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Characterization of wastes from construction and demolition sector

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Abstract In Republic of Korea, construction and demolition (C&D) waste accounts for 49.9 % of the total waste. In the present work, the mineralogical composition, the concentrations of 11 heavy metals, 19 PAH, and 7 polychlorinated biphenyl (PCB) congeners present in the 6 broad category (9 subcategories) of C&D hazardous waste were discussed along with their leaching characteristics. In concrete/mixed cement waste, the concentrations of As, Cr^{6+}, Hg, and Zn were in the range of 1.76–7.86, ND-1.63, 0.026–0.047, and 110.90–280.17 mg/kg, respectively. The asphalt waste sample A1 possessed relatively high concentrations of phenanthrene, fluoranthene, pyrene, benz(*a*)anthracene, benzo(*a*)pyrene, and indeno(1,2,3-*cd*)pyrene comparing to the other samples and it contains 0.08–0.1 % of coal tar. Hazardous nature of the C&D wastes greatly depends on the source of the collection. Zn concentration was above 1000 mg/kg for road asphalt waste samples A4 and A5. Total PCB concentration were high in the soil waste sample S1 (130 μg/kg) as it was the excavated soil obtained from the premises of an oil station. Leaching of As, Ba, CN^-, and F^- were observed in most of the C&D waste samples.

Keywords Construction and demolition waste · Asphalt waste · Waste soil · Heavy metals · PAH · PCB

Abbreviations

1-Mnap	1-Methyl naphthalene
2-Mnap	2-Methyl naphthalene
3-MChl	3-Methylcholanthrene
Acne	Acenaphthene
AcNy	Acenapthylene
An	Anthracene
BaA	Benzo(*a*)anthracene
BaP	Benzo(*a*)pyrene
BbF	Benzo(*b*)fluoranthene
BghiP	Benzo(*g*,*h*,*i*)perylene
BkF	Benzo(*k*)fluoranthene
C&D	Construction and demolition
Chr	Chrysene
DBahA	Dibenz(*a*,*h*)anthracene
Fl	Fluorene
FLA	Fluoranthene
IP	Indeno[1,2,3-*cd*]pyrene
Nap	Naphthalene

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Phe	Phenanthrene
Py	Pyrene

Introduction

Construction and demolition waste (C&D) is defined as the solid waste generated from construction, renovation, and demolition activities (Lu et al. 2011). C&D waste can be originated from residential, commercial, industrial, and governmental activities (Jang and Townsend 2001). Construction and demolition (C&D) debris represents one of the largest components of solid waste generated from municipal activities. In the European Union, about 461 million tons of C&D wastes are produced per year (Jiménez et al. 2012). In South Korea, C&D waste accounts for 49.9 % of the total waste with the generation capacity of 186,417 tons/day. Among them, concrete, asphalt, mixtures, and soil constitute 65.0, 18.9, 10.6, and 2.6 %, respectively. About 98.1 % of C&D waste has been used as recycling aggregates, whereas 1.4 % and 0.5 % are disposed as landfill and incineration, respectively (MOE of Korea 2011a).

Major components of C&D debris include wood, concrete (including masonry products), asphalt, gypsum, metal, and soil (Townsend et al. 2004). The European Waste Catalogue (EWC) classifies C&D waste into the eight major categories which further sub classified into 38 subcategories out of which 16 are absolute/mirror hazardous entries (EA 2011).

The hazardous substances present in C&D waste can cause health and environmental risks if it is not properly handled. When these materials are applied as recycling aggregates, water from rain, surface water, or groundwater comes in contact with them, and hazardous elements may be leached (Galvin et al. 2012). Therefore, the content of harmful substances in these materials should be kept low, and the leaching behavior of these elements should be acceptable for materials used in construction and engineering, both during their service life and in subsequent recycling (Roussat et al. 2008).

Thus, the objective of the present work is to study the detailed characterization with their leaching behavior of the different types of hazardous C&D wastes. This study will act as a foundation to set up the regulatory standards for all the inorganic and organic components present in the C&D waste in South Korea. In this paper, we discussed about the mineralogical composition, the concentrations of 11 heavy metals, F^-, CN^-, 19 PAH, 7 polychlorinated biphenyl (PCB) congeners, and their leaching behavior present in six broad category (9 subcategories) of C&D hazardous waste reported in EWC. It covers concrete/mixed cement waste, waste asphalt, waste soils (three types), waste wood, waste metals (two types), and waste capacitors.

Materials and methods

Sampling procedure

Construction and Demolition waste (C&D waste) were categorized as the absolute and mirror entries under the EWC code 17 (C&D waste) as per the European Waste Catalogue (EA 2011). Absolute entries are considered as hazardous regardless of any threshold concentrations. Mirror entries are considered to be hazardous only if dangerous substances are present above threshold concentrations. Among that, waste which is applicable to Korea were selected. In total, 23 hazardous C&D waste samples had been collected during March to October 2012 around South Korea. Table 1 provides the nature and details of the sampling.

Sample preparation and analytical procedures

Collected samples were manually crushed and sieved through a 5-mm sieve to homogenize. Microwave digestion of samples had been carried out using the equipment MARS (CEM Corporation, USA). Microwave digestion methods EPA 3051A or EPA 3052 or EPA 3546 was selected depending on the nature of the samples and the analytes. The methodology used to measure the concentration of the heavy metals, PAH and PCB present in the hazardous waste is presented in Table 2. Standard solutions were purchased from PlasmaCAL and if required, diluted using distilled deionized water. Detection limit of the analytes is given in Table S1.

X-ray diffraction analysis

X-ray diffraction (XRD) experiments were performed using Rigaku Ultima IV X-ray diffractometer for 2θ values from 10 to 80 using Cu Kα radiation at a wavelength of $\lambda=1.54$ Å. Quantitative analysis was carried out using reference intensity ratio (RIR) in the PDXL

Table 1 Details of the sample collection

Broad C&D categories	Total no. of samples	Sample label	Sample description
Concrete, bricks, tiles, and ceramics	4	C1	Demolished building concrete
		C2	Demolished building concrete
		MCW1	Mixture of concrete, bricks, and tiles from demolished structures
		MCW2	Mixture of concrete, bricks, and tiles from demolished structures
Bituminous mixtures (asphalt)	5	A1	Demolished roof sealant asphalt
		A2	Demolished roof sealant asphalt
		A3	Demolished roof sealant asphalt
		A4	Demolished road asphalt
		A5	Demolished Highway road asphalt
Soil (including excavated soils), stones, and dredging spoil	6	S1	Excavated soil from a construction site
		S2	Excavated soil from a construction site
		S3	Dredging spoils of demolished sewerage system
		S4	Dredging spoils of demolished sewerage system
		S5	Demolished railway track ballast
		S6	Construction railway track ballast
Wood	2	W1	Waste wood from a demolished structure
		W2	Waste wood from a demolished structure
Metals	4	M1	Demolished concrete reinforcement steel
		M2	Demolished concrete reinforcement steel
		M3	Metals from demolished cables
		M4	Metals from demolished cables
Wastes containing PCB	2	PW1	Demolished capacitor containing transformer oils
		PW2	Demolished capacitor containing transformer oils

Table 2 Analytical procedures with details of the instrument used

Analytes	Method no.	Instrument	Make and model of the instrument used
As	ES06403.1[a]	AAS	VARIAN 280 FS
Hg	ES06404.1[a]	AAS	Thermo Scientific Solaar M6
Cd	ES06405.2[a]	ICPES	Jobin Yvon, US/Ultima V5
Cr	ES6406.2[a]	ICPES	Jobin Yvon, US/Ultima V5
Cu	ES06401.2[a]	ICPES	Jobin Yvon, US/Ultima V5
Pb	ES06402.2[a]	ICPES	Jobin Yvon, US/Ultima V5
Ba, Ni, V & Zn	USEPA 6020A	ICPES	Jobin Yvon, US/Ultima V5
CN^-	ES06351.1[a]	UV-vis	Thermo, GENESYS 5
F^-	USEPA 340.3	UV-vis	Thermo, GENESYS 5
Cr^{6+}	ES06407.3[a]	UV-vis	Thermo, GENESYS 5
PAHs	USEPA 8275A	HRGC-HRMS	Agilent HP6890N - Thermo Finnigan MAT 95XP
PCBs	USEPA 1668A	HRGC-HRMS	Agilent HP6890N - Thermo Finnigan MAT 95XP

[a] Korean standard method (MOE of Korea 2011b)

software program (Rigaku Corp., Japan). The RIR values were obtained from ICDD database.

Leaching procedure

Leaching test was carried out using the Korean standard official method ES 06150 (MOE of Korea 2011b; Kang et al. 2014). The leachate solution of pH 5.8–6.3 (adjusted with HCl) was used; the ratio of the sample to leachate volume was 1:10 (*w*:*v*); the leaching time was 6 h and agitated horizontally with 200 RPM. The leachate was pretreated (if required) and filtered through 1-μm glass fiber filter (Nam and Namkoong 2012).

Results and discussion

Concrete and mixed cement wastes

Four cement-based demolition waste samples were analyzed for the 11 heavy metals, F^- and CN^-. The concentrations of Cr, Pb, As, Cr^{6+}, Hg, and V were in the range of 57.26–84.29, 11.38–84.41, 1.76–7.86, ND-1.63, 0.026–0.047, and 16.49–23.25 mg/kg, respectively (Fig. 1). Among all the heavy metals, Zn was observed in higher concentration (110.90–280.17 mg/kg). Townsend et al. (2004) also observed Zn as the highest mean concentration (200 mg/kg) among all the heavy metals apart from Al in C&D debris. They reported the mean concentration of As and Hg as 2.7 and 0.16 mg/kg, respectively. We observed very high concentrations of Cu (237.87 mg/kg), Ni (78.25 mg/kg), and Zn (280.17 mg/kg) in the sample MCW1 and also Cd (6.26 mg/kg) was detected only in this sample (Fig. 1). The metal concentrations in the MCW1 may also be elevated because of the nature of the soil in this particular location (Townsend et al. 2004). Thus, the elevated levels may also be due to the high heavy metals concentration present in the soil (sample S4) of the same locality, which will be further detailed in the Section 3.3.

The leaching behavior of the sample are presented in Table 3. Most of the heavy metals were found below the detectable limit but As was observed in both of the mixed samples leachate. The leaching of Ba was observed in the samples C1 and MCW2, which contains Ba in its content concentration. The concentration of the F^- in the leachate was observed in the range of ND-1.38 mg/L. Roussat et al. (2008) reported that F^-, As, and Ba possess similar leaching behavior in mixed type of hazardous demolition waste. Galvin et al. (2012) reported the leaching behavior of mixed type of C&D waste using UNE-EN 12457-3 method in which deionized water was used as the leachant. They also observed that Ba was released in a higher concentration (0.053–0.656 mg/kg) than any other heavy metals. Townsend et al. (2004) reported most of the metals were not in the detectable range in the leaching of C&D debris and As leached to a greater extent (6.5 %) than any other metals.

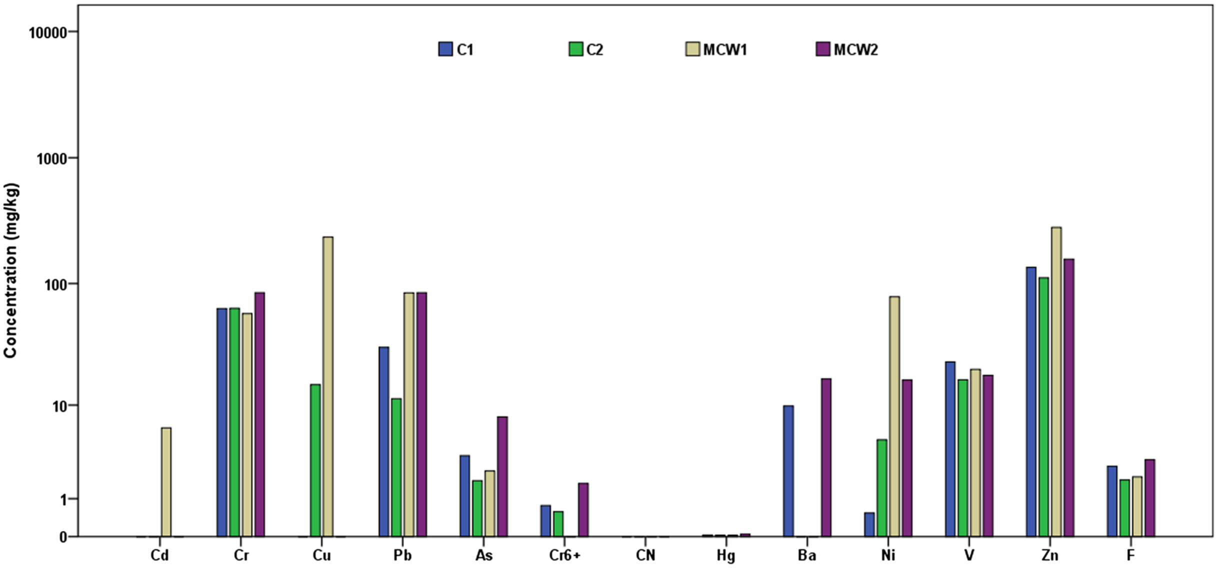

Fig. 1 Concentration of heavy metals, F^-, and CN^- in concrete/mixed cement waste samples

Table 3 Heavy metal leaching characteristics of C&D waste samples (mg/L)

Sample	pH	Cd	Cr	Cu	Pb	As	Cr^{6+}	CN^{-}	Hg	Ba	Ni	V	Zn	F
C1	10.4	ND	ND	ND	ND	ND	ND	ND	ND	0.681	ND	ND	ND	ND
C2	11.4	ND	0.031	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	1.382
MCW1	9.9	ND	ND	ND	ND	0.006	ND	ND	ND	ND	ND	ND	ND	0.663
MCW2	9.6	ND	ND	0.065	ND	0.005	ND	ND	ND	0.287	ND	ND	ND	0.667
A1	10.0	ND	ND	ND	ND	ND	ND	1.937	ND	0.288	ND	ND	ND	0.188
A2	9.7	ND	ND	ND	ND	0.029	ND	ND	ND	ND	ND	ND	ND	ND
A3	9.5	ND	ND	ND	ND	ND	ND	0.644	ND	0.345	ND	ND	ND	0.407
A4	9.3	ND	ND	ND	0.035	ND	ND	ND	ND	ND	ND	ND	ND	0.198
A5	7.8	ND	ND	ND	ND	ND	ND	0.757	ND	ND	ND	ND	ND	0.181
S1	8.3	ND	ND	ND	ND	0.005	ND	ND	0.001	0.627	ND	ND	ND	ND
S2	11.1	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	0.519
S3	7.7	ND	ND	ND	ND	0.015	ND	ND	0.002	1.837	ND	ND	ND	2.670
S4	7.6	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
S5	9.4	ND	ND	ND	ND	0.020	ND	2.418	ND	ND	ND	ND	ND	0.142
S6	8.9	ND	ND	ND	ND	0.025	ND	0.232	ND	ND	ND	ND	ND	0.333
W1	6.4	ND	ND	ND	ND	0.022	ND	ND	ND	ND	ND	ND	ND	0.307
W2	5.3	ND	ND	ND	ND	0.006	ND	82.086	ND	ND	ND	ND	ND	6.248
M1	7.3	ND	ND	ND	ND	ND	ND	0.686	ND	ND	ND	ND	ND	ND
M2	8.3	ND	ND	ND	ND	ND	ND	6.865	ND	ND	ND	ND	ND	ND
M3	8.5	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	0.059
M4	8.8	ND	ND	ND	ND	ND	ND	0.500	ND	ND	ND	ND	ND	0.453

ND not detected

Figure S1 showed the XRD pattern of the cement and mixed cement waste samples and their mineralogical composition were shown in Table 4. It showed that quartz was high in all the samples. The concentration of gypsum was high for mixed waste samples rather than concrete samples. The phases such as portlandite ($Ca(OH)_2$), tobermorite (CSH), ettringite (Aft), and calcium aluminate monosulfate (AFm) were observed in a minor quantity among all the samples. When trace elements bound in specific cement phases transferred to specific cement hydrates, the hydroxides phase is responsible for the primary fixation of higher volatile elements Cd, Pb, As, and Hg, whereas secondary fixation of V, Zn, Ba, Cr, and Cu. But, the elements V, Zn,

Table 4 Mineralogical composition of concrete and mixed cement wastes

Phases	C1	C2	MCW1	MCW2
Quartz	78.541	75.705	63.302	75.329
Calcite	1.308	14.467	4.471	5.829
Microcline	4.892	3.342	10.023	5.980
Albite	11.823	2.116	9.004	4.846
Muscovite	1.653	1.872	3.903	3.731
Portlandite	1.028	1.704	0.505	0.149
Ettringite (Aft)	0.121	0.131	0.149	0.263
Tobermorite (C-S-H)	0.010	0.055	0.069	0.082
Calcium aluminate monosulfate (AFm)	0.383	0.460	0.072	0.039
Gypsum	0.184	0.148	8.265	3.750

Ba, Cr, and Cu are primarily fixed in CSH phase also. The phase Aft/AFm is responsible for fixing Zn, Cr, Cu, and Ni as primary and Cd, Pb, As, and Hg as secondary (Achternbosch et al. 2003).

Due to demolition, the properties such as porosity, grain size, and the crushing structure are modified. Mechanical and chemical weathering on the new surfaces accelerates the access of acids. Thus, the destabilization of hydroxide and the complete decomposition of CSH into SiO_2 and $CaCO_3$ under a complete release of the incorporated trace metals take place. Aft/AFm remains unchanged until the slightly acidic range is reached. The leachate concentrations of trace metals have been found to exhibit equilibrium values that depend strongly on the leachate pH (Van der Sloot 2000). The leaching behavior of these metals in construction materials is mainly controlled by the alkaline nature and acid buffering capacity of the stabilized matrix (Li et al. 2001).

During the lifetime of a structure, higher buffer capacity of $Ca(OH)_2$ above pH 12 prevents trace metals from being mobilized. Following the consumption of the $Ca(OH)_2$ buffer (after demolished), the CSH buffer determines the trace element mobilization of trace metals between pH 11 and pH 9. If the pH drops below 9, a pH of 5.5 is reached rapidly in which the carbonate and AFm buffer becomes effective (Achternbosch et al. 2003). We observed the pH of these samples in the range of 9.6–11.4 (Table 3). The leaching of heavy metals increases when the alkaline nature of the sample decreases (Galvin et al. 2012). Thus, the leaching observed slightly higher in MCW1 and MCW2 rather than C1 and C2.

One way to control heavy metals present in concrete and mixed cement wastes is to regulate the alternative raw materials and the auxiliary fuel used in the cement manufacturing process. Ministry of Environment in Republic of Korea regulated the heavy metals (Pb, Cu, Cd, As, and Hg) standards for the alternative raw materials and the auxiliary fuel to be used in the cement manufacturing process (MOE of Korea 2012), and the standards have been tabulated in the supplementary material Table S2.

The applicability of these cement wastes as recycling aggregates had been demonstrated by comparing the regulatory standards (content and leaching) presented in Korean Waste Management Act (MOE of Korea 2012). The content standard and leaching standard of the heavy metals for recycling aggregates are presented in the Table S3. Only the sample MCW1 was found not suitable because of the high Cu concentration than the content standard value. None of the sample exceeded the leaching standard.

Asphalt (bituminous) wastes

The main application of bitumen/asphalt is to coat the surfaces of roads, roofs, linings of water basins, and pipes (Brandt and de Groot 2001). Five asphalt samples (demolition) have been analyzed for 11 heavy metals, F^-, CN^-, 19 PAH, and 7 congeners of the PCB.

Heavy/trace metal concentration of these samples is shown in Fig. 2. The results showed that Zn concentration was in the range of 59–289 mg/kg for A1–A3 samples, whereas it was above 1000 mg/kg for samples A4 and A5. The concentration of Pb and CN^- were in the range of 10–77 mg/kg and ND-6 mg/kg, respectively, for samples A1–A4, whereas A5 showed the highest values as 442 mg Pb/kg and 21.6 mg CN^-/kg. The sample A5, being the asphalt demolition waste collected from one of the heavy traffic roads, most of the heavy metals were high in this sample (Legret et al. 2005). The sample A4, which also belongs to the demolition waste from the road, is attributed to the very high concentration of Zn (Huang et al. 2007). This road had been mostly used by bicycle riders.

Heavy metals are encountered in various emission sources related to automobiles. Zinc and cadmium are deposited mainly through tire wear and corrosion of galvanized steel crash barriers, whereas the source of copper is the brake line (Legret and Pagotto 2003). Even though the use of leaded gasoline as automobile fuels was not allowed in Korea for more than two decades, a large amount of Pb has been still identified due to heavy traffic (Duong and Lee 2011). This is because Pb can be still released from tire wear, lubricating oil use, and bearing wear to the road environment (Zhu et al. 2008). Other metals such as barium and chromium could result from a lubrication additive or from crankcase drippings. Gadd and Kennedy (2003) reported that the concentrations of Ni and Zn contained in road bitumen samples were higher than those in raw bitumen samples. Legret et al. (2005) reported the concentrations of heavy metal Cr, Cu, N,i and Zn for conventional asphalt as 54, 20, 20, and 86 mg/kg, respectively, which was in line with our results.

The leaching of heavy metals in samples A1 to A5 was shown in Table 3. Leaching of Ba, CN^-, and F^-

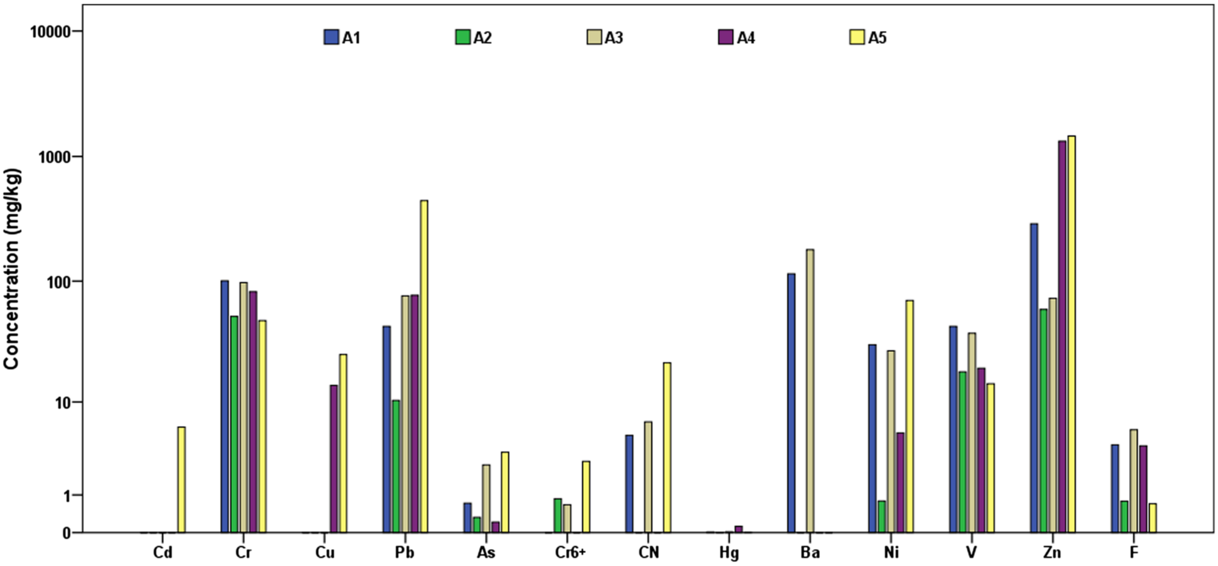

Fig. 2 Concentration of heavy metals, F$^-$, and CN$^-$ in waste asphalt samples

observed in all the samples which contain them in content concentration. The CN$^-$ leaching was very high (1.937 mg/L) in the sample A1 though the content concentration was lower than the other samples. The concentration of As was observed in the leachate of A2 (0.029 mg/L) though it posses lower content concentration of As (Fig. 2). Most of the metals (except As and Ba) were in the below the detectable limits which could be due to the alkaline nature of the leachate pH (Table 3). Legret et al. (2005) also observed that the leaching of heavy metals such as Cu, Zn, Pb, and Hg in reclaimed asphalt was below the detectable limit at slightly alkaline pH, whereas high leaching at acidic pH.

The concentration of the heavy metals of these asphalt samples was also compared with the recycling aggregates regulatory standards (Table S3) presented in Korean Waste Management Act (MOE of Korea 2012). None of the sample exceeded the content standard; however, leaching CN$^-$ standard was exceeded by the samples A1, A3, and A5.

Figure S1 represents the XRD pattern of asphalt C&D waste which showed that quartz, kaolinite, muscovite, pyroxene, microcline, and palygorskite as the major phases.

The sum of 19 PAH for the samples A1 to A5 were depicted in the Fig. 3a. It clearly shows that the total PAH of A5 sample was very high (13.38 mg/kg) in comparison with the other samples (1.97–6.60 mg/kg). Asphalt being derived from petrogenic source, all the samples showed a low molecular weight (LMW) to high molecular weight (HMW) ratio greater than one (Hu et al. 2010; Wang et al. 2006), whereas the samples A4 (24) and A5 (37) being the road asphalts, possessed the highest ratio of LMW/HMW. Traffic-related sources of PAHs include vehicle exhaust, lubricating oils, gasoline, diesel fuel, and tire particles (Brandt and de Groot 2001; Liu et al. 2007; Murakami et al. 2005). LMW compounds might be accumulated in crankcase oils from admixed gasoline. Road surface PAHs in samples A4 and A5 may be derived primarily from crankcase oil, tire, and brake wear (Liu et al. 2007).

In comparison to all the samples, the isomer pattern of A1 was different, and TPAH of this sample (6.6 mg/kg) was even greater than the road asphalt sample A4 (Fig. 3a). To evaluate the presence of coal tar in these samples, we applied source identification techniques such as comparisons of the relative PAH composition and quantitative analysis of isomer ratios (Ahrens and Depree 2010). Coal tar was used as a cost-effective and readily available material before being replaced by petroleum-based (bituminous) binders. Isomer ratios tended to be lower for petrogenic source materials (asphalt) and higher for pyrogenic materials (coal tar). Instead of using the simple ratio of two isomers (e.g., benz(*a*)anthracene/chrysene), the ratio of one isomer to the sum of its isomer concentration is preferred (e.g., benz(*a*)anthracene/(benz(*a*)anthracene+chrysene)), which results in less variability of the calculated ratio (Oros and Ross 2005).

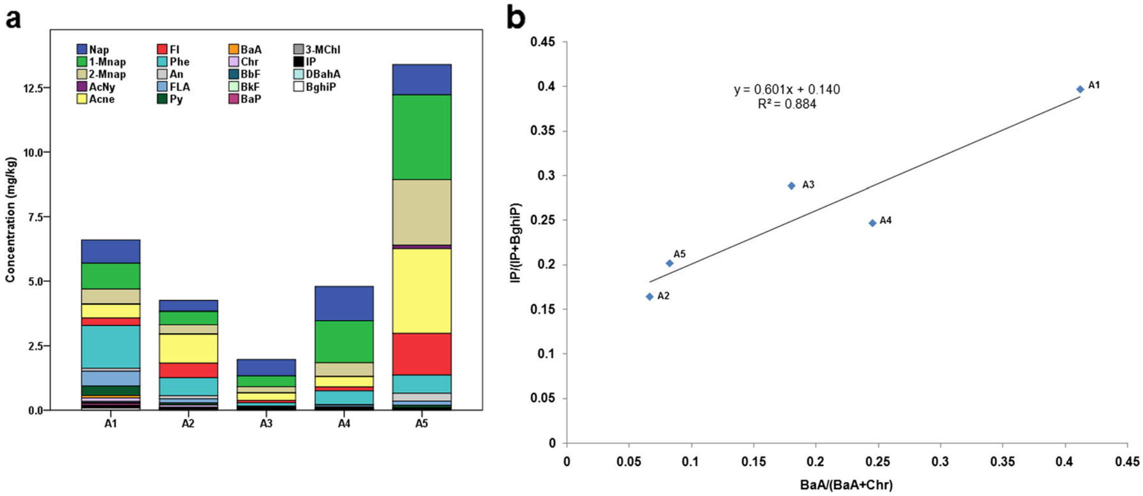

Fig. 3 PAHs concentrations (**a**) and Scatter plot of IP/(IP+BghiP) versus BaA/(BaA+Chr) (**b**) in waste asphalt samples

Ahrens and Depree (2010) reported that the asphalt pavements had a low BaA/(BaA+Chr) ratio of 0.16–0.39, whereas coal tar pavements had a BaA/(BaA+Chr) ratio of 0.51–0.56. We observed the ratio as 0.412 in A1 and other samples in the range of 0.067–0.246.

Scatter plot between the ratios of two isomer pairs BaA/(BaA+Chr) and IP/(IP+BghiP) against each other showed that the sample A1 bounded at one end and of the apparent line, whereas samples A2 and A5 at the other end (Fig. 3b). Ahrens and Depree (2010) observed coal tar and bitumen as end members in the same type of plot, whereas mixtures in between them. And also, A1 sample possessed relatively high concentrations of Phe, FLA, Py, BaA, BaP, and IP comparing to the other samples. These results indicated that the sample A1 may contain 0.08–0.1 % of coal tar and the samples A3 and A4 with 0.001–0.005 % of coal tar in it, whereas A2 and A5 showed no traces of coal tar contamination (Ahrens and Depree 2010).

Legret et al. (2005) reported the sum of the 16 PAHs amounted to about 4.3 mg/kg for the new conventional asphalt and 1.8 mg/kg for the reclaimed asphalt. Brandt and de Groot (2001) reported the sum of 15 PAHs in pure bitumen from several sources as ranging from 6.4 to 15.2 mg/kg. Van Metre et al. (2009) reported sum of 16 PAH concentrations of less than 6 mg/kg for asphalt seal-coated pavements in western US cities, and up to 1000 times higher concentrations for coal tar seal-coated pavements in eastern US cities (3400 mg/kg).

Asphalt samples were also analyzed for seven PCB isomer patterns (CB-28, CB-52, CB-101, CB-118, CB-138, CB-153, and CB-180) ranging from tri- to hepta-PCB congeners and presented in Fig. 4. Like PAH, total PCB concentration was higher in the sample A5 (113 μg/kg) due to the leakage of lubricating oils from vehicles in the road (Sures et al. 2001). Though the total PCB concentration in A1 (64 μg/kg) and A4 (62 μg/kg) was nearly equal, the isomer pattern of A1 was entirely different from other samples due to the relative high amount of coal tar in it. Most of the samples (A2 to A5) showed the higher concentration of CB-52 (tetra-PCB congener), whereas A1 showed an equal distribution (10 μg/kg) of all the isomer except CB-180 (hepta-PCB congener).

Waste soils

Six samples were collected under soil category, and Fig. 5 shows the 11 heavy metals, F^- and CN^- concentrations for these samples. S5 being a track ballast-based demolished waste (Table 1) in a frequently used railway track the concentration of Zn (581.65 mg/kg), Pb (79.69 mg/kg), As (7.98 mg/kg), and CN^- (5.23 mg/kg) were high (Fig. 5). Galvanization of train tires consists of more than 99 % of Zn. The heavy metal Cr resulted from the rails and GG brakes of train, whereas Pb from S brakes of the trains (Burkhardt et al. 2008). S1 sample showed very high concentration of Ba and Cu than any other samples because it was the excavated soil collected within the premises of an oil station (Nadal et al. 2004).

The sample S4 showed relatively high concentrations of Cd, Cr, Cr^{6+}, Pb, and Ni as 5.82, 59.36, 2.59, 92.84,

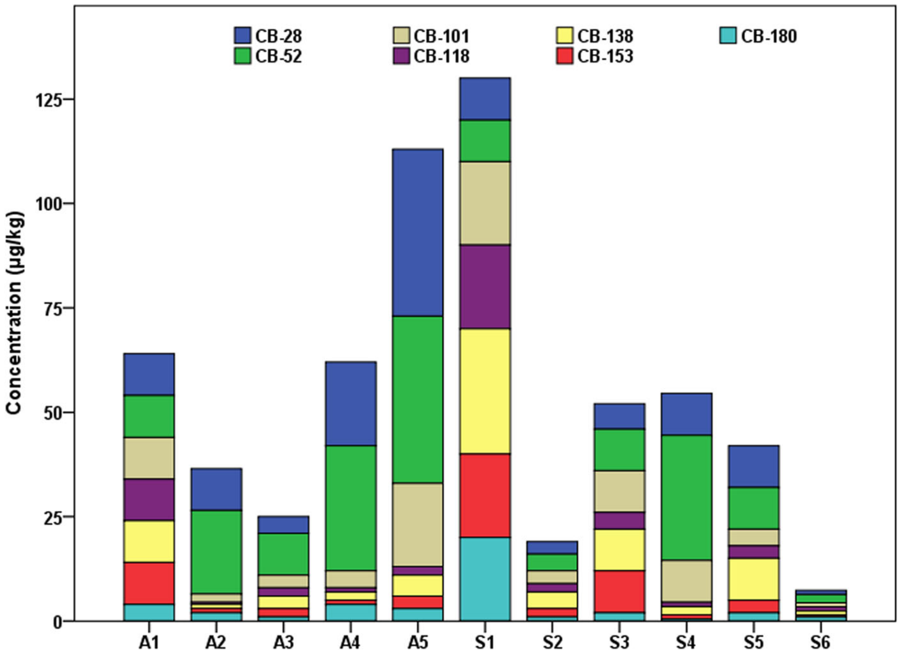

Fig. 4 PCBs isomer patterns of waste asphalt and waste soil samples

and 74.64 mg/kg, respectively, and slightly elevated levels of Zn (221.09 mg/kg) and CN$^-$ (4.99). This sample had been collected in the region where an abandoned mine is located approximately at a distance of 3–4 km which may attribute to the higher concentrations of heavy metals (Kim et al. 2005; Lee et al. 2001). Many authors reported the elevated levels of heavy metals in soils around the abandoned mines in Korea. Ji et al. (2013) reported the mean concentrations in soils near the abandoned mines were 62.71 mg Pb/kg and 249.17 mg Zn/kg. Lee et al. (2001) reported 0.4–4.76 mg Cd/kg and 21–484 mg Pb/kg in the soils located near an abandoned mine.

Most of the heavy metals were below the detectable limit in the leachate except As, Hg, Ba, CN$^-$, and F$^-$ (Table 3). The leaching of As was observed in the range

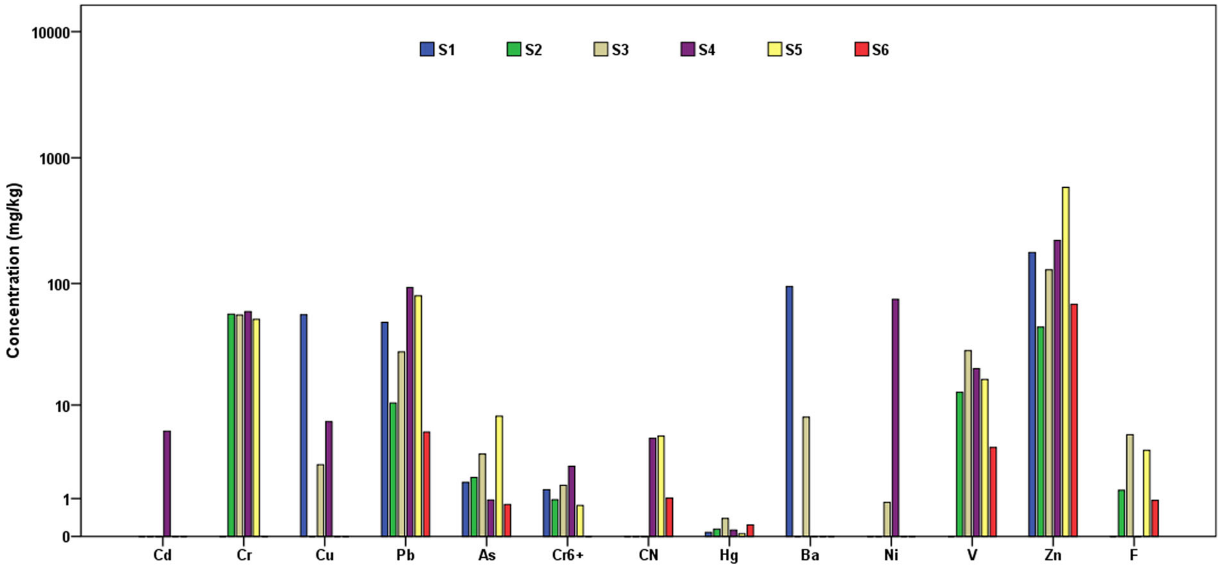

Fig. 5 Concentration of heavy metals, F$^-$, and CN$^-$ in waste C&D soils

of ND-0.025 mg/L. The Hg was present in the leachate of S1 (0.001 mg/L) and S3 (0.002 mg/L) but not in the other samples.

Table 5 showed the mineralogical composition of the samples S1–S4 before and after leaching. The samples S5 and S6 being track ballast, we could not able to study its mineralogical composition. The major compositions of the soil samples were quartz, albite, kaolinite, and illite/montmorillonite along with the minor soil phases such as brushite ($CaHPO_4$), palygorskite, and anglesite (Fig. S1).

Hartley et al. (2010) reported that the arsenic in soil was associated with 40 % in Fe and Al fraction and 20 % in carbonate fraction. It has been demonstrated that As may also be highly mobilized in phosphorus amended soils largely due to competitive anion exchange (Zhang and Selim 2008). Hg is also likely to be associated with Fe and Al organic complexes and/or with organic coatings on Fe/Al oxides (Guedron et al. 2009). The presence of clay minerals and Fe-oxyhydroxides represents relatively favorable conditions for Hg adsorption to the mineral surfaces (Hojdová et al. 2009).

We observed that the decrease in weight percent of Al fractions such as albite and kaolinite and weight percent $CaCO_3$ in S1 and S3, whereas no decrease of these fractions in S4 (Table 5). Thus, the stability of these phases at the time of leaching was also responsible for the release of As and Hg. Though the decrease in Al fractions was observed for S2, no leaching observed in this sample which may be due to the high alkaline nature of the soil (Jing et al. 2003; Yoon et al. 2010). The pH >11 of S2 was due to the carbonate alkalinity as evident by slightly higher phases of calcite and dolomite, and also the weight percent of calcite in this sample increases tremendously after leached (from 1.772 to 21.080 %).

Soil samples were also analyzed for seven PCB isomer patterns (CB-28, CB-52, CB-101, CB-118, CB-138, CB-153, and CB-180) ranging from tri- to hepta-PCB congeners and presented in Fig. 4. Total PCB concentration were high in the sample S1 (130 μg/kg) as it was the excavated soil obtained from the premises of an oil station. Though the total PCB concentration in S3 (52 μg/kg) and S4 (54.5 μg/kg) were nearly equal, their isomer pattern has got slight difference. All the samples showed either the highest concentration of CB-52 (tetra-PCB congener) or CB-138 (hexa-PCB congener).

The concentrations of heavy metals and PCB in soil samples were compared with regulatory standards of Soil Environmental Conservation Act of Korea (MOE of Korea 2011c). Three types of warning standards such as 1°, 2°, and 3° are established to differentiate between the three different zones which is explained in Table S4. Reusage of the C&D soil samples should be based on these standards. The samples S4 and S5 cannot be

Table 5 Mineralogical composition of soil samples before and after leaching

Phases	Before leaching				After leaching			
	S1	S2	S3	S4	S1	S2	S3	S4
Quartz	50.284	61.083	52.566	75.422	44.017	33.178	47.092	62.412
Albite	19.770	14.501	20.870	6.839	17.183	8.045	16.987	11.856
Kaolinite	8.859	4.355	9.336	1.178	3.447	1.196	3.016	11.853
Brushite	0.941	0.297	0.864	0.066	1.189	3.279	1.734	2.063
Gypsum	0.075	0.166	0.064	1.088	3.913	0.003	2.974	4.022
Palygorskite	1.538	0.071	1.456	4.962	1.880	7.863	1.621	4.693
Anglesite	0.196	0.409	0.190	0.290	0.089	0.094	0.079	0.074
Illite/montmorillonite	15.974	15.374	12.654	8.687	19.945	12.368	17.465	0.528
Calcite	1.215	1.772	0.971	0.513	0.055	21.080	0.340	1.808
Pyrite	0.077	0.118	0.065	0.027	0.352	0.079	0.346	0.119
Calcium hydroxide	0.424	0.030	0.324	0.207	0.408	0.053	0.331	0.131
Hematite	0.043	0.185	0.063	0.029	0.058	0.004	0.064	0.031
Chlorite	0.506	0.103	0.493	0.213	6.401	12.650	7.854	0.044
Dolomite	0.097	1.537	0.084	0.479	1.065	0.110	0.097	0.368

allowed in 1° zone because of the high concentration of Cd and Zn, respectively, whereas other samples can be used in all the zones.

Other types of C&D waste

Under the category of "other types of C&D waste," we examined eight samples comprising two demolished wood wastes (W1 and W2), four metal demolition wastes (M1–M4), and two waste capacitors which used transformer/insulator oils (PW1 and PW2). All the samples were analyzed for 11 heavy metals, F^- and CN^- (Fig. 6), and the samples PW1 and PW2 were also analyzed for 19 PAH and 7 PCB congeners (Fig. 7).

Wood-demolished wastes (W1 and W2) possessed high concentration of fluoride (134.2–182.9 mg/kg) and cyanide (34.8–66 mg/kg). Hydrogen fluorides, bifluorides, silicofluorides, and thiocyanates are the famous biocides used in wood preservatives, and hence, this may be the reason for the high concentration of F^- and CN^-(OECD 2003). Most of the heavy metals (Cd, Cr, Cu, Hg, Pb, Ni, and Zn) were high in the concrete reinforcement steel metal waste M1 and M2 (Fig. 6). The steel manufacturing process uses iron/steel scrap as the raw material which contains Cd and Hg as contaminants in it (EC 2002; Shin et al. 2013). The heavy metals Cu and Zn both have got good alloying properties and used as a protective finish for steel. The metals Cr and Cd both are known for its corrosion resistance properties and commonly used in electroplating of steel (EC 2013; Shin et al. 2013).

Although waste metals possessed high concentration of heavy metals, leachate of them possessed only the concentrations of CN^- and F^- (Table 3). None of the heavy metals were leached from C&D metal wastes. In spite of the lower concentration of As in wood-demolished waste, they possessed the high leaching of As (13.8 % in W1 and 22.2 % in W2).

Waste capacitors fall under the special category "Construction and demolition wastes containing PCB" (EA 2011). PW1 (500 μg/kg) and PW2 (390 μg/kg) showed very high concentration of PCB than any other samples (Fig. 7a). High concentration of PCB containing oils was used as dielectric/coolant fluids in most of the capacitors and transformers because of their low dielectric constant, high boiling point, and good fire resistant properties (UNEP 2002). The CB-28 (tri-PCB congener) and CB-52 (tetra-PCB congener) were observed as the majority percentage among all the seven congeners analyzed. Takasuga et al. (2006) reported the total PCB concentrations of transformer oils as 940–1300 ng/g (*w/w*) with sum of these seven congeners as 136–250 ng/g. They also observed that tri and tetra-CBs were in higher percentage among the all other congeners

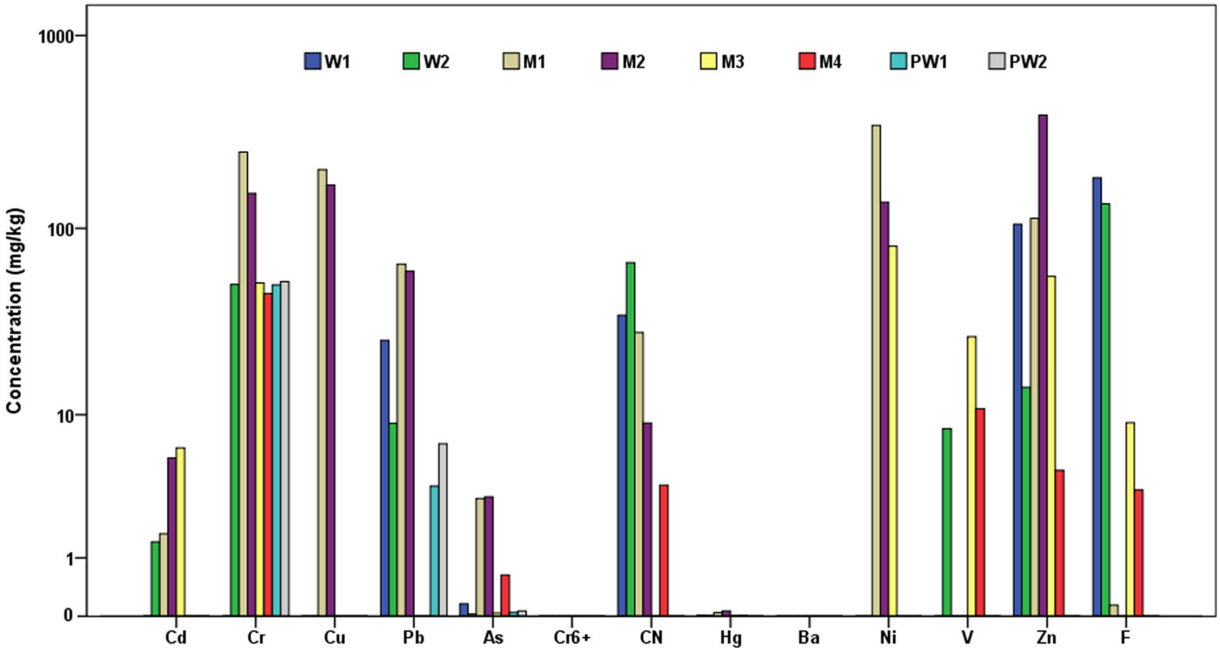

Fig. 6 Concentration of heavy metals, F^-, and CN^- in waste wood, waste metal, and waste capacitor samples

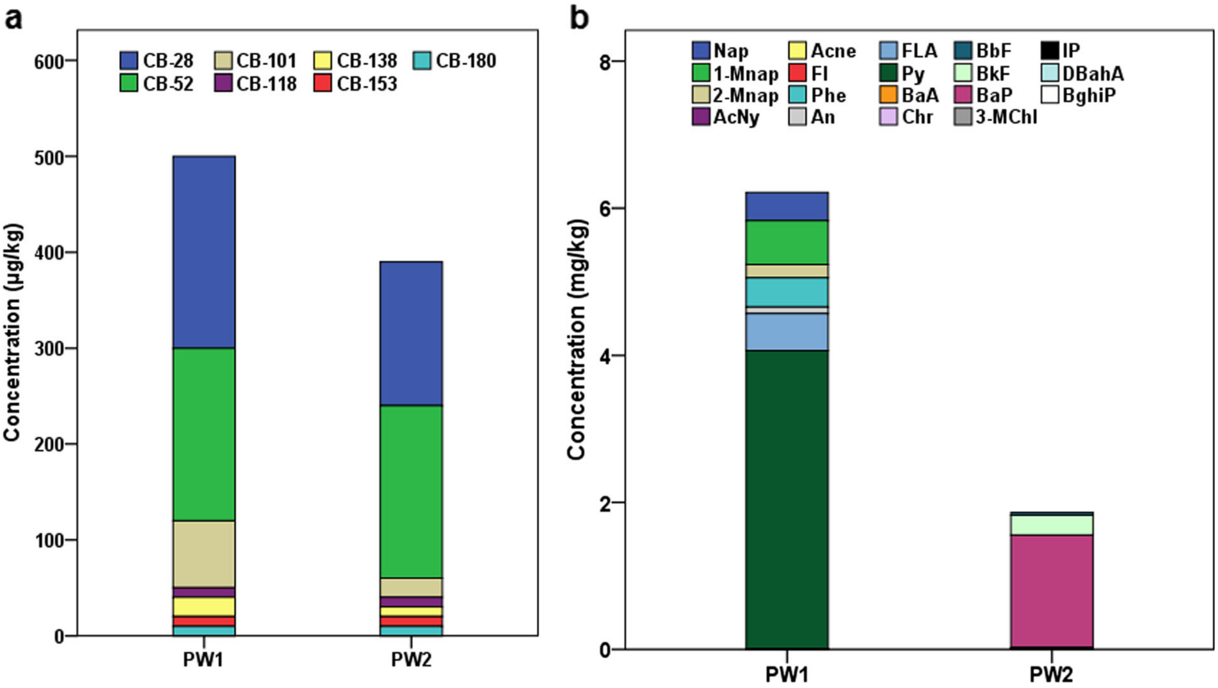

Fig. 7 PCBs isomer pattern (**a**) and PAHs concentrations (**b**) in waste capacitors

in PCB-fortified transformer oils. Huang et al. (2011) also observed that the tri-CBs (40.4–43.6 %) and tetra-CBs (34.6–40.4 %) were most abundant homologues in insulating oil samples from Chinese electrical capacitors. PW1 and PW2 possessed a high level of HMW-PAH than LMW-PAH (Fig. 7b). The capacitor PW1 showed Py (4.06 mg/kg) as the major PAH in it, whereas high BaP in PW2 (1.53 mg/kg).

In South Korea, PCB-containing waste is governed by both Waste Management Act (from the year 1999) and POPs management law (from the year 2008). According to Waste Management Act, any liquid waste such as oils should be considered as hazardous waste if it exceeds the total PCB concentration of 2 mg/L and solid waste will be considered as hazardous if its leachate contains more than 0.003 mg/L of total PCB (MOE of Korea 2012). POPs management law specially governs the capacitors/transformers using PCB-containing oils (MOE of Korea 2008). The owner of transformers/capacitors should report to the mayor or provincial governor regarding the complete details of the products and their oil content. Those using the transformers/capacitors manufactured after 2008 with the oil containing a total PCB concentration lesser than 0.05 mg/L are exempted from reporting. The transformers/capacitors with the total PCB exceeding 2 mg/L in its insulation/transformer oil are not allowed for export/import. Recycling of the transformer oils is allowed only when the PCB is not detected in it.

Conclusion

We analyzed hazard characterization of different types of C&D waste. In Korea, most of the C&D wastes (98.1 %) are reused. We found that hazardous nature of these wastes also greatly depends on the source of its collection point. Asphalt demolition waste (A5) collected from one of the heavy traffic road possessed higher concentration of most of the heavy metals and PAH (13.38 mg/kg). Demolished track ballast (S5) collected from a frequently used railway track showed high concentration of Zn (581.65 mg/kg), Pb (79.69 mg/kg), As (7.98 mg/kg), and CN^- (5.23 mg/kg). Thus, it is necessary to consider the end disposal of these waste based upon the source of its generation.

Among all the heavy metals, Zn was obtained in higher concentration (110.90–280.17 mg/kg) in cement-based waste. The waste capacitor PW1 (500 µg/kg) and PW2 (390 µg/kg) showed very high concentration of PCB than any other samples. We observed the leaching of As, Ba, CN^-, and F^- in most of the C&D waste. The C&D waste samples MCW1, A1, A,3 and A5 exceeded the regulatory standards for recycling aggregates. Though Ministry of Environment in Republic of Korea regulated the content and leaching standard of some of the pollutants (Cd, Cu, As, Hg, Pb, Cr^{6+}, CN^{-}), it is mandatory to regulate all the heavy metals, PAH, and PCB concentration to minimize their leaching contamination. Thus, Ministry of Environment is in progress for setting up the regulatory standards for all inorganic and organic components present in the C&D waste to categorize them between hazardous and nonhazardous waste. The other type of wastes (which cannot be reused) should be taken into special consideration for disposal.

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