Appendices

Recycled Concrete Aggregate Leachate: A Literature Review

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Appendix A: Sand and Gravel General Permit - A *National Pollutant Discharge Elimination System* (NPDES) and State Waste Discharge General Permit 2021

The Sand and Gravel General Permit is available on Washington State Department of Ecology's website:
https://apps.ecology.wa.gov/ezshare/wq/permits/S&G_GP_Final_Draft.pdf

Appendix B: Select Abstracts of Leaching Literature Used Throughout the Recycled Concrete Aggregate Leaching: A Literature Review

Appendix B provides abstracts of select leaching literature used throughout the *Recycled Concrete Aggregate Leachate: A Literature Review* report. This list is not intended to be exhausted, as only select leaching abstracts are provided. These were selected because of the information the articles present on recycled concrete aggregate leaching.

Abbaspour, A., B.F. Tanyu, and B. Cetin. 2016. Impact of aging on leaching characteristics of recycled concrete aggregate. *Environmental Science Pollution Research* 23: 20835–20852.

The focus of this study was to evaluate the effects of stockpiling (aging) on leaching of elements in recycled concrete aggregate (RCA) that may contribute to tufaceous constituent formation. Speciation and leaching controlling mechanisms of these elements were identified via geochemical modeling. The effects of stockpiling were simulated by comparing freshly produced RCA with RCA aged as part of this study for 1 year both in the laboratory and in the field. Leachate samples were generated following batch water leach test (WLT) and US Geological Survey leach test (USGSLT) methods. USGSLTs were conducted both on the laboratory and field samples while WLT was only conducted on laboratory samples. During the laboratory aging, it is observed that the carbonate content of RCA, measured as calcite equivalent, increased 20 % (i.e., from ~100 to 120 mg/g) within a year time frame. The leachate extracted from RCA showed minor changes in pH and more significant decreases in electrical conductivity (i.e., ~300 to 100 µS/cm). A comparison between laboratory and field samples revealed that the RCA aged much slower in the field than in the laboratory within a year. Comparisons between two leach extraction methods on the laboratory conditions showed that the total leached concentrations (TLCs) of most of the constituents from USGSLT were appreciably lower than the ones measured via WLT method. The results of geochemical modeling analyses showed that Al, Si, Fe, Ca, Mg, and Cu exist in their oxidized forms as Al3+, Fe3+, Si4+, Ca2+, Mg2+, and Cu2+ and results revealed that these elements are primarily controlled by the solubility of gibbsite, hematite, silica gel, calcite, magnesite, and tenorite solid phases, respectively. One of the significant findings of the study was to identify the changes in leaching behavior of Ca, Si, Mg, Al, Fe, and Cu due to carbonation.

Barbudo, A., A.P. Galvín, F. Agrela, J. Ayuso, and J.R. Jiménez. 2012. Correlation analysis between sulphate content and leaching of sulphates in recycled aggregates from construction and demolition wastes. Waste Management 32(6):1229-1235.

In some recycled aggregates applications, such as component of new concrete or roads, the total content of soluble sulphates should be measured and controlled. Restrictions are usually motivated by the resistance or stability of the new structure, and in most cases, structural concerns can be remedied by the use of techniques such as sulphur-resistant cements. However, environmental risk assessment from recycling and reuse construction products is often forgotten. The purpose of this study is to analyse the content of soluble sulphate on eleven recycled aggregates and six samples prepared in laboratory by the addition of different gypsum percentages. As points of reference, two natural aggregates were tested. An analysis of the content of the leachable amount of heavy metals regulated by European regulation was included. As a result, the correlation between solubility and leachability data allow suggest a limiting gypsum amount of 4.4% on recycled aggregates. This limit satisfies EU Landfill Directive criteria, which is currently used as reference by public Spanish Government for recycled aggregates in construction works.

Ben Maaouia, O., R. Hamzaoui, A. Bennabi, J. Colin, and H. Colina. 2018. Chromium stabilization and trapping in the cement matrix of recycled concrete aggregates. Construction and Building Materials 191:667-678.

Recycled concrete aggregates (RCA) originated from old deconstructed concrete may contain considerable amounts of heavy metals like chromium for example. In this work, we study the presence of chromium impact in the cementitious matrix of RCA, cement doped paste (OPC) and mortar with RCA (30% and 100% of RCA) from an environmental point of view. The leaching tests are carried out on monolithic and granular samples, using carbonated and non-carbonated RCA. Cr (VI) pH dependent leaching and Cr (VI) leaching mechanism have been studied. The experimental results has shown that aggregates are inert waste and can be used for road construction as substitution of original aggregates. Moreover, carbonation seems to have a positive effect on the decrease of the release of hexavalent chromium from the cementitious matrix. It was also confirmed that chromium is highly bound in the ettringite structure still present in the RCA matrix.

Bestgen, J.O., B. Cetin, and B.F. Tanyu. 2016a. Effects of extraction methods and factors on leaching of metals from recycled concrete aggregates. Environmental Science and Pollution Research 23:12983–13002.

Leaching of metals (calcium (Ca), chromium (Cr), copper, (Cu), iron (Fe), and zinc (Zn)) of recycled concrete aggregates (RCAs) were investigated with four different leachate extraction methods (batch water leach tests (WLTs), toxicity leaching procedure test (TCLP), synthetic precipitation leaching procedure test (SPLP), and pH-dependent leach tests). WLTs were also used to perform a parametric study to evaluate factors including (i) effects of reaction time, (ii) atmosphere, (iii) liquid-to-solid (L/S) ratio, and (iv) particle size of RCA. The results from WLTs showed that reaction time and exposure to atmosphere had impact on leaching behavior of

metals. An increase in L/S ratio decreased the effluent pH and all metal concentrations. Particle size of the RCA had impact on some metals but not all. Comparison of the leached concentrations of metals from select RCA samples with WLT method to leached concentrations from TCLP and SPLP methods revealed significant differences. For the same RCA samples, the highest metal concentrations were obtained with TCLP method, followed by WLT and SPLP methods. However, in all tests, the concentrations of all four (Cr, Cu, Fe, and Zn) metals were below the regulatory limits determined by EPA MCLs in all tests with few exceptions. pH-dependent batch water leach tests revealed that leaching pattern for Ca is more cationic whereas for other metals showed more amphoteric. The results obtained from the pH-dependent tests were evaluated with geochemical modeling (MINTEQA2) to estimate the governing leaching mechanisms for different metals. The results indicated that the releases of the elements were solubility-controlled except Cr.

Bestgen, J.O., M. Hatipoglu, B. Cetin, and A.H. Aydilek. 2016b. Mechanical and Environmental Suitability of Recycled Concrete Aggregate as a Highway Base Material. Journal or Materials in Civil Engineering 28(9) 13 pp.

The use of recycled concrete aggregate (RCA) materials in highway constructions is economically viable and reduces virgin natural resource demands on the environment. To evaluate their potential use in highway construction, two different RCA materials and four virgin granular aggregate base (GAB) materials and their select mixtures were tested in the laboratory for strength, resilient modulus, permanent deformation, and durability. Laboratory water leach tests and pH-dependent leaching tests were conducted to determine the environmental suitability of the RCA materials. The leaching behavior of Ca, Cr, Cu, Fe, and Zn and the effects of pH, curing time, liquid-to-solid (L:S) ratio, and particle size on metal leaching from the RCAs were investigated. Summary resilient moduli (SMR) of the RCAs were up to 2.6 times higher than that of the GAB materials. Their stiffness also increased when subjected to freezing and thawing cycles. Consistent trends could not be observed with percent RCA addition and strength or SMR; however, the RCAs generally yielded higher permanent deformations compared with the GABs. Prolonged curing caused rehydration of cement particles and, in general, yielded a decrease in pH and leached metal concentrations. Increasing the L:S ratio decreased leaching of elements significantly because of the dilution of leached elements in the aqueous solutions. pH excursions yielded cationic leaching patterns for Ca and amphoteric leaching patterns for Cr, Cu, Zn, and Fe.

Brás, I., P.C. Silva, R. Almeida, and M.E. Silva. 2018 Recycling Wastes in Concrete Production: Performance and Eco-toxicity Assessment. Waste and Biomass Valorization 11:1169–1180(2020).

The growing concern about the environmental sustainability, the risk of natural resources depletion and the increase amount of wastes generation endorse the need to develop new materials, namely for the construction industry. However, both the technical performance and the environmental behaviour of new materials are key factors in their acceptance. In this work it was intended to evaluate the effect of aggregates substitution by different wastes in the concrete production. Wastes from local industries (biomass fly ashes and lime sludge) were used for

replacing 50 and 100% of the natural fine aggregates. The fresh and hardened properties of the concrete samples were evaluated and the environmental eco-toxicity was assessed by bioassays using duckweed and microorganisms as biomarkers. Bioleaching tests were done with the same materials in order to evaluate the concrete effect in biological activity. The results showed that the addition of wastes to the concrete mix lead to a slight decrease in the compressive strength when fly ashes were used (3%), but 35% decrease when lime was the replacing waste. The duckweed grow did not show different performances between conventional concrete and concrete produced with fly ashes or lime sludge but bioleaching revealed possible negative effect in micro species when compared with control. In bacterial growth the effect was more evident with a significant different behaviour between the control and the concrete assays, but also with the traditional concrete showing a higher negative effect in the development of microorganisms.

Butera, S., T.H. Christensen, and T.F. Astrup. 2014. Composition and leaching of construction and demolition waste: Inorganic elements and organic compounds. Journal of Hazardous Materials 276:302-311.

Thirty-three samples of construction and demolition waste collected at 11 recycling facilities in Denmark were characterised in terms of total content and leaching of inorganic elements and presence of the persistent organic pollutants PCBs and PAHs. Samples included (i) "clean" (i.e. unmixed) concrete waste, (ii) mixed masonry and concrete, (iii) asphalt and (iv) freshly cast concrete cores; both old and newly generated construction and demolition waste was included. PCBs and PAHs were detected in all samples, generally in non-critical concentrations. Overall, PAHs were comparable to background levels in urban environments. "Old" and "new" concrete samples indicated different PCB congener profiles and the presence of PCB even in new concrete suggested that background levels in raw materials may be an issue. Significant variability in total content of trace elements, even more pronounced for leaching, was observed indicating that the number of analysed samples may be critical in relation to decisions regarding management and utilisation of the materials. Higher leaching of chromium, sulphate and chloride were observed for masonry-containing and partly carbonated samples, indicating that source segregation and management practices may be important. Generally, leaching was in compliance with available leaching limits, except for selenium, and in some cases chromium, sulphate and antimony.

Butera, S., T.H. Christensen, and T.F. Astrup. 2015. Life cycle assessment of construction and demolition waste management. Waste Management 44:196-205.

Life cycle assessment (LCA) modelling of construction and demolition waste (C&DW) management was carried out. The functional unit was management of 1 Mg mineral, source separated C&DW, which is either utilised in road construction as a substitute for natural aggregates, or landfilled. The assessed environmental impacts included both non-toxic and toxic impact categories. The scenarios comprised all stages of the end-of-life management of C&DW, until final disposal of all residues. Leaching of inorganic contaminants was included, as was the production of natural aggregates, which was avoided because of the use of C&DW. Typical uncertainties related to contaminant leaching were addressed. For most impact categories, utilisation of C&DW in road construction was preferable to landfilling; however, for most

categories, utilisation resulted in net environmental burdens. Transportation represented the most important contribution for most nontoxic impacts, accounting for 60-95 per cent of these impacts. Capital goods contributed with negligible impacts. Leaching played a critical role for the toxic categories, where landfilling had lower impacts than utilisation because of the lower levels of leachate per ton of C&DW reaching the groundwater over a 100-year perspective. Leaching of oxyanions (As, V and Sb) was critical with respect to leaching. Typical experimental uncertainties in leaching data did not have a pivotal influence on the results; however, accounting for Cr immobilisation in soils as part of the impact assessment was critical for modelling the leaching impacts. Compared with the overall life cycle of building and construction materials, leaching emissions were shown to be potentially significant for toxicity impacts, compared with contributions from production of the same materials, showing that end-of-life impacts and leaching should not be disregarded when assessing environmental impacts from construction products and materials. CO2 uptake in the C&DW corresponding to 15 per cent carbonation could out-balance global warming impacts from transportation; however, carbonation would also likely result in increased toxicity impacts due to higher leaching of oxyanions.

Chen, J., S. Bradshaw, C.H. Benson, J.M. Tinjum, and T.B. Edil. 2012. pH-dependent leaching of trace elements from recycled concrete aggregate. Proceedings of GeoCongress, American Society of Civil Engineers 3729-3738.

Recycled concrete aggregate (RCA) has excellent mechanical properties and is often used as base course in pavement construction. However, highly alkaline leachate from RCA has been observed in laboratory studies. The associated high-pH leaching patterns can be of concern, especially when compared to the neutral pH environment observed in actual road sections using RCA as base course. In this study, the pH-dependent leaching concentrations of trace elements copper (Cu) and zinc (Zn) and the oxyanion chromium (Cr) were investigated on unfractionated RCA samples and fractionated RCA samples (i.e., fine particles <0.075 mm, sand-sized particles <4.75 mm and >0.075 mm, and gravel-sized particles <75 mm and >4.75 mm). A pH-buffering plateau was observed between pH 4.9 and 7.0 in the acid neutralization capacity curve. Cu and Zn showed the highest levels of leaching at pH≅2, and the lowest leaching at pH>7.5. Cr showed the lowest level of leaching between pH 5.0 and 6.5, and higher leaching concentrations towards the acid and alkali directions. The fine particles tended to leach more Cu and Zn than sand- and gravel-sized particles at 2<pH<13, while leaching of Cr from the fine fraction was not elevated except at pH<2.

Clark, K.L., J.G. Hunter, M.M. Bundy, and D.H. Kang. 2013. State Highway Administration Research Report. Evaluation of Waste concrete road materials for use in oyster aquaculture. Project Number: SP109B4E. Final report. Morgan State University, Baltimore, United States.

The primary objective of this study was to determine the suitability of recycled concrete aggregate (RCA) from road projects as bottom conditioning material for on-bottom oyster aquaculture in the Chesapeake Bay. The testing was designed to (1) evaluate the impact on water chemistry from the introduction of RCA and (2) evaluate the effect of RCA on the survivorship and growth of oyster spat. The results of this project showed that using RCA as a base material

for oyster reefs did not adversely affect oysters spat growth and survival, or the surrounding environment.

Coudray, C., V. Amant, L. Cantegrit, A. Le Bocq, F. Thery, A. Denot, and L. Eisenlohr. 2017. Influence of Crushing Conditions on Recycled Concrete Aggregates (RCA) Leaching Behaviour. Waste and Biomass Valorization 8:2867–2880.

The French construction industry generates almost 250 million tons of mineral waste per year. This waste can be used, after preparation, to replace natural materials used for construction work. This can preserve natural resources by contributing to a circular economy. A better understanding is necessary with regards to the deconstruction waste behaviour when used in redevelopment project or construction work, as backfill or embankments. This article intends to better understand how crushing influences recycled concrete aggregates leaching behaviour. Four concrete samples were studied from French power plant deconstructions. The leaching behaviour, of different grain size classifications, was tested with standard (i.e. with size reduction < 4 mm) and non-standard leaching tests (i.e. without size reduction). The samples were crushed with different industrial tools. The results showed that the final products maximum grain-size (Dmax) for crushing operation seems to have an influence on fine grain production. The role of the crushing technique used still remains uncertain. The analytical results from the leaching tests showed that the major elements leached are calcium, sulphates, carbonates, potassium, aluminium and silica. The trace elements were usually found in the smallest grain-size classification (0–6 mm). For the standard leaching tests, the total dissolved solids rose for the larger grain size classifications, whereas for non-standard leaching tests (performed without size reduction) the opposite occurred. All samples followed the environmental acceptability requirements. It seems essential to control the crushing parameters to sustain and strengthen continued concrete waste recovery to help improve French and European waste recovery objectives.

Del Rey, I., J. Ayuso, A.P. Galvín, J.R. Jiménez, M. López, and M.L. García-Garrido. 2015. Analysis of chromium and sulphate origins in construction recycled materials based on leaching test results. Waste Management 46:278-286.

Twenty samples of recycled aggregates from construction and demolition waste (CDW) with different compositions collected at six recycling plants in the Andalusia region (south of Spain) were characterised according to the Landfill Directive criteria. Chromium and sulphate were identified as the most critical compounds in the leachates. To detect the sources of these two pollutant constituents in recycled aggregate, environmental assessments were performed on eight construction materials (five unused ceramic materials, two old crushed concretes and one new mortar manufactured in the laboratory). The results confirmed that leached sulphate and Cr were mainly released by the ceramic materials (bricks and tiles). To predict the toxicological consequences, the oxidation states of Cr (III) and Cr (VI) were measured in the leachates of recycled aggregates and ceramic materials classified as non-hazardous. The bricks and tiles mainly released total Cr as Cr (III). However, the recycled aggregates classified as non-hazardous according to the Landfill Directive criteria mainly released Cr (VI), which is highly leachable and extremely toxic. The obtained results highlight the need for legislation that

distinguishes the oxidative state in which chromium is released into the environment. Leaching level regulations must not be based solely on total Cr, which can lead to inaccurate predictions.

Engelsen, C. J., H.A. van der Sloot, G. Wibetoe, G. Petkovic, E. Stoltenberg-Hansson, and W. Lund. 2009. Release of major elements from recycled concrete aggregates and geochemical modelling. Cement and Concrete Research 39(5):446–459.

The pH dependent leaching characteristics were assessed for different types of recycled concrete aggregates, including real construction debris and crushed fresh concrete samples prepared in laboratory. Carbonation effects were identified from the characteristic pH dependent leaching patterns for the major constituents Al, Ca, Fe, Mg, Si and SO42–. The original particle size ranges were different for the samples investigated and this factor influenced the cement paste content in the samples which in turn controlled the leachable contents. Cement paste contents for concrete samples with fine particle size fractions (0–4 mm) were found to be higher than the originally present amount in the hardened concrete. Geochemical speciation modelling was applied over the entire pH range using the speciation and transport modelling framework ORCHESTRA, for which mineral saturation, solution speciation and sorption processes can be calculated based on equilibrium models and thermodynamic data. The simulated equilibrium concentrations by this model agreed well with the respective measured concentrations. The main differences between the fresh and aged materials were quantified, described and predicted by the ORCHESTRA. Solubility controlling mineral phase assemblages were calculated by the model as function of pH. Cement hydrate phases such as calcium silicate hydrate, calcium aluminate hydrate (AFm and AFt) and hydrogarnet were predominating at the material pH. The concentration of carboaluminates was found to be strongly dependent on the available carbonates in the samples. As the pH was decreased these phases decomposed to more soluble species or precipitates were formed including iron- and aluminium hydroxides, wairakite and amorphous silica. In the most acid region most phases dissolved, and the major elements were approaching maximum leachability, which was determined by the amount of cement paste.

Engelsen, C. J., H.A. van der Sloot, G. Wibetoe, H. Justnes, W. Lund, and E. Stoltenberg-Hansson. 2010. Leaching characterisation and geochemical modelling of minor and trace elements released from recycled concrete aggregates. Cement and Concrete Research 40(12):1639–1649.

The pH dependent release of Cd, Cr, Cu, Mn, Mo, Ni, Pb, V and Zn from different recycled concrete aggregate samples was determined. Geochemical speciation modelling was applied on the concentrations of Cu, Cr, Mo and Ni in the leachates in order to predict the measured concentrations and the specific release mechanisms. The model was able to reproduce the characteristic pH dependent release patterns for these elements and reasonable to sometimes excellent matches between the predicted and measured concentrations were achieved. Binding of Mo and Cr as oxyanions (MoO_4^{2-} and CrO_4^{2-}) to ettringite was modelled with fair agreement for Cr only. For Cu and Ni, the predicted and measured concentrations agreed well for the partly carbonated sample at high alkaline pH (11–13). The importance of complexation to humic substances was also shown in samples derived from construction debris.

Engelsen, C.J., G. Wibetoe, H.A. van der Sloot, W. Lund, and G. Petkovic. 2012. Field site leaching from recycled concrete aggregates applied as sub-base material in road construction. Science of the Total Environment 427:86–97.

The release of major and trace elements from recycled concrete aggregates used in an asphalt covered road sub-base has been monitored for more than 4 years. A similar test field without an asphalt cover, directly exposed to air and rain, and an asphalt covered reference field with natural aggregates in the sub-base were also included in the study. It was found that the pH of the infiltration water from the road sub-base with asphalt covered concrete aggregates decreased from 12.6 to below pH 10 after 2.5 years of exposure, whereas this pH was reached within only one year for the uncovered field. Vertical temperature profiles established for the sub-base, could explain the measured infiltration during parts of the winter season. When the release of major and trace elements as function of field pH was compared with pH dependent release data measured in the laboratory, some similar pH trends were found. The field concentrations of Cd, Ni, Pb and Zn were found to be low throughout the monitoring period. During two of the winter seasons, a concentration increase of Cr and Mo was observed, possibly due to the use of de-icing salt. The concentrations of the trace constituents did not exceed Norwegian acceptance criteria for ground water and surface water Class II.

Engelsen, C.J., H.A. van der Sloot, and G. Petkovic. 2017. Long-term leaching from recycled concrete aggregates applied as sub-base material in road construction. Science of the Total Environment 587-588:94-101.

In the present study, the metal leaching from recycled concrete aggregates (RCA) used in road sub-base is presented after >10years of exposure. The released levels of inorganic constituents, the effect of small variation of pH and the use of de-icing salt during winter season were studied. In addition, speciation modelling for the major elements has been provided. The pH varied from 7.5 to 8.5 for the sub-base constructed with RCA whereas the pH of around 8 was obtained for the test section not affected by the traffic and de-icing salts. Despite a small variation in pH, the leachability of Al, Ca and Mg was found to be strongly dependent on pH and fair agreement between the measured and predicted concentrations was obtained. The speciation modelling indicated that gibbsite, calcite and magnesite controlled the solubility of Al, Ca and Mg, respectively, which was in agreement with the expected carbonation products. Due to the larger pH fluctuations in the test sections exposed to the road traffic, increased concentrations were observed for the oxyanions. The same effect was not seen for the trace metal cations Cd, Cu, Ni, Pb and Zn. The distinct pH dependent leaching profile (solubility maximum in the mildly basic pH region) for vanadium could be seen after 10years of exposure. The simplified risk assessment showed that the released quantities did not exceed the chosen acceptance criteria for groundwater and fresh water. The results obtained for the test section not influenced by road dust and de-icing salts, complied with these criteria even without considering any dilution effects caused by the mixing of pore water with groundwater.

Galvín, A.P., J. Ayuso, F. Agrela, A. Barbudo, J.R. Jiménez. 2013. Analysis of leaching procedures for environmental risk assessment of recycled aggregate use in unpaved roads. Construction and Building Materials 40:1207-1214.

The leaching behaviour of recycled materials from construction and demolition projects needs to be deemed acceptable before they are used for civil infrastructure. The study examines three leaching procedures for characterisation of the potential release of heavy metals and anions regulated by the EU Landfill Directive on seven recycled aggregates and two natural materials. The goal of the study is to relate the complex procedures designed for analysis of material leaching behaviour to quick leaching tests used for regulatory purposes. To integrate the data, results of the compliance test, availability test and percolation test were related to each other. The results revealed that two recycled aggregates (the asphaltic and a concrete material) could be classified as inert material and the remainder were categorised as non-hazardous. Finally, the statistical analysis conducted permitted the identification of the group of heavy metals which are close to their acceptance thresholds. Thus, the noticeable amounts of Ni, Cr, Sb, Zn and Cu warrant their consideration as relevant from an environmental point of view.

Galvín, A.P., J. Ayuso, I. García, J.R. Jiménez, and F. Gutiérrez. 2014a. The effect of compaction on the leaching and pollutant emission time of recycled aggregates from construction and demolition waste. Journal of Cleaner Production 83:294-304.

Urban solid waste from demolition and construction engineering sites has been demonstrated to be mechanically suitable for reuse in civil infrastructures. However, the application of recycled materials as a replacement for natural aggregates demands an assessment of the pollution potential of the material in its second life cycle.

Actually, plant managers of construction wastes assess the materials according to concise leaching tests that do not consider the compaction stage of the materials when they are applied in civil infrastructures. For that reason, the aim of the present study is to evaluate the effect of compaction on the leaching behaviour of concrete and mixed recycled aggregates.

A percolation test for materials under compaction conditions was designed. The release levels measured in the water percolated through the compacted aggregates were compared with a conventional percolation leaching test. Besides, the compliance test allowed identifying the most conflictive elements according to the measured concentrations in the leachate: chromium and sulphate. The results revealed that under compaction, the highest levels of release were obtained for the concrete material. It was due to its high susceptibility to compaction which increased the content of fine particles affecting to the leaching behaviour. The study also includes the formulation of an equation to determine the emission release time of pollutants. Calculations were developed for two common applications as granular material: embankments and structural road layers.

Głuchowski, A., W. Sas, J. Dzięcioł, E. Soból, and A. Szymański. 2019. Permeability and Leaching Properties of Recycled Concrete Aggregate as an Emerging Material in Civil Engineering. Applied Sciences 9(81) 18pp.

Creating models based on empirical data and their statistical measurements have been used for a long time in the economic sciences. Increasingly, these methods are used in the technical sciences, such as construction and geotechnical engineering. This allows for reducing the costs of geotechnical research at the design stage. This article presents the research carried out on Recycled Concrete Aggregate (RCA) material with is reclaimed crushed concrete rubble. Permeability tests were carried out using the constant head method. Tests were conducted on blends of RCA with the following particle size ranges: 0.02–16 mm, 0.05–16 mm, 0.1–16 mm, and 0.2–16 mm. The gradients used during the tests were between 0.2 to 0.83, which corresponds to gradients encountered in earth construction and are below the critical gradient. Directly from the tests, the flux velocity for the range of tested gradients were calculated based on filtered water volume measurements. The values of the permeability coefficient (k) were then recalculated. Finally, statistical methods were used to determine which physical parameters of the tested material affect the permeability coefficient. The physical parameters selected from the statistical analysis were used to create a model describing the phenomenon. The model can be used to determine the permeability coefficient for a mixed RCA material. The article ends with conclusions and proposals concerning the threshold gradients obtained from the statistical analysis, suffosion analysis, and flux velocity.

Gupta, N., M. Kluge, P.A. Chadik, and T.G. Townsend. 2018. Recycled concrete aggregate as road base: Leaching constituents and neutralization by soil Interactions and dilution. Waste Management 72:354-361.

Recycled Concrete Aggregate (RCA) is often used as a replacement for natural aggregate in road construction activities because of its excellent mechanical properties, and this trend should increase as more transportation departments include RCA in specifications and design manuals. Concerns raised by some engineers and contractors include impacts from leachate generated by RCA, both from transport of metals to water sources and the impact of a high pH leachate on corrosion of underlying metal drainage pipes. In this study, RCA collected from various regions of Florida exhibited pH ranging from 10.5 to 12.3. Concentrations of Al, Ba, Cr, Fe, Mo, Na, Ni, Sb, and Sr measured using batch leaching tests exceeded applicable risk-based thresholds on at least some occasions, but the concentrations measured suggest that risk to water supplies should be controlled because of dilution and attenuation. Two mechanisms of pH neutralization were evaluated. Soil acidity plays a role, but laboratory testing and chemical modeling found that at higher liquid-to-solid ratios the acidity is exhausted. If high pH leachate did reach groundwater, chemical modeling indicated that groundwater dilution and carbonation would mitigate groundwater pH effects.

Limbachiya, M.C., E. Marrocchino, and A. Koulouris, Chemical–mineralogical characterisation of coarse recycled concrete aggregate. Waste Management 27(2):201-208.

The construction industry is now putting greater emphasis than ever before on increasing recycling and promoting more sustainable waste management practices. In keeping with this approach, many sectors of the industry have actively sought to encourage the use of recycled concrete aggregate (RCA) as an alternative to primary aggregates in concrete production. The results of a laboratory experimental programme aimed at establishing chemical and mineralogical characteristics of coarse RCA and its likely influence on concrete performance are reported in this paper. Commercially produced coarse RCA and natural aggregates (16–4 mm size fraction) were tested. Results of X-ray fluorescence (XRF) analyses showed that original source of RCA had a negligible effect on the major elements and a comparable chemical composition between recycled and natural aggregates. X-ray diffraction (XRD) analyses results indicated the presence of calcite, portlandite and minor peaks of muscovite/illite in recycled aggregates, although they were directly proportioned to their original composition. The influence of 30%, 50%, and 100% coarse RCA on the chemical composition of equal design strength concrete has been established, and its suitability for use in a concrete application has been assessed. In this work, coarse RCA was used as a direct replacement for natural gravel in concrete production. Test results indicated that up to 30% coarse RCA had no effect on the main three oxides (SiO2, Al2O3 and CaO) of concrete, but thereafter there was a marginal decrease in SiO2 and increase in Al2O3 and CaO contents with increase in RCA content in the mix, reflecting the original constituent's composition.

Märkl, V., and D.A. Stephan. 2016. Release Behaviour of Major Elements and Superplasticiser from Cement Suspensions. Water, Air, & Soil Pollution 227:30.

In this study, the leaching of inorganic and organic species from micro fine cement suspensions for grouting purpose was investigated. The leaching experiments were conducted according to the German tank leaching test with demineralised water and Berlin tap water and lasted up to 56 days. The release behaviour of the superplasticiser was studied by total organic carbon (TOC) measurements and ultraviolet-visible spectroscopy (UV-Vis) detection. Depending on the availability and the solubility of the inorganic species, the release is controlled by the water to cement (w/c) ratio and porosity thereafter. The eluent is also responsible for the leached amount of ions, whereas Berlin tap water is less aggressive. Even adsorption of ions is possible when leaching with Berlin tap water. Superplasticiser leaching is controlled by surface wash-off effects during the first leaching steps, followed by diffusion. UV-Vis measurements showed that only up to 2 % of the total active component of the superplasticiser can be released. As the superplasticiser is a mixture of melamine and naphthalene sulfonate condensate, their release happens in a two-stage process. During the first leaching steps, melamine sulfonate condensate is leached, which alternates later on to a favoured leaching of naphthalene sulfonate condensate.

Mulugeta, M., C.J. Engelsen, G. Wibetoe, and W. Lund. 2011. Charge-based fractionation of oxyanion-forming metals and metalloids leached from recycled concrete aggregates of different degrees of carbonation: A comparison of laboratory and field leaching tests. Waste Management 31(2):253-258.

The release and charge-based fractionation of As, Cr, Mo, Sb, Se and V were evaluated in leachates generated from recycled concrete aggregates (RCA) in a laboratory and at a field site. The leachates, covering the pH range 8.4-12.6, were generated from non-carbonated, and artificially and naturally carbonated crushed concrete samples. Comparison between the release of the elements from the non-carbonated and carbonated samples indicated higher solubility of the elements from the latter. The laboratory leaching tests also revealed that the solubility of the elements is low at the "natural pH" of the non-carbonated materials and show enhancement when the pH is decreased. The charge-based fractionation of the elements was determined by ion-exchange solid phase extraction (SPE); it was found that all the target elements predominantly existed as anions in both the laboratory and field leachates. The high fraction of the anionic species of the elements in the leachates from the carbonated RCA materials verified the enhanced solubility of the oxyanionic species of the elements as a result of carbonation. The concentrations of the elements in the leachates and SPE effluents were determined by inductively coupled plasma mass spectrometry (ICP-MS).

Natarajan, B.M.,Z. Kanavas, M. Sanger, J. Rudolph, J. Chen, T. Edil, M. Ginder-Vogel. 2019. Characterization of Recycled Concrete Aggregate after Eight Years of Field Deployment. Journal of Materials in Civil Engineering 31(6):04019070 8 pp.

Recycled concrete aggregate (RCA) is a high-quality substitute for virgin aggregate as base or subgrade material in pavement construction. However, heavy metal leaching and/or production of high pH leachate are environmental risks commonly associated with the use of RCA. To characterize changes in physical and chemical properties after use, RCA base course and subgrade soil samples were recovered from the Minnesota road research (MnROAD) field site after eight years and compared to the original RCA physical and chemical characteristics. RCA samples were analyzed to determine their mineralogy, carbonate content, acid neutralization capacity (ANC), material pH, and trace element leaching potential. ANC was higher in the recovered RCA and higher for the fine-grained RCA particles than the coarse particles, which was confirmed by extensive carbonation of the fines fractions during field deployment. Material pH of RCA and subgrade soil samples were significantly higher than leachate pH measured in previous and current field investigations of this site, suggesting that conventional laboratory techniques do not represent field conditions and should be modified to better represent field conditions.

Oliveira, M.L.S., M. Izquierdo, X. Querol, R.N. Lieberman, B. K. Saikia, L.F.O. Silva. 2019. Nanoparticles from construction wastes: A problem to health and the environment. Journal of Cleaner Production 219:236-243.

The present study deals with the nano-mineralogy and geochemistry of ultrafine particles in construction waste from the Porto Alegre region in Southern Brazil. Uncontrolled construction waste dumps and poor management practices in formal disposal sites in the area may increase exposure risks to population. Whilst the physicochemical properties of construction wastes are well documented in the literature, the characteristics of nanoparticles in their formulations are not well known. Given that degradation of construction materials may unlock and enable further release of nano-particulates present, we focused on the <63 μm fraction to examine the geochemistry of inhalable nano-particulates that could cause adverse health impacts on local communities. A particular feature across the studied wastes are the numerous aerodynamically favourable, spherical-shaped nanoparticles of magnetite, rutile and anatase. The detected nanoparticles contained a number of elements including Al, As, Au, Ca, Cd, Co, Cr, Cu, Hg, Na, Fe, K, S, Sn, Si and. An enrichment in metals and metalloids such as As, Co, Cr, Cu, Hg, Fe, Sn or Ta in particles in the nano-scale range in relation to larger particles was observed. The presence of carbon nanotubes was also noted. The leaching tests showed that the construction wastes did not reach the limits for their disposal as hazardous waste according the European Directive. Whilst the majority of trace elements were highly immobile, the water extractability for oxyanionic-forming metalloids suggests possible migration to surface and groundwater bodies. This work seeks to bring awareness on the impacts of unsustainable construction waste management, and the relevance of improved regulations regarding their final disposal.

Poon, C.-S., X.C. Qiao, and D. Chan. 2006. The cause and influence of self-cementing properties of fine recycled concrete aggregates on the properties of unbound sub-base. Waste Management 26(10):1166-1172.

The use of coarse recycled concrete aggregates (CRCA) in conjunction with fine recycled concrete aggregates (FRCA) as sub-base materials has been widely studied. Although research results indicate that it is feasible to employ both CRCA and FRCA as granular sub-base, the influence of the unhydrated cement in the adhered mortar of the RCA on the properties of the sub-base materials has not been thoroughly studied. Generally, it is known that the strength of the sub-base materials prepared with RCA increases over time. However, this mechanism, known as the self-cementing properties, is not well understood and is believed to be governed by the properties of the fine portion of the RCA (<5mm). This paper presents an investigation on the cause of the self-cementing properties by measuring X-ray diffraction patterns, pH values, compressive strength and permeability of various size fractions of the FRCA obtained from a commercially operated construction and demolition waste recycling plant. Their influence on the overall sub-base materials was determined. The results indicate that the size fractions of <0.15 and 0.3-0.6mm (active fractions) were most likely to be the principal cause of the self-cementing properties of the FRCA. However, the effects on the properties of the overall RCA sub-base materials were minimal if the total quantity of the active fractions was limited to a threshold by weight of the total fine aggregate.

Rodrigues, P., J.D. Silvestre, I. Flores-Colen, C.A. Viegas, J. de Brito, R. Kurad, and M. Demertzi. 2017. Methodology for the Assessment of the Ecotoxicological Potential of Construction Materials. Materials 10(6):649.

Innovation in construction materials (CM) implies changing their composition by incorporating raw materials, usually non-traditional ones, which confer the desired characteristics. However, this practice may have unknown risks. This paper discusses the ecotoxicological potential associated with raw and construction materials, and proposes and applies a methodology for the assessment of their ecotoxicological potential. This methodology is based on existing laws, such as Regulation (European Commission) No. 1907/2006 (REACH-Registration, Evaluation, Authorization and Restriction of Chemicals) and Regulation (European Commission) No. 1272/2008 (CLP-Classification, Labelling and Packaging). Its application and validation showed that raw material without clear evidence of ecotoxicological potential, but with some ability to release chemicals, can lead to the formulation of a CM with a slightly lower hazardousness in terms of chemical characterization despite a slightly higher ecotoxicological potential than the raw materials. The proposed methodology can be a useful tool for the development and manufacturing of products and the design choice of the most appropriate CM, aiming at the reduction of their environmental impact and contributing to construction sustainability.

Roque, A.J., I.M. Martins, A.C. Freire, J.M. Neves, and M.L. Antunes. 2016. Assessment of Environmental Hazardous of Construction and Demolition Recycled Materials (C&DRM) from Laboratory and Field Leaching Tests Application in Road Pavement Layers. Procedia Engineering 143:204-211.

A research project aiming to contribute to the sustainable implementation of recycling of Construction and Demolition Waste (C&DW) in road pavements is ongoing. The use of Construction and Demolition Recycled Materials (C&DRM) in road pavements is envisaged as a solution with major environmental and economic benefits. Their application as unbound granular material in pavement layers (base, sub-base and capping layers) also has the advantage to allow the incorporation of large amounts of this type of materials, even coming from different sources. Engineering and environmental performance of these materials are being assessed through laboratory tests and field tests. The evaluation of the environmental hazardous of C&DRM is based in their leachability from compliance (batch test) and basic characterisation (column test and lysimeter test) leach tests. The results already obtained in leaching tests are presented and discussed in the paper. In case of compliance leach test, the results are compared with leaching limit values defined in the Portuguese legislation for waste acceptable at landfills for inert waste.

Sadecki, R.W., G.P. Busacker, K.L. Moxness, K.C. Faruq, and L.G. Allen. 1996. Minnesota Department of Transportation, Investigation of Water Quality in Runoff from Stockpiles of Salvaged Concrete and Bituminous Paving. National Technical Reports Library - NTIS. Minnesota Department of Transportation, Oakdale, MN.

The Stockpile Runoff Project addressed environmental concerns regarding the quality of runoff water from salvaged pavement stockpiles. Three experimental stockpiles were studied, one pile consisted of coarse concrete, a second consisted of fine concrete material, and the third consisted

of salvaged bituminous material (recycled asphalt product) obtained from a pavement milling project.

The leachate water from the piles flowed through a sampling and flow monitoring system with data loggers and automated sequence samplers. Composite water samples were analyzed using EPA approved methods and quality control protocols. Comparing the observed median values for the stockpile runoff with Minnesota standards for surface waters, the pH exceeded and chromium may have exceeded the standards. Although there are sediment and leachates emanating from stockpiles, the long-term concern reduces to suspended and dissolved solids, and pH. Polynuclear aromatic hydrocarbons (P AH) concentrations from the bituminous millings pile were near or below detectable limits.

Planning for stockpile storage sites should include management practices of controlling runoff similar to those that are used for construction sites. Berms, straw bales, grass or other filter channels, and locating stockpile sites some distance from surface waters may be appropriate practices. Possible impacts on the ground water system should be considered.

Steffes, R.. 1999. Laboratory Study of the Leachate from Crushed Portland Cement Concrete Base Material. Iowa Department of Transporation, Ames, Iowa. 13 pp.

Since the 1980's, the Iowa Department of Transportation has increased its use of recycled Portland Cement Concrete (PCC) as drainable base material below some new pavements. Water flowing out of the longitudinal drains on projects having recycled PCC drainable bases was found to have a high pH value. The high pH water impedes vegetation growth and becomes a contributing factor to soil erosion at the drain outlet. In addition, the high pH water contributes to the growth of crystalline deposits on the drain outlet wire mesh rodent guard and in some cases caused it to become completely blocked. This research determined which of three choices of recycled PCC drainable base material, gradation, and design would give the lowest pH value in the drain discharge water.

The drainable base material having its fines separated out and placed as a 2" bottom layer, below the remaining coarse material, generally gave pH values around 11.2 while other designs tested gave pH values around 11.5.

Strufe, N., N. Trap, and E.K. Lauritzen. 2006. Kortlægning af Forurenende Stoffer iBygge- og Anlægsaffald (Mapping of pollutants in construction and demolition waste). Project No. 1083 2006. Danish EPA. (in Danish).

Translated into English

"The background for this project is that in recent years around the country have been found examples of contamination of concrete, asphalt and bricks in construction waste. It has not been so far possible to determine the extent of the problems, just as it has not been possible to identify sources and causes of the pollution. This has resulted in some waste fractions could not be fully recycled, as provided for in Action Plan Waste 21. On this basis, the Danish Environmental Protection Agency has chosen to finance the implementation of a project mapping the extent of the problem."

Zhang, Y.B., J.N. Chen, M. Ginder-Vogol, and T.B Edil. 2018. Effect of pH and Grain Size on the Leaching Mechanism of Elements from Recycled Concrete Aggregate. In: Farid A., Chen H. (eds) Proceedings of GeoShanghai 2018 International Conference: Geoenvironment and Geohazard. GSIC 2018. Springer, Singapore.

Using recycled concrete aggregate (RCA) as base course in pavement construction also requires the investigation on the potential environmental risk. In this study, leaching characteristics of major elements including aluminum (Al), calcium (Ca), iron (Fe) and magnesium (Mg), trace and minor elements including arsenic (As) and barium (Ba) from RCA under different pH conditions (pH~2–14) were investigated by laboratory batch leaching tests in accordance with the United States Environmental Protection Agency (USEPA) leaching method 1313. Geochemical speciation modelling by Visual Minteq was applied to determine leaching mechanisms of these elements. Results showed that leaching of Fe followed a cationic leaching pattern, where the elemental concentrations leached from RCA decreased with an increase in pH. Leaching of Al present the amphoteric pattern, and leaching behavior of Ca, Mg, As and Ba showed different leaching patterns, which is less pH dependent. Maximum leaching concentrations of the majority elements were measured at extreme acidic (pH ~ 2). The fine particles tended to leach more trace elements than sand and gravel-sized particles at pH > 10. Leaching of Al from all RCA samples are controlled by dissolution/precipitation of (hydr)oxides mineral solid phases. Leaching of Ba is controlled by witherite from pH of 8 to 10, and it seems to be controlled by barite at extremely alkaline pH condition (pH = 13).