Environmental suitability of recycled concrete aggregates used in geotechnical applications

Qualités environnementales requises des adjuvants pour béton recyclé dans des applications géotechniques

T. Inui & T. Katsumi
Kyoto University, Kyoto, Japan

M. Kamon
Takamatsu National College of Technology, Takamatsu, Japan

ABSTRACT

Solid waste and by-products have been widely recycled as construction or geotechnical materials. They may contain several inorganic toxic chemicals such as heavy metals. Thus, a testing framework to evaluate their leaching behaviours and the relevant environmental impact needs to be developed. A parametric study was conducted using FE analysis to calculate the transport of the contaminant of concern (COC) in the surrounding subsurface to discuss the effects of influential factors such as the leaching concentration, infiltration rate, and flow rate of aquifer. In addition, a series of leaching tests was conducted for recycled concrete aggregates (RCAs) to determine the leaching potential/concentration of COC for the environmental impact assessment. Three different acceleration tests; wetting-drying, freezing-thawing and abrasion, which actually occur in field conditions, were conducted respectively to evaluate the effect of the exposure to these conditions on the leaching of hexavalent chromium (Cr(VI)) contained in the RCA, since physical and chemical properties of cement based secondary materials, such as RCA, may change under environmental conditions due to the loss of soluble constituents and/or the surface wearing. Exposure to these accelerated conditions, particularly the wetting-drying, promoted the leaching of Cr(VI). Leaching amounts of granular RCA exposed to these conditions are no more than that with the conventional batch leaching test, which is conducted for crushed RCA with < 2 mm in grain size. This finding suggests that the Cr(VI) leaching amount in the field can be conservatively estimated by the conventional batch leaching test.

RÉSUMÉ

Les déchets solides et les sous-produits ont été largement recyclés pour servir de matériaux de construction ou de matériaux géotechniques. Ils peuvent contenir plusieurs produits chimiques inorganiques et toxiques tels que des métaux lourds. Une structure d'essais visant à évaluer leur comportement de lixiviation et l'impact environnemental associé doit donc être mise en place. Une étude paramétrique a été menée au moyen d'une méthode des éléments finis pour le calcul du transport de l'agent contaminant dans le sol environnant afin d'examiner les effets des facteurs d'influence tels que la concentration de lixiviation, le taux d'infiltration et le débit de la couche aquifère. En outre, une série d'essais de lixiviation ont été menés sur les adjuvants pour béton recyclé afin de déterminer le potentiel/la concentration de lixiviation de l'agent contaminant dans le cadre d'une évaluation de l'impact environnemental. Trois essais d'accélération différents, à savoir un essai de mouillage et de séchage, un essai de gel et de dégel et un essai d'abrasion respectivement, reflétant en fait des conditions réelles, ont été menés afin d'évaluer l'effet qu'a une exposition à ces conditions sur la lixiviation du chrome hexavalent (Cr(VI)) contenu dans les adjuvants pour béton recyclé, étant donné que les propriétés physiques et chimiques des matériaux secondaires à base de ciment, tels que les adjuvants pour béton recyclé, peuvent s'altérer dans des conditions environnementales en raison de la perte de composants solubles et/ou de l'usure de surface. L'exposition à ces conditions accélérées, en particulier le mouillage et le séchage, a favorisé la lixiviation du Cr(VI). La lixiviation des granulats pour béton recyclé dans ces conditions n'est pas plus importante que celle obtenue lors d'un essai de lixiviation en bachée classique réalisé pour des adjuvants broyés dont la dimension de grain est inférieure à 2 mm. Cette découverte suggère que la lixiviation du Cr(VI) en conditions réelles peut être évaluée de manière conventionnelle par un essai de lixiviation en bachée classique.

Keywords : environmental impact, hexavalent chromium, leaching, recycled concrete aggregate

1 INTRODUCTION

Geotechnical and geoenvironmental engineering has contributed to the sound reuse/recycle of waste and by-products in Japan, since large amount of them not only from construction works but also from various industries and human activities has been accepted as geo-materials. In addition, various types of ground improvement techniques have been widely employed to modify their engineering properties (Kamon & Katsumi 1994). However, some waste and by-products contain toxic and hazardous substances such as heavy metals, and therefore, subsurface contamination due to the leaching of them should be prevented. Generally, a regulatory leaching test is performed for the recycled material to characterize the leaching potential of the constituent of concern (COC). However, the actual leaching concentration/amount and the relative flux of COC into the surrounding media, which are deeply related to the environmental impact, depend on the given field condition, and a single regulatory leaching test does not have a capability of providing enough information to quantitatively evaluate these parameters. Thus, a testing framework to evaluate the environmental impact needs to be developed for achieving the environmentally suitability and economical design of secondary material utilization (e.g. Kosson et al. 2002).

Figure 1 shows the scenario and the concept of the environmental risk assessment for recycled materials in geotechnical applications. From the viewpoint of the human health risk, exposure pathways to the toxic chemicals are limited mainly to the intake and dermal contact of the contaminated water, since most recycled waste materials such as the slag or the incinerated ash normally contain only inorganic toxic chemicals. Thus, environmental risk can be estimated as a function of the chemical intake, which is proportional to the chemical concentration in the medium of concern. Chemical concentration in the aquifer is dominated by the mass flux of the chemical leaching from recycled materials,

Proceedings of the 17th International Conference on Soil Mechanics and Geotechnical Engineering
M. Hamza et al. (Eds.)

doi:10.3233/978-1-60750-031-5-340

the dimension of recycled material, and the flow rate in the aquifer as shown in Fig. 1. To evaluate the mass flux, long-term leaching behaviour is a key issue, since physical and chemical properties of solid waste may change significantly under environmental conditions due to the loss of soluble constituents and/or the surface wearing.

In this paper, a parametric study was firstly conducted using advection-dispersion FE analysis to calculate the aquifer contamination level relative to the leaching concentration and to evaluate effects of the factors such as infiltration rate, flow rate in the aquifer and the dimension of the recycled material quantitatively. Road base construction with recycled aggregates, which are typically processed from slag materials and waste concrete, was assumed in the analysis. Secondly, a series of leaching tests were conducted for various recycled concrete aggregates (RCAs) to discuss the methodology to determine the leaching concentration/potential of COC for the environmental impact assessment. Three different acceleration tests; wetting-drying test, freezing-thawing test and abrasion test, which are considered to actually occur in field conditions, were conducted respectively to evaluate the effect of the exposure to these conditions on the leaching characteristics of hexavalent chromium (Cr(VI)) contained in the mortar of RCAs (Kamon 2001). Based on the testing results, a concept was proposed to evaluate the long-term leaching potential and the relevant environmentally suitability of RCAs.

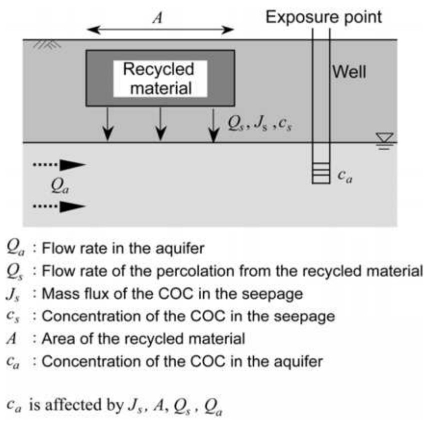

Figure 1. Concept of the environmental risk assessment for the recycled material

2 ANALITYCAL STUDY

2.1 *Method*

A parametric case study was conducted to discuss the influential factors on the environmental impact when the recycled aggregate was utilized in road base construction. Effects of the dimension (width) of the road base, the flow rate in the aquifer and the rainfall infiltration rate on the COC concentration in the aquifer were calculated by the advection-dispersion chemical transport FE analysis. Figure 2 shows the cross section assumed in the analysis. A 0.5 m thickness road base constructed with the recycled aggregate was overlaid by the asphalt concrete layer of 0.05 m thickness. A homogenous sand layer was assumed to surround the road base. Table 1 shows their material properties. Water retention property of the typical sandy ground was set for the surrounding layer. To prevent the underestimation of the COC transport, adsorption and transition of COC in subsurface was neglected. Infiltration ratio from the surface was set parametrically according to the 2%, 5%, and 10% of the annual average precipitation in Japan, 1.6 m/year. Leaching concentration of COC from the road base, C_0, was set constant temporally. An exposure point was set 10 m away from the edge of the road base.

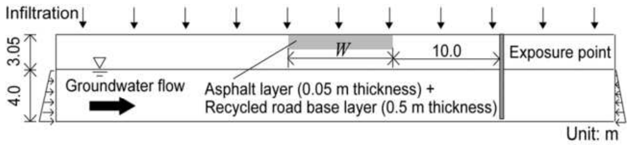

Figure 2. Cross section assumed in the analytical study

Table 1 Material properties used in the analysis

Parameters	Unit	Recycled road base	Asphalt layer	Sandy soil
Hydraulic conductivity	m/s	1.0 x 10^{-2}	1.0 x 10^{-9}	2.1 x 10^{-4}
Transversal dispersivity	m	0.1	0.1	0.1
Longitudinal dispersivity	m	0.01	0.01	0.01
Molecular diffusivity	m^2/s	1.0 x 10^{-9}	1.0 x 10^{-9}	1.0 x 10^{-9}
Effective porosity	–	0.30	0.18	0.25
Retardation factor	–	1.0	1.0	1.0

2.2 *Results and discussions*

Figures 3 show the average COC concentration, C, at the exposure point after 5 years, which is normalized by the leaching concentration, C_0. The obtained values are plotted with a function of (a) the infiltration rate, (b) the flow velocity of the aquifer, and (c) the width of road base, respectively. C/C_0 values have an excellent linear correlation with the infiltration rate, since the infiltration rate is proportional to the influx of COC into the aquifer (Fig. 3(a)). Groundwater flow velocity in the aquifer has also a significant effect on the COC concentration (Fig 3(b)). This is because the higher groundwater flow rate under the constant influx of COC can reduce the concentration inversely. Width of road base does not increase the C/C_0 value linearly (Fig. 3(c)), since the different hydraulic conductivity values were set for these two medium and the preferential flow and Cr(VI) leaching occurred along the vertical boundary between them.

From these calculation results, a power approximate equation of $C/C_0 = A{\cdot}I{\cdot}Q^{-1}{\cdot}W^{0.34}$ can be drawn with the coefficient of determination of 0.96; where A is the constant (2.53 x 10^2), I is the infiltration rate, Q is the flow volume in the aquifer, and W is the width of the road base. Thus, these three factors as well as the leaching concentration have so significant influence on the environmental impact that they should be carefully assessed in the environmental impact assessment.

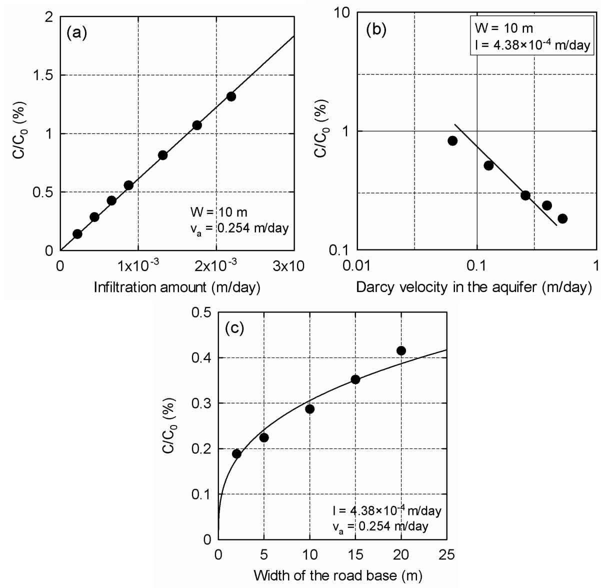

Figure 3. Effect on (a) infiltration rate, (b) flow rate in the aquifer and (c) width of the road base on the COC concentration.

Focusing on the calculated C/C_0 values, they are approximately 1.3% at most. This result indicates that COC concentration at the exposure point is very minor compared with the leaching concentration under typical conditions for the recycled aggregate to be utilized in the road base construction. Generally, the COC leaching concentration of the recycled material is identically limited to the values according to the regulation for groundwater quality, in Japan. However, if the environmental impact under the given field condition is verified, the criteria for the leaching concentration of the recycled material can be determined more flexibly.

Although the leaching concentration is assumed to be constant in this study, the authors also conducted the analytical study considering the temporal change of leaching concentration based on the column test (Inui et al. 2007).

3 LEACHING POTENTIAL / BEHAVIOUR OF RECYCLED CONCRETE AGGREGATES

3.1 *Materials and leaching tests*

Annual discharge of waste concrete from demolition works has reached 32 million ton in Japan. In the year of 2005, 98% of waste concrete is reused or recycled. Most of waste concrete is processed into RCA by crushing and grain-size control and recycled as geo-materials. However, a certain amount of chromium is contained in raw materials for cement (Kamon 2001). Accordingly, the Cr (VI) leaching with considerable concentrations from the mortar fraction of RCA has been observed. In this study, Cr(VI) leaching behaviour was tested for four types of RCAs shown in Table 2.

Table 2 Basic properties of four RCAs used in the experiment

Sample	RCA-1	RCA-2	RCA-3	RCA-4
Site	Tokyo, Japan	Kanagawa, Japan	Tokyo, Japan	–
Age of original structure	–	40 years	40 years	–
Natural water content (%)	3.3	5.5	4.2	–
Water absorption capacity (%)	5.4	7.0	5.2	–
Grain size distribution (%)				
19 mm –	14	0	0	24
9.5 mm – 19 mm	41	13	23	54
4.75 mm – 9.5 mm	22	50	55	11
– 4.75 mm	23	37	22	11

Conventional batch and tank leaching tests were conducted for RCAs. Table 3 lists the testing conditions of these tests. Solid samples for the batch leaching test were prepared in three different forms; 1) original form, 2) sieving through a 13.2 mm-opening sieve and 3) crushed with the maximum grain size less than 2 mm. The third one is equivalent to the method of the official batch leaching test for the soil quality, regulated by the Japanese Environmental Agency notification No.46, 1991 (JLT46). In addition, acid solvents were employed to evaluate the pH effect on the leaching behaviour. In tank leaching test, RCA was immersed in the solvent for 28 days with or without the solvent renewal. In the former case, the solvent was renewed after 1, 3, 7 and 14 days. The leachate was filtered using a 0.45 µm-opening membrane filter and then analyzed with the diphenylcarbazide absorption method to determine the Cr(VI) concentration immediately after the sample collection.

Table 3 Test conditions of batch and tank leaching tests

Test type	Batch test			Tank test
Sample form	Original form	≤ 13.2 mm	≤ 2 mm	Original form
Sample mass (g)	200	80	50	200
Solvent	Distilled water (pH = 5.8 to 6.3) or Acid solvent			
Solvent volume (ml)	2,000	800	500	2,000
Liquid to solid ratio	10	10	10	10
Duration	6 hours	6 hours	6 hours	28 days
Remarks	Horizontal shaking (200 times/min)			With /without solvent renewal

3.2 *Acceleration tests*

Three types of acceleration tests, wetting-drying test, freezing-thawing test and abrasion test, were conducted. For the RCA subjected to each accelerated exposure, batch and tank leaching tests were conducted respectively to quantify the Cr(VI) leaching amount. Cr(VI) leaching during the acceleration test was also analyzed and considered.

Abrasion test assumes the situation where the surface of RCA was gradually worn out under environmental conditions. RCA was kept in a rotary mill until the abrasion loss (the ratio of 2 mm under fraction in dry weight) reached 5, 10 and 15%, respectively. Then, leaching test was conducted for both gravel fraction and ≤ 2 mm fraction.

In wetting-drying test, RCA was firstly placed in a sealed oven to provide the temperature at 60 ± 3 ºC for 24 hours. After cooling the specimen in the chamber, it was immersed in the distilled water at 20 ± 3 ºC for 23 hours. The volume of the water represented by L/S (liquid to solid ratio) was 10. The test was terminated after the number of this cycle reached 12.

Freezing-thawing test simulates the following process; in the cold district where the temperature changes around 0 ºC, water fraction in RCA freezes up and expands, and with the temperature raising it melts. This process can cause the physical damage to RCA. RCA specimen was immersed in the water (L/S = 1.5). Then the specimen in the water was exposed to the freezing-thawing cycle (4 hours/cycle, freezing at -18 ºC, thawing at 5 ºC) until the number of cycles reached 180 at most.

3.3 *Results and discussions*

Cr(VI) leaching concentrations of RCAs with different forms are shown in Fig. 4. Hereafter, Cr(VI) leaching concentration and mass are normally reported by the average value of three-duplicate tests and its variation (only duplicate tests in the freezing-thawing test) except RCA-D. Grain size effect on the Cr(VI) leaching concentration is so significant that leaching concentrations of ≤ 2 mm specimen are 2.5 to 11 times higher than those of original-form RCAs. This indicates that the official leaching test (JLT46), which is conducted for ≤ 2 mm specimen, tends to overestimate the Cr(VI) leaching concentration from the RCA utilized in original form.

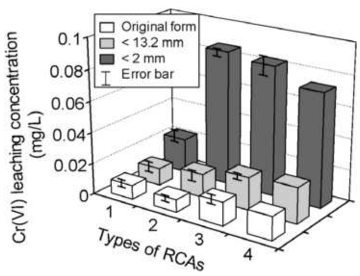

Figure 4. Cr(VI) leaching concentration in the batch leaching tests

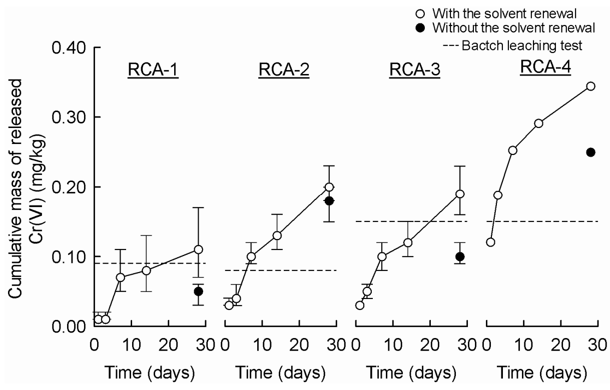

Figure 5. Mass of Cr(VI) leached in the tank leaching test.

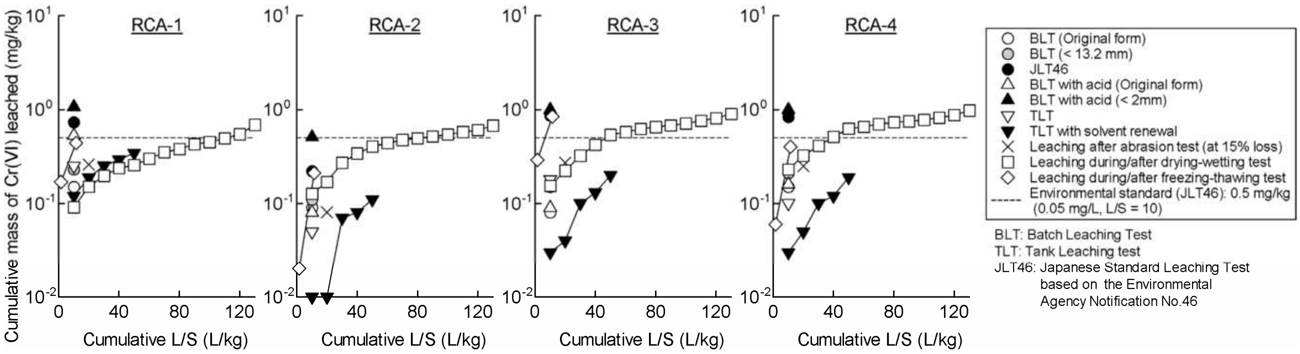

Figure 6. Comparison of Cr(VI) leaching amounts obtained in various testing methods

Figures 5 indicate the mass of Cr(VI) leached from the original-form RCAs in the tank leaching test. In the following, results of the leaching tests are provided by converting the leaching concentration into the mass leached from unit-weight RCA to compare the results of various testing methods. Renewal of the solvent promoted the Cr(VI) leaching; average leaching mass after 28 days with the solvent renewal are larger than those without the solvent renewal for all RCA specimens. This is because the fresh solvent could promote the diffusive leaching of Cr(VI). Compared with the results of batch leaching test, leaching amounts are larger particularly for RCA-2 and 4. Based on the visual observation, larger amounts of mortar were adhered to the surfaces of RCAs-2 and 4 than others, which might be attributed to the diffusive leaching of Cr(VI) from the mortar fraction.

Figure 6 shows the comparison of Cr (VI) leaching amounts obtained in all the test cases for RCA 1 to 4, which include those during/after each acceleration test. The leaching amounts of Cr(VI) are plotted with the cumulative volume of solvent contacting with RCA during both acceleration and leaching tests, represented by the L/S. Japanese criterion of Cr(VI) leaching for the soil quality is also shown.

The wetting-drying test provided the largest leaching mass of three different acceleration tests. In addition, for the RCAs with the larger mortar content (RCAs-2 and 4), the freezing-thawing promotes the Cr(VI) leaching to the same degree.

Comparing the leaching amounts after the accelerated exposure with those in conventional leaching tests (batch and tank leaching tests, acid addition test), the sum of leaching amounts during and after each accelerated test was larger than that in the batch leaching for RCA in its original form. However, they are no more than those in the acid addition test for 2 mm under specimens for all RCA samples. Considering how simple and time-saving the batch leaching test is, it can be concluded that the acid addition test can be employed to estimate quantitatively the Cr(VI) leaching potential of RCA subjected to environmental conditions for the safe side. Of course, further studies is necessary to identify the mechanisms of promoting the Cr(VI) leaching influenced by testing procedures.

3.4 *Practical implications*

Based on the results of batch and tank leaching tests, it can be concluded that Cr(VI) leaching behaviour is influenced a lot by (1) specific surface of RCA, (2) water flow volume, and (3) duration to contact with the water. Thus, it requires a complicated model test to determine the temporal variations of the Cr(VI) leaching concentration precisely including the effect of long-term exposure to the field. Considering the fact that the human health risk can be estimated by the cumulative intake of COC in the averaged time, however, the leaching potential of COC could be regarded as a key parameter, which is representative of the environmental suitability of the recycled material. Thus, it is a reasonable and practical solution to employ the leaching potential by conducting the simple batch test for crushed RCA in the environmental assessment.

4 CONCLUSIONS

Environmental suitability of the recycled aggregates utilized in road base construction was assessed based on both analytical and experimental studies. Particularly, the testing protocols to evaluate the leaching of Cr(VI) from the recycled concrete aggregate (RCA) and the relevant environmental impact through the groundwater contamination were discussed. The conclusions obtained can be summarized as follows:

(1) Based on the results of a parametric study, which assumed the typical conditions of the road base construction using the recycled aggregates, effects of the infiltration rate, the groundwater flow rate, and the dimension of the road base on the COC concentration in the aquifer were quantitatively analyzed.

(2) Exposure to three different accelerated conditions; wetting-drying, freezing-thawing and abrasion, increased the amount of Cr(VI) leached from RCA. Particularly, effect of the wetting-drying was most remarkable. For the RCA which had a relatively larger amount of mortar on its surface, freezing-thawing promoted the Cr(VI) leaching to the same degree as well.

(3) Leaching amounts of granular RCA exposed to a certain accelerated condition is no more than that in the conventional batch leaching test, which is conducted for crushed RCA with < 2 mm in grain size. This finding suggests that the Cr(VI) leaching potential in the field can be conservatively estimated by the conventional batch leaching test.

REFERENCES

Kosson, D.S., van der Sloot, H.A., Sanchez, F. & Garrabrants, A.C. 2002. An integrated framework for evaluating leaching in waste management and utilization of secondary materials. *Environmental Engineering Science* 19: 159-204.

Kamon, M. 2001. Remediation techniques by use of ground improvement, In J.L. Hanson & R.J. Termaat (eds), *Soft Ground Technology*, *Proceedings of the United Engineering Foundation / ASCE Geo-Institute Soft Ground Technology Conference*, Noordwijkerhout, Netherlands, May 28-June 2, 2000: ASCE.

Kamon, M. & Katsumi, T. 1994. Civil engineering use of industrial waste in Japan. In A.S. Barasubramaniam et al. (eds), *Development in Geotechnical Engineering, Proceedings of the Symposium on Developments in Geotechnical Engineering,* Bangkok, Thailand, January 12-16, 1994: 265-278, Rotterdam: A.A. Balkema.

Inui, T., Kamon, M. & Katsumi, T. 2007. Suitability of the solid waste utilization in geotechnical applications from a viewpoint of environmental risk, In S.E. Burns, P.J. Culligan, J.C. Evans, P.J. Fox, K.R. Reddy & N. Yesiller (eds), *Geoenvironmental Engineering, Geotechnical Special Publication No.163*: on CD, ASCE.