaching—compliance test for leaching of granular waste materials and sludges—Part 2: one stage batch test at a liquid to solid ratio of 10 l/kg for materials with particle size below 4 mm (without or with size reduction)

28. CEN/TS 14405 (2004). Characterization of waste—leaching behavior tests—up-flow percolation test (under specified conditions)

29. Pacheco Torgal F, Miraldo S, Labrincha JA, De Brito J (2012) An overview on concrete carbonation in the context of eco-efficient construction: evaluation, use of SCMs and/or RAC. Constr Build Mater 36:141–150

30. Engelsen Christian CJ, Van der Sloot HA, Wibetoe G, Petkovic G, Stoltenberg-Hansson E, Lund W (2009) Release of mayor elements from recycled concrete aggregates and geochemical modelling. Cem Concr Res 39:446–459. doi:10.1016/j.cemconres.2009.02.001

31. Butera S, Christensen TH, Astrup TF (2014) Composition and leaching of construction and demolition waste: inorganic elements and organic compounds. J Hazard Mater 276:302–311. doi:10.1016/j.jhazmat.2014.05.033

32. Wahlstrom M, Laine-Ylijoki J, Maatanen A, Luotojarvi T, Kivekas L (2000) Environmental quality assurance system for use of crushed mineral demolition wastes in road constructions. Waste Manag 20:225–232. doi:10.1016/S0956-053X(99)00319-0

33. Barbudo A, Galvin A, Agrela F, Ayuso J, Jimenez JR (2012) Correlation analysis between sulfate content and leaching of sulfates in recycled aggregates from construction and demolition wastes. Waste Manag 32:1229–1235. doi:10.1016/j.wasman.2012.02.005

34. Harber AJ, Forth RA (2001) The contamination of former iron and steel works sites. Environ Geol 40:324–330

35. Ghose MK (2002) Physico-chemical treatment of coke plant effluents for control of water pollution in India. Indian J Chem Technol 9:54–59