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RESEARCH ARTICLE

Characterizing the environmental impact of metals in construction and demolition waste

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Abstract

Large quantities of construction and demolition (C&D) waste are generated in China every year, but their potential environmental impacts on the surrounding areas are rarely assessed. This study focuses on metals contained in C&D waste, characterizing the metal concentrations and their related environmental risks. C&D waste samples were collected in Shenzhen City, China, from building demolition sites, renovation areas undergoing refurbishment, landfill sites, and recycling companies (all located in Shenzhen city) that produce recycled aggregate, in order to identify pollution levels of the metals As, Cd, Cr, Cu, Pb, Ni, and Zn. The results showed that (1) the metal concentrations in most demolition and renovation waste samples were below the soil environmental quality standard for agricultural purposes (SQ-Agr.) in China; (2) Cd, Cu, and Zn led to relatively higher environmental risks than other metals, especially for Zn (DM5 tile sample, 360 mg/kg; R4 tile sample, 281 mg/kg); (3) non-inert C&D waste such as wall insulation and foamed plastic had high concentrations of As and Cd, so that these materials required special attention for sound waste management; and (4) C&D waste collected from landfill sites had higher concentrations of Cd and Cu than did waste collected from demolition and refurbishment sites.

Keywords Construction and demolition waste · Hazardous characterization · Metals · Recycled aggregate

Introduction

Large volumes of construction and demolition (C&D) waste (Yuan and Wang 2011, Yuan 2013) are being generated from large-scale urbanization and construction during the current rapid economic development in China. The environmental impact of C&D waste disposal has begun to attract more and more attention from government, the public, and scholars (Ritzen et al. 2016, Van Praagh and Modin 2016).

The materials involved in C&D waste can be divided into inert and non-inert categories. Most construction materials, such as concrete, bricks, and soil, are inert waste and can be treated as non-hazardous waste (Llatas et al, 2011). However, C&D wastes such as insulation fixtures, wires, cables, lamps, and bulbs are non-inert materials. These materials contain hazardous substances (Ritzen et al. 2016) such as asbestos, brominated flame retardants, mercury, lead paint, and metal-containing wood preservatives (Li et al. 2016, Zhang et al. 2008). In addition, C&D waste can be contaminated during chemical, metallurgical, or pharmaceutical processes (Duan et al. 2016). Buildings can be repositories of metals, and if these repositories are not treated properly, the C&D wastes may become sources of metal contamination (Chen et al. 2016, Duan et al. 2015b, Prieto-Taboada et al. 2013). Currently, there are worldwide efforts to find new recycling applications for demolition waste (Banias et al. 2011). Yet such efforts should be undertaken with

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caution, because when recycling transfers hazardous materials to derived products, the corresponding health risk is transferred as well (Powell et al. 2015).

Developed countries like the USA and Germany effectively manage C&D waste (Townsend et al. 2004, Deloitte 2015). The majority of C&D waste in China, however, is disposed of in simple landfills with no environmental pollution controls. These dumping sites usually include gravel pits, farm land, abandoned residential land, borrow pits, river banks, and other low-lying areas. Among C&D waste materials, concrete contributes approximately 53% to total landfill volume, followed by brick blocks, at 25%, and ceramics, at 10%. The recycling rate for C&D waste is very low in China, and almost 90% of concrete and masonry waste is removed from building sites with no regard for recycling strategies. C&D scrap metals, together with scrap metal from household waste and industrial waste sites, are collected by enterprises that specialize in processing this type of waste. Most of the renovation wastes, such as insulation materials and fixed fragments, are not recycled at all and are usually deposited in landfills or mixed in with municipal solid waste (Zheng et al. 2017). Mixtures of metal wastes can lead to environmental contamination, and these wastes present serious environmental risks (Duan et al. 2016).

Many researchers have focused their studies on green building and waste minimization in the initial building design stages (Li et al. 2015, Lu et al. 2015, Udawatta et al. 2015, Zuo and Zhao 2014). But so far, only a few studies have focused on hazardous characterization and identification of C&D waste that pose threats to the environment. Metal pollution comes mainly from municipal solid waste (Yao et al. 2017). When persistent metals like As, Cd, Cr, Cu, Pb, Ni, and Zn are leached from improperly disposed C&D waste through the surrounding water, they become mobile and present grave environmental and health hazards (Duan et al. 2015a). Several health hazards such as ulcers, diarrhea, respiratory disorders, cancer, cardiovascular disease, and liver damage have been associated with accidental consumption of metals (Ajah et al. 2015). There are still some gaps in existing research, concerning the environmental risks of metal contaminants in C&D wastes. For example: (1) What is the connection between metal pollution and the various categories of C&D waste? (2) What are the levels of metal concentration in this waste? (3) Which types of C&D waste are sources of high metal concentration?

Here, four different sources of C&D metal wastes were analyzed: a building demolition site, a renovation area, a landfill, and a Chinese industrial recycling site. These sites were chosen because of their high content of common construction materials. An extensive dataset was built for seven metals: As, Cd, Cr, Cu, Pb, Ni, and Zn; all were chosen because of their high content in the most common construction materials. The most critical substances for metal contamination in the C&D wastes were identified. The original sources of metals and their transfer to the samples were discussed. Finally, the importance of source segregation for C&D waste management was evaluated.

Materials and methods

Sample collection

C&D waste samples were collected from 2015/05 to 2016/05 in Shenzhen, Guangdong province, China (see Table 1). These samples were divided into four categories: building demolition sites waste (DM1–DM10), building renovation area wastes (RN1–RN13), landfill sites C&D wastes (L1-L15), and recycled products from C&D waste recycling plants (RP1–RP7). The building demolition waste samples were obtained on the campus of Shenzhen University, from sites undergoing demolition. The representative wastes of demolition processes were massive concrete, brick, soil, wood, and plastic substances derived from tube and wall insulation. The renovation waste samples were collected from several communities of the Nanshan district in Shenzhen. These materials were mainly tiles, glass, paint, plastics, concrete, and bricks. The samples of landfill waste were taken from Tanglangshan Landfill and contained both inert and non-inert wastes. The recycled product samples were acquired from a C&D waste recycling enterprise, Shenzhen Lvfar Pengcheng Environmental Technology Co. Ltd. These recycled aggregates were mainly produced by C&D waste generated from building construction and demolition sites in Shenzhen. Three samples were collected for each type of waste, to make the samples representative. The number of samples was 30 of the building demolition sites waste, 36 of the building renovation waste, 30 of the landfill sites waste, and 21 of the recycled products. The sampling processes were carried out according to the Chinese Edition of the Technical Specifications on Sampling and Sample Preparation from Industrial Solid Waste HJ/T20-1998. Samples were gathered manually from different locations with a shovel and collected in sample bags for further processing in the laboratory. All C&D waste samples were air-dried at room temperature and then ground in an agate mortar and collected after passage through a 100-mesh plastic sieve. The samples represented a broad range of materials: crushed concrete, asphalt, bricks, tiles, soil, and polymeric substances. Metal concentrations of As, Cd, Cr, Cu, Pb, Ni, and Zn were determined.

Sample preparation and analytical methods

For each sample, 0.5 to 1 g of dry waste was weighed and digested with mixed acids (HNO_3: HCl: HF = 5:2:5) heated stepwise in a microwave oven. The digested solution was then diluted with deionized water before metal determinations. Concentrations of Cr, Zn, Cu, Pb, Ni, and Cd were determined with atomic absorption spectrometry (AAS) on a model A-

Table 1 Details of the sample collection

Category	Description	Label
Building demolition sites waste	Concrete	DM1
	Red brick	DM2
	Soil	DM3
	Sandy soil	DM4
	Tile	DM5
	Gypsum board	DM6
	Asphalt	DM7
	Plastic	DM8
	Woven bag	DM9
	Wood	DM10
Building renovation waste	Concrete	R1
	Brick	R2
	Stone	R3
	Tile	R4
	Lime sand	R5
	Glass	R6
	Stalinite	R7
	Paint	R8
	Board	R9
	Composite board	R10
	Aluminum alloy	R11
	Aluminum plastic; composite panel	R12
Landfill sites waste	Concrete	L1
	Sintered brick	L2
	Tile	L3
	Glass	L4
	Asphalt	L5
	Wall insulation	L6
	Wood	L7
	Foamed plastic	L8
	Mixed waste: plastic, concrete, sponge, wood, foam	L9
	C&D waste mixed with MSW: paper, plastic, wrapping, thermal insulation pipe, wood, etc.	L10
Recycled products	Muck	RP1
	Lime	RP2
	Stone aggregate	RP3
	Brick aggregate	RP4
	Concrete aggregate	RP5
	Coarse aggregate	RP6
	Fine aggregate	RP7

6300C Spectrometer (Shimadzu, Japan). For As, 0.1 to 0.5 g of waste was digested with mixed HNO_3 and HCl (HNO_3: HCl = 1:3) at 180 °C for 30 min, and the digestion liquid was determined by atomic flame spectrometry (AFS) in a model 8220 Spectrometer (Beijing Titan Instruments Co., Ltd., China).

The detection sensitivity of the metal As is much better when atomic flame spectrometry (AFS) is used rather than (AAS). For other metals, though, the analyzed results were better with AAS.) The analytical methods were chosen in accordance with the features of each particular metal. A multi-element instrument calibration standard was prepared at a concentration of 10 mg/L. The calibration was validated with a quality control standard of 8 mg/L, developed internally from different reagent stocks. Any sample exceeding the calibration range was diluted accordingly, in duplicate, and re-analyzed (Jensen et al., 2000, Yang et al. 2009).

Results and discussion

Metals in demolition wastes

The total metal concentrations (As, Cd, Cr, Cu, Pb, Zn, and Ni) of the demolition waste samples are summarized in Fig. 1. For better understanding of the pollution levels of the metals, the threshold values of metals for the soil environmental quality standard for agricultural purposes (SQ-Agr.) and the background values of the metals in the soils in Guangdong province (BV-GD) and in China (BV-CN) are shown in Table 2. The background values can be used to assess potential metal contamination in the soil and groundwater where the C&D wastes were dumped or landfilled illegally, indicating possible environmental pollution and health hazards to the people residing near or working at the locations. The levels of the metals in the waste samples were indeed found to be much higher than the background values. The metal levels of the waste samples were also compared with the soil environmental quality standards for agricultural purposes, to assess potential metal contamination to soil that served as farmland. It can be seen from Fig. 1 that most of the samples contained metals. For all the samples, the concentrations of As were lower than the SQ-Agr., and the As concentrations of four samples—red bricks, DM2; sandy soil, DM4; tile, DM5; and Asphalt, DM7—exceeded the BV-CN. The highest As concentration (28 mg/kg) was found in the red brick sample. All the other samples, except for the soil DM3 and the woven bag DM9, were found to exceed the Cd concentrations of the BV-GD, but only the red brick DM2 and the plastic DM8 samples had concentrations above the SQ-Agr. The Cd concentrations in the plastic substances (3 mg/kg) exceeded the SQ-Agr. by a factor of 9. Four samples—red brick, DM2; tile, DM5; Asphalt, DM7; and wood, DM10—exceeded the Cu concentration of BV-CN, but only the red brick (75 mg/kg) and tile samples (69 mg/kg) were higher than the SQ-Agr. Only the concentrations of Cr, Pb, and Ni in the red brick sample (Cr, 99 mg/kg; Pb, 60 mg/kg; Ni, 84 mg/kg) were higher than the BV-GD, but they were still much lower than the SQ-Agr. The red brick, tile, and asphalt samples had large Zn

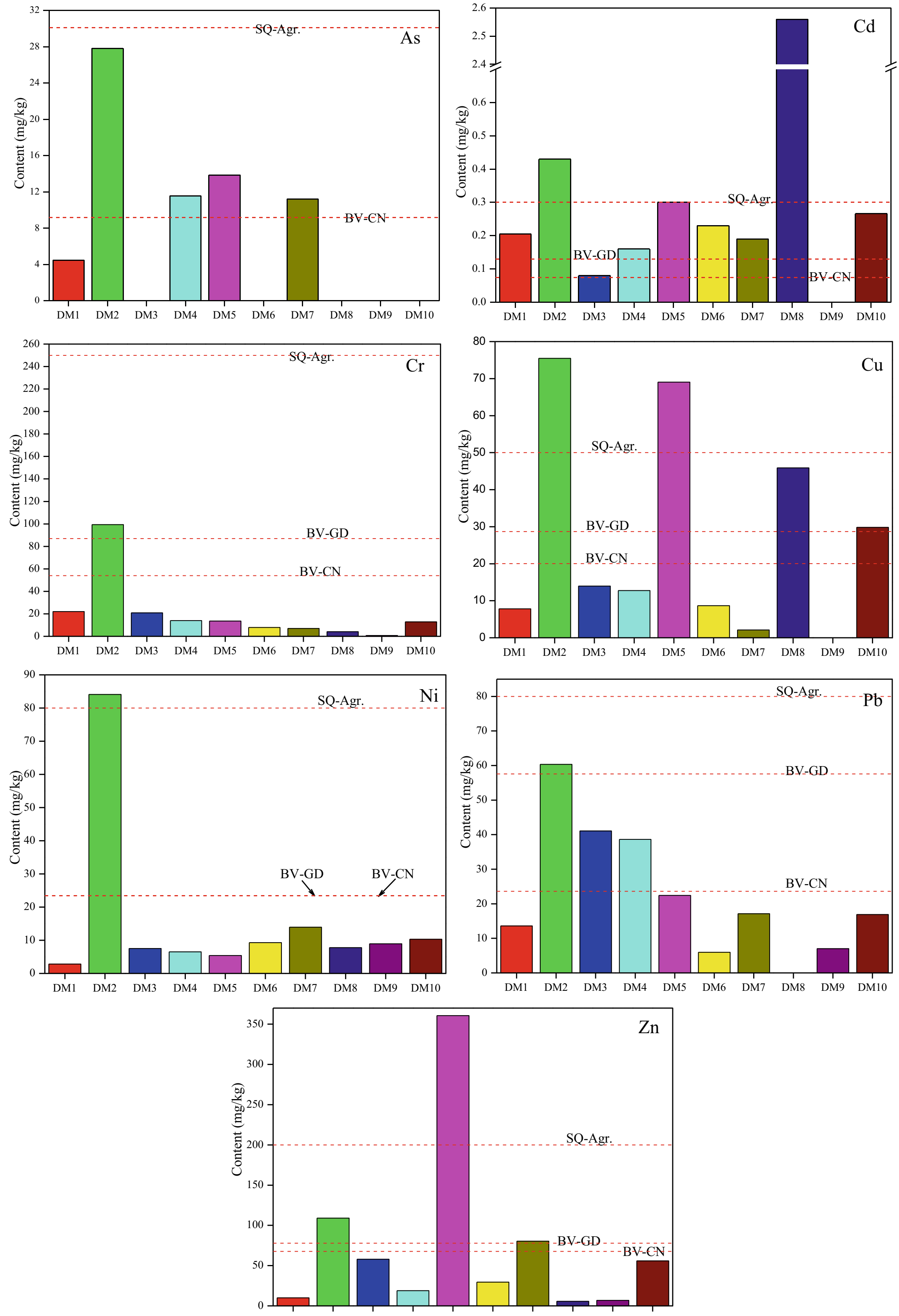

Fig. 1 Metal content of demolition waste components

Table 2 Threshold values of metals for soil environmental quality standards, and for background values of soils (mg/kg)

	As	Cd	Cr	Cu	Pb	Zn	Ni
BV-GD	–	0.13	87	29	58	78	24
BV-CN	9	0.07	54	20	24	68	23
SQ-Agr.	30	0.3	250	50	80	200	80

BV-GD background value in Guangdong province, China; *BV-CN* background value in China; *SQ-Agr.* Soil Environmental Quality Standard for Agricultural Purposes (GB15168-1995) (Chen et al. 2011)

concentrations, which all exceeded the BV-GD. Only the Zn concentration of the tile sample (360 mg/kg) was higher than the SQ-Agr. Possibly, the Zn concentration exceeded the SQ-Agr because decorative tiles now have Zn added in as an anti-bacterial feature.

These data suggest that the metal Cd concentrations in the red brick and plastic substances, the Cu concentrations in the red brick and tile, and the Zn concentration in the tile samples, which all exceeded the SQ-Agr., deserve more attention. Looking only at waste type, the red brick, tile, and plastic substances had higher metal concentrations. In China, brick-making has a 2000-year-old history, and an incalculable number of red and gray bricks have been used in construction since 1900 (Wu et al. 2011). Red brick waste is red because it contains iron. To maintain the required color and properties, silicon dioxide (SiO_2), ferric oxide (Fe_2O_3), and calcium oxide (CaO) are now used in bricks (Demir and Orhan 2003). The metal concentration in the red brick may also have been elevated because of the nature of the soil used to make the bricks in any particular location (Wu et al. 2011).

According to the above analysis, the metal concentrations in most of the demolition waste samples were approximately similar to the background values in the soil, and below the national soil environmental quality standards for agricultural purposes. This result strongly suggests that the management of C&D waste should proceed from demolition processes to avoid metal contamination of soils.

Metals in renovation wastes

The renovation samples selected in the study included concrete, cement, tile, glass, composite board, aluminum alloy, and paint. The results are presented in Fig. 2**.** The As, Cd, and Ni concentrations in all the samples were lower than the SQ-Agr. The highest As, Cd, and Ni concentrations were found in the brick sample R2, the concrete sample R1, and the stalinite sample R7, respectively. The Cr concentrations in the stalinite sample were the highest, up to 288 mg/kg, and the stalinite sample was the only sample whose Cr concentration exceeded the SQ-Agr. This result was possibly caused by the use of chromate in stalinite manufacturing. Environmental concerns relating to corrosion protection using Cr products have led to a worldwide replacement search. Only the Cu concentration in aluminum alloy sample R11 exceeded the SQ-Agr., because of its typical alloy compositions, Al-Cu-Mg. All the other samples had relatively lower Cu concentrations compared to the BV-CN. There was a very high concentration of Pb in the aluminum plastic, R12 (5676 mg/kg), about 71 times the SQ-Agr. However, the Pb concentrations in the other samples were lower than the SQ-Agr. Only the Zn concentration of the tile sample R4 (281 mg/kg) was higher than the values for the BV-GD and SQ-Agr. The reason for the large Zn concentrations is that Zn is used as an anti-bacterial in decorative tile. The Zn concentrations in the samples of aluminum alloy R11 (112 mg/kg) and aluminum plastic R12 (131 mg/kg) were higher than the background values of the soil, but below the SQ-Agr.

Environmental risk, based on the metal concentrations in all samples, was roughly in the order Zn > Pb > Cr > Cu > Ni > Cd. A similar order was observed for the building demolition waste samples. Most the samples from the renovation waste showed metal concentrations below the BV-GD and SQ-Agr. From the perspective of sustainable metals management, the concentrations of Cr in the stalinite, Cu in the aluminum alloy, Pb in the aluminum plastic, and Zn in the tile all deserve attention. In general, stalinite, aluminum alloy, and aluminum plastic should be separated from C&D waste for recycling and safe treatment. Tile should be given the highest priority for renovation waste management and treatment.

Metals in C&D waste landfill sites

Landfill C&D waste samples were collected to determine the pollution levels of metals. The total metal concentrations in the C&D waste components, and their comparisons with background values in soil and the national soil environmental standards, are presented in Fig. 3.

The As concentrations, except for the wall insulation L6, had relatively small variances with the compositions of C&D waste components. The As concentrations for all the C&D waste components, except wall insulation, were also lower than the SQ-Agr. The As concentration of the wall insulation L6, however, was well above both the SQ-Agr. and other standards, at more than 900 mg/kg. Wall insulation is a primary source of As in landfill C&D waste.

There were also small variances with compositions of C&D waste components for the Cr concentrations of the tested samples, most of which were lower than the BV-GD, but higher than the BV-CN. The Cd, Pb, Cu, and Zn concentrations in most of the waste samples were higher than the BV-CN. Moreover, the concentrations of Cd and Cu in the foamed plastic sample L8 was about ten times greater than in the inert C&D waste of brick and concrete. This result implies that the non-inert C&D wastes, including furniture, PUR foam, and

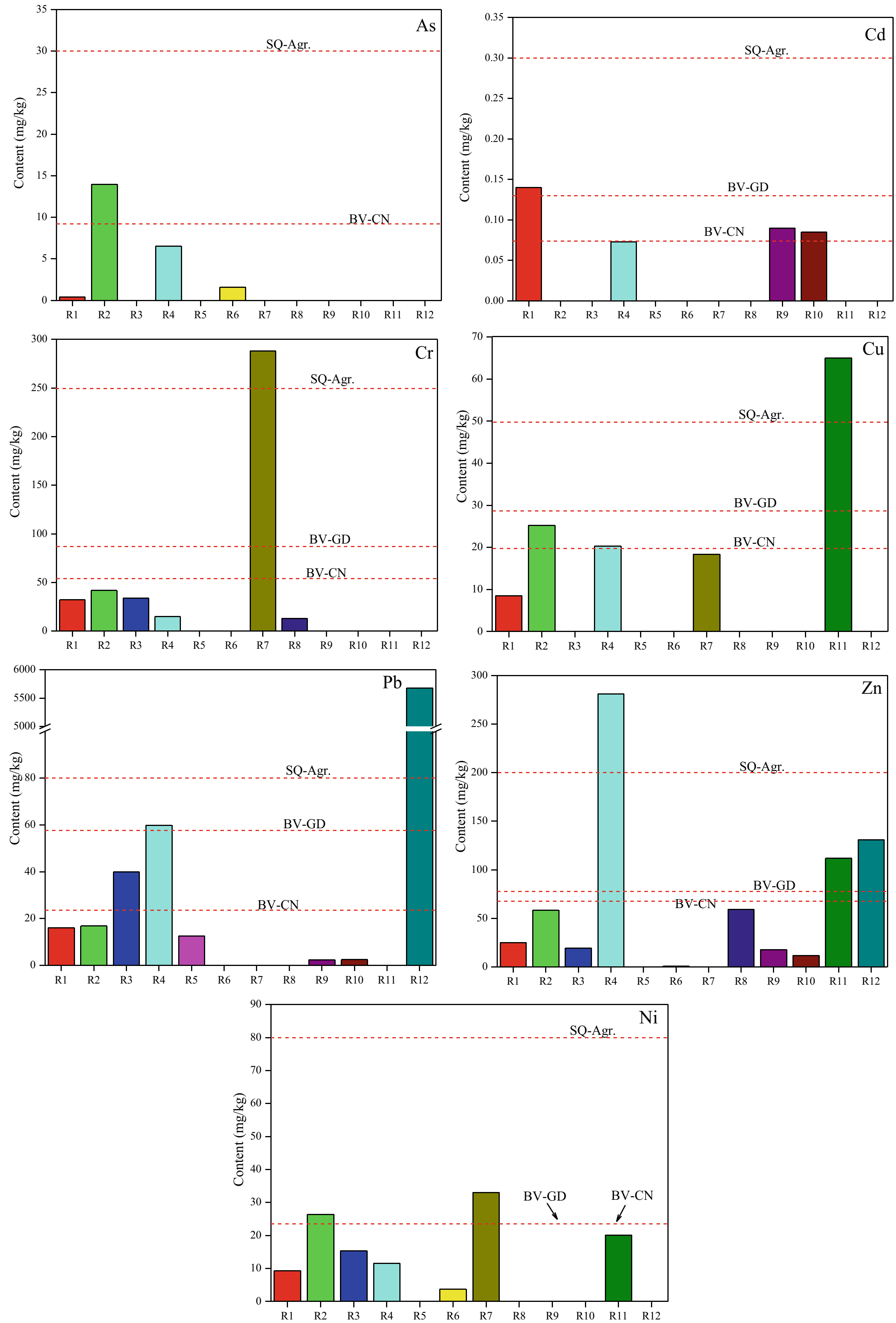

Fig. 2 Metal content of renovation waste components

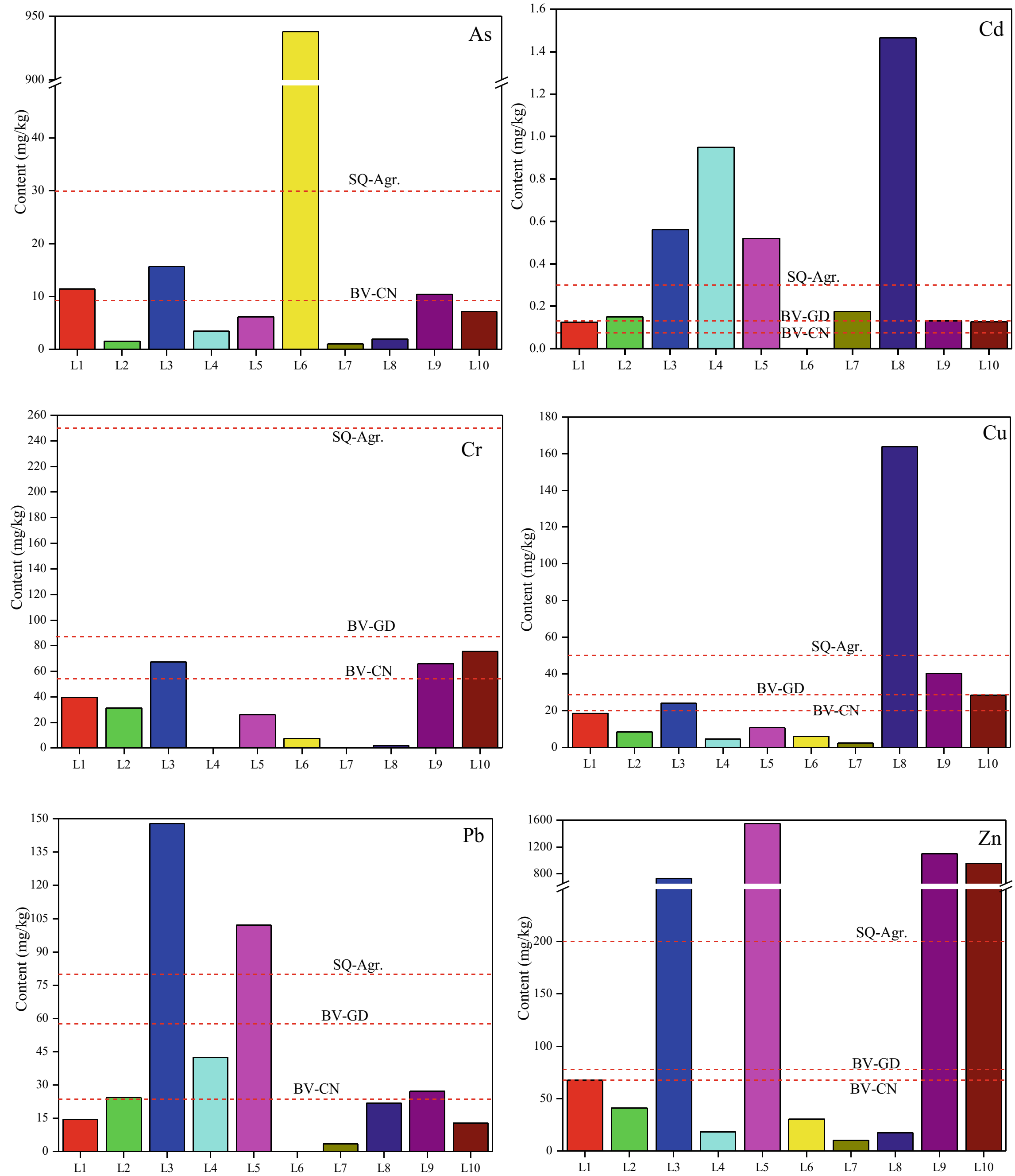

Fig. 3 Metal content of C&D waste components from landfill sites

other polymeric substances, are contaminated with metals. Nicolas et al. investigated construction waste landfill leachate, and their results indicated that Cr and Cd contamination occurred in landfills not equipped with an impermeable barrier (Butera et al. 2014, Jang 2001). The concentration of Zn (727–1550 mg/kg) in the inert C&D waste (brick, stone, soil, and concrete) mixed with paperboard, foam, artificial leather, and thermal insulation for pipes was five to ten times greater than the threshold values. Zinc contamination may come from building material components such as pigments, paints, lacquers, manganese batteries, and coatings. Zn contamination can be reduced by removal of surface materials before recycling.

Additional concerns should be focused on C&D waste management to avoid metal contamination. It is hard to avert the pollution of these metals by means of only a simple landfill or random stacking (Roussat et al. 2008); it is necessary to dispose of metal-containing wastes in regular landfills only with corresponding safeguards. Most importantly, it is necessary to develop a classification system to separate the PUR foam or polymer-substance materials and avoid mixing them into other wastes. Polymer substances are often mixed into

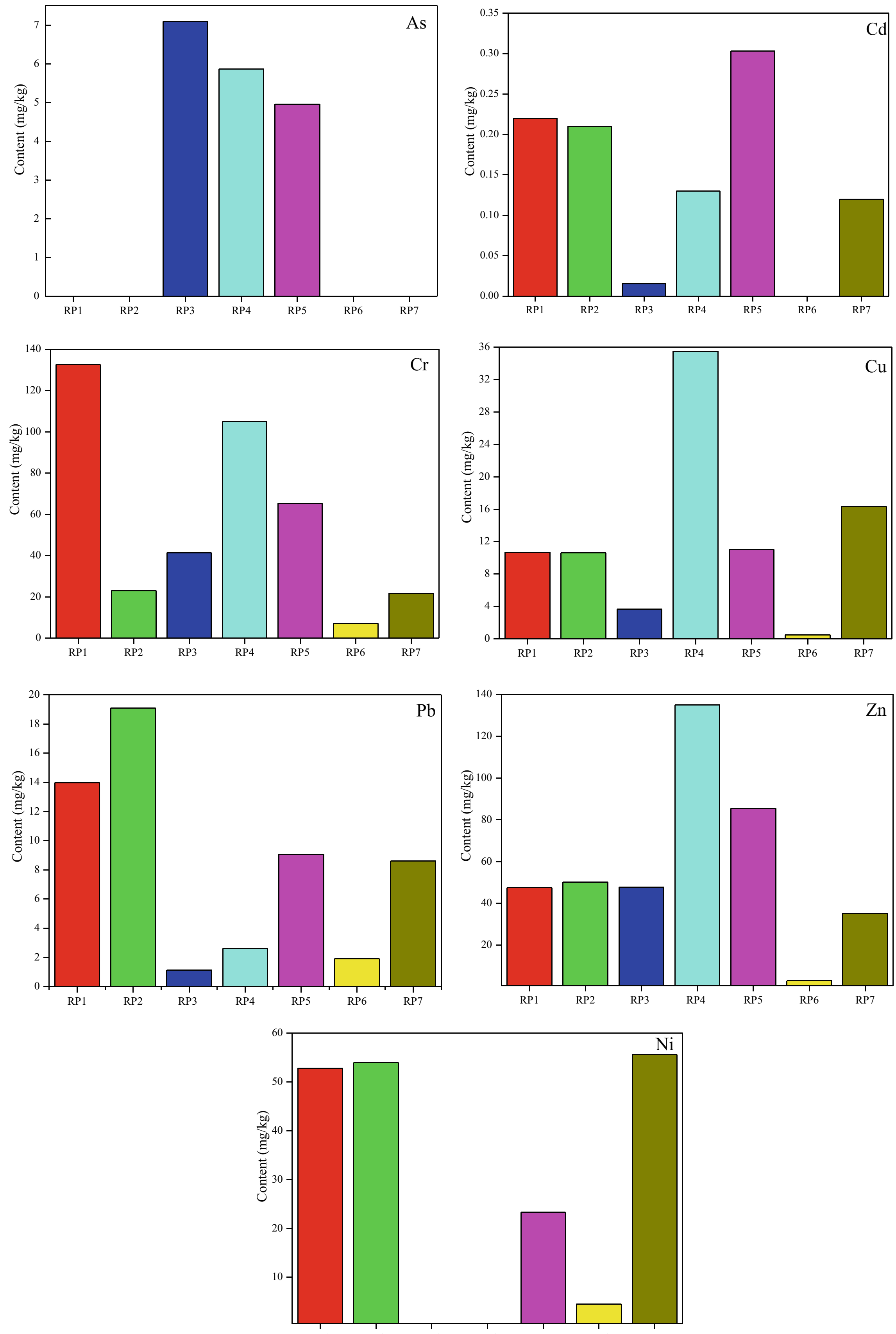

Fig. 4 Metal content of recycled products of C&D wastes (mg/kg)

household garbage, and this issue needs more attention as well. Before reusing C&D waste, the possibility of Zn contamination needs to be carefully considered. More extensive experiments should be conducted, on environmentally sound recycling methods, to establish standards for quality and safety.

Metals in recycled products

Recycling C&D waste is a significant step toward a more sustainable society (Arulrajah et al. 2015). Recycling also creates new market opportunities (Ding et al. 2016). Any environmental risk present in the precursors of these recycled products, however, will be transferred to the recycled products. Risk assessments regarding environmental and health safety should therefore be made. Recycled product samples processed from C&D wastes were therefore collected in this study, to evaluate the residual metal contamination. The results are shown in Fig. 4. Most of the samples of recycled products were found to contain more than five types of metals; however, the total metal concentrations in the recycled products were relatively low compared with other C&D waste samples. Zn was found to have the highest concentration, at 135 mg/kg. The muck products and brick aggregate showed higher metal concentrations than the other products. In China, residential C&D wastes are the primary raw materials for recycled products; these, fortunately, cause little environmental risk.

Conclusions

The contamination levels of these C&D wastes depend largely on the collection points and building usage. In general, Cd, Cu, and Zn showed the highest potential risk for most of the samples; their concentrations were above the BV-GD and SQ-Agr. values. Wastes collected from the landfill site had higher concentrations for most of the metals (especially Cd and Cu) than those from building demolition and renovation wastes. This result indicates that the metals in C&D waste lead to higher levels in landfills. Most inert demolition and renovation wastes, including concrete, stone, and soil, meet these metals' requirements of the BV-GD and SQ-Agr. These wastes can be recycled without prior treatment. The data show that the potential risk of metal contamination from red brick, tile, wall insulation, foamed plastic, and non-inert C&D waste mixtures (plastic, paper, foam, or other substances) is large, and treatment for this contamination should be considered part of sustainable management. A C&D waste-based classification system should also be designed, along with procedures to divert or separate non-inert materials in demolition wastes. Moreover, dumping sites for C&D wastes should be well managed to avoid acid rain, which can accelerate leaching. Sea reclamation (sea filling), a burgeoning waste disposal method in China, should also be examined, because of possible corrosive leaching.

This study is arguably the first attempt to examine the concentrations of metals (As, Cd, Cr, Cu, Pb, Ni, and Zn) in C&D waste components collected from the specific resources, including demolition sites, renovation areas, landfills, and recycling enterprises, in China. The findings in this study provide useful information for the selection of sustainable materials and guidelines for the safe disposal of C&D wastes. The environmental implications and risks can be evaluated, and corresponding waste management strategies can be developed. The outcomes are important for policy considerations for environmentally sound management of C&D wastes. This approach for monitoring metals can also be applied to the determination of toxic substances in other solid wastes and related materials.

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Compliance with ethical standards

Competing interests The authors declare that they have no competing interests.

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