Environmentally sustainable use of recycled crushed concrete aggregate in earthworks

Utilisation écologiquement durable de l'agrégat de béton concassé recyclé dans les travaux de terrassement

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ABSTRACT: Recently, new environmental concerns regarding earthwork constructions have emerged. Such concerns are considerably wide, ranging from water economy to carbon dioxide emissions and waste control in construction phases. To decrease the use of non-renewable natural resources as well as environmental effects of earthworks, natural aggregate materials can be replaced with recycled materials such as recycled crushed concrete aggregate. The effect of crushed concrete to sustainability is manifold: high deformation modulus produces savings in layer thickness, the aggregate is approximately 10 % lighter, and its "urban" availability produces savings in transport and less waste to landfills, it allows savings in transport and in natural aggregates, and produces stiffer base and subbase layers and thereby less maintenance, etc. One of the largest contributors of the greenhouse gas emission is the production of cement for use in concrete. However, concrete is well-known for its carbon dioxide (CO_2) uptake by carbonation. The uptake rate becomes higher in a recycling process because the reacting surface area is increased by crushing processes. The use of recycled crushed concrete aggregate therefore benefits environment by reducing greenhouse gas emissions and energy consumption, and by conserving natural aggregate sources.

RÉSUMÉ : Pour diminuer l'utilisation de ressources naturelles non renouvelables ainsi que les effets environnementaux des travaux de terrassement, les matériaux d'agrégats naturels peuvent être remplacés par des matériaux recyclés tels que l'agrégat de béton concassé recyclé. Récemment, de nouvelles préoccupations environnementales concernant les constructions de terrassements ont émergé. De telles préoccupations sont considérablement étendues, allant de l'économie de l'eau aux émissions de dioxyde de carbone et au contrôle des déchets dans les phases de construction. L'effet du béton concassé sur la durabilité est varié: haut module - économies d'épaisseur de couche, ≈10% plus léger et existence «urbaine» - économies de transport, moins de déchets vers les sites d'enfouissement - économies de transport et agrégats naturels, - moins d'entretien, etc. L'un des principaux contributeurs de l'émission de gaz à effet de serre est la production de ciment pour utilisation dans le béton. Cependant, le béton est bien connu pour son absorption de dioxyde de carbone (CO_2) par la carbonatation. Le taux d'absorption devient plus élevé dans un processus de recyclage parce que la surface de réaction est augmentée par des procédés de concassage. L'utilisation du béton concassé recyclé contribue à l'environnement en réduisant les émissions de gaz à effet de serre et la consommation d'énergie et en préservant les agrégats naturels.

KEYWORDS: recycled crushed concrete aggregate, C&DW, Emission, climate change, LCA, sustainability, resource efficiency

1 INTRODUCTION

Climate change and the depletion of natural resources are two of our most pressing global problems. As construction activity contributes about 20 to 25% to global carbon emissions, it is therefore essential to reduce emissions in construction to pursue sustainable development (Correia 2015). In addition road, street and railway construction account for a highly significant share of the consumption of non-renewable natural resources. Infra construction accounts for approximately 50% of the depletion of the soil and rock in Finland. (Korkiala-Tanttu et. al 2006) Construction and demolition practices are among the biggest sources of waste in Europe and construction and demolition waste (C&DW) is one of the major waste types produced by modern society (Butera et. al 2015). Transport and diesel vehicles are also the most significant contributors for a wide range of health problems in Europe, according to the European Environmental Agency (Transport and public health, 2016). The growing trend of urbanisation affects construction and maintenance of the built environment. The costs and harm originating from construction and transportations will increase in the future unless improved practices for aggregate maintenance and construction are conceived and developed.

Circular economy is a novel economic model in which the focus is on reusing materials and value. In such an economic system, material wastage and generation of waste are minimised. In a circular economy, the use of resources and materials will be enhanced, with raw materials retaining their value in the life cycle of resources. By reusing and recycling the material, large amounts of valuable non-renewable natural rock material can be conserved. Additionally, considerable savings in transport costs and particle emissions in the air can be achieved.

Geomaterials used in transportation infrastructures in the construction, maintenance and rehabilitation have an important impact in the sustainability of the system through the energy consumption and emissions generated in extraction, processing, and transportation (Correia 2015). Today many construction materials, such as concrete, can be reused or recycled and used to replace natural aggregates. Crushed recycled concrete can be used in road and field constructions and in earthwork construction of new infrastructure as well as in diverse ways in urban construction, for example in landscaping mounds, retaining walls and pavements (roads and streets), rainwater management infrastructure and noise barriers to build a unique character for areas in an ecologically, economically and socially sustainable way. When natural aggregates are replaced with recycled crushed concrete, all environmental impacts will be decreased, especially with increasing hauling distance to disposal sites (Niemelin, T. and Kreft-Burman, K. 2015).

2 PLANNING AND DESIGN

2.1 *Design with recycled materials*

Currently the construction and design guidance of recycled materials are primarily concerned with execution of the project. A broader scope should be considered for utilization applications and earlier interaction in planning. The potential utilization sites are often disregarded due to lack of environmental permit (time schedules commonly have not taken environmental permitting process into account), the contract agreements are prepared in a way that recycled materials are prohibited, or contractors and designer are lacking information regarding material behaviour and performance.

Involving environmental design considerations in earlier stages of design, will give decision-makers tools to make a justified decision and provide them with the ability to compare the feasibility, environmental values and technical suitability of the alternatives. In the case of crushed concrete aggregate (CCA), various studies have observed that technical and economical properties of CCA are in some cases superior than those of natural aggregates. The technical suitability of CCA as a high quality infrastructure construction aggregate has been demonstrated with several long-term follow up studies (spanning a period of over two decades), including extensive field and laboratory testing (Dettenborn et. al 2016; Dettenborn et. al 2015a; Dettenborn et. al 2015b). Based on several decades of follow-up studies of CCA mechanical behaviour (Dettenborn et al. 2015a) natural aggregates may be replaced with crushed concrete at a rate of 1:1, or in certain cases with a thinner layer of CCA.

Recycling and re-using the excavated CCA from another site is possible and recommended. In metropolitan areas clean CCA (not mixed in other aggregates) can also be re-used and stored using special recycling centres. In metropolitan areas these special recycling centres are arranged by the municipality itself, or by CCA suppliers. If CCA has no re-use potential in earth construction, it is disposed as concrete waste.

2.2 *Technical properties and performance of crushed concrete aggregate*

The Finnish classification for different CCA categories is presented in Table 1 (classified by its raw material and technical properties). The raw material can originate, for instance, from waste concrete elements as a spoil from manufacturing process requirements (category I) or from the demolition of old concrete structures or buildings (category II-IV). The basic properties of the categories of CCA are summarized in Table 1, and a photograph showing a stockpile of high quality CCA is presented in Figure 1.

Table 1. Basic properties and content of harmful materials. (Finnra 2000)

Category	Grain size distribution [mm]	Self-hardening properties	Frost suscepti-bility	E-modulus [MPa]	Max. content of bricks [weight-%]	Max. content of other materials ** [weight-%]
I	0/50	Hardens	No	700	0	0,5
II	0/50	Hardens	No	500	10	1
III	0/50	Uncertain	No	280	10	1
IV	Varies	No hardening	Varies	≤200*	30	1

* to be considered in each case

** wood, plastic, etc. In addition of the weight-% demand there may not be harmful amounts of special light materials (such as polystrene and other insulation materials).

The highest level of allowed content of harmful compounds, which are defined in standards or in national regulations for different applications, shall not be exceeded in applications using CCA. For example, the standard BS EN 933-11 (Tests for geometrical properties of aggregates. Classification test for the constituents of coarse recycled aggregate) sets requirements for testing of certain elements and their testing methods

Figure 1. High quality CCA crushed to stockpile

Insufficient bearing capacity in the base or subbase layer may lead to deformations in road structure (Korkiala-Tanttu 2008). Figure 2 presents back-calculated CCA E-moduli observed in Finnish trials and in other structures. Common to both Finnish and other full-scale trial sites is the increase of CCA E-moduli, and therefore the total bearing capacity of the pavement structure likewise increases. The gradual increase of strength with time is related to the rehydration of cement bonds. (Dettenborn et al. 2015a). Therefore the increasing bearing capacity indicates that the long-term behaviour of the CCA-based structures improves after construction. The superior technical characteristics of CCA can be utilized in road construction design by, for example, enabling thinner pavements layers having better resistance to deformation and therefore extending maintenance intervals.

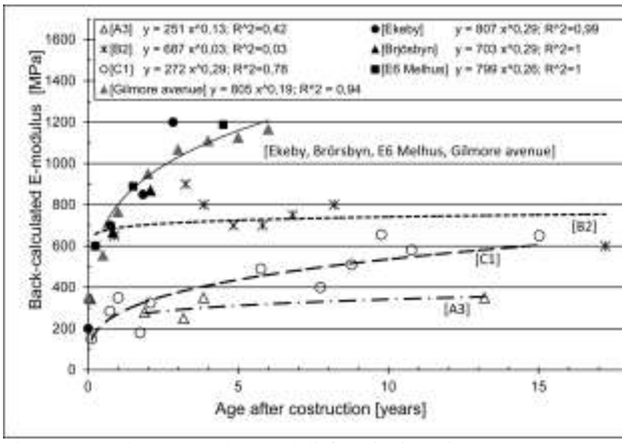

Figure 2. Back-calculated E-moduli for Finnish trials and some other Swedish test structures. A3: VT4 Highway, B2: Rusutjärvi-Paijala Road, C1: VT3 Highway. (Dettenborn et. al .2015a).

2.3 *Economical benefits*

Transportation of heavy aggregates is expensive. Sequential tasks such as excavation, transportation, spreading and compaction are strongly reliant on heavy mechanical equipment and repetitive processes, thus becoming as economically demanding as they are time consuming (Correia 2015). Relative costs for aggregate transportations are calculated based on Rapal FORE construction cost database that are normalized for reference transportation (100 %) as 30 to 50 km (RAPAL). The reference transportation is average for natural aggregate transportation in metropolitan area. Transportation costs compared to reference are following: 5 to 10 km 35 %, 15 to 20 km 60 % and over 50 km 150 %. As demolition sites or recycling centres are much closer to construction site in metropolitan area 40 to 65 % savings can be achieved in transportation costs.

2.4 *Environmental aspects*

The primary environmental impacts in construction are depletion of natural aggregate sources, and airborne emissions generating from energy consumption and transportation (Niemelin & Kreft-Burman 2015). In addition, a life cycle assessment study of construction and demolition waste concluded that transportation represented 60 to 95 % for most nontoxic impacts. Transportation of C&DW to and from the crushing facility provided large contributions, estimated to be 40 to 50 % of all impacts (Butera et al. 2015). Long transportation distances increase emissions and noise from traffic and decrease safety. These in turn weaken the quality of life and well-being of the citizens living in the area.

When natural aggregates are replaced with recycled crushed concrete, all environmental impacts will be decreased, especially when the transportation distance of natural aggregates is long (Niemelin & Kreft-Burman 2015). Concrete structures can be crushed on site at a concrete crushing station. Onsite crushing avoids unnecessary costs and emissions of transportation as the demolished material does not need to be transported to and from an external crushing station. According to Butera et. al. (2015), crushing of C&DW contributed up to 30 % of the environmental impacts. When the crushing takes place indoors, additional benefits from noise and dust reduction are realized during the crushing process, which further increases the attractiveness of the site development area during construction process.

In practise the relative benefits of the crushing of C&DW at site or at a recycling centre must be studied case by case considering for example the amount of the C&DW, the space at the site, the quality of the concrete, distance to the recycling centre, etc.

A simplified allocation of the virgin aggregate and recycled concrete aggregate processes is presented in Figure 3. When CCA is used, the most significant impacts to the environment (cement production generates enormous amount of CO_2 emissions) are omitted, as only the screening of the CCA is allocated to the CCA life cycle. The demolition of the structure to be demolished is not allocated because the structure is not demolished specifically to fulfil the needs of infra construction, but rather would be demolished in any case and the C&DW transported to landfill if no re-use potential exists for the waste fraction. The colours in the Figure 3 represent different stages; red for natural aggregate production, green for road (or other earth construction structure) life cycle stages when C&DW is used. The grey colour represents stages that are not relevant anymore when the road (or other earth construction structure) is constructed.

Fengming et. al (2016) conclude that carbonation of cement products represents a substantial carbon sink that is not currently considered in emissions inventories. Carbonation may lead to significant CO_2 uptake after the initial crushing process owing to the smaller particle size, and therefore larger surface area (e.g., Engelsen et al. 2005). After the fresh concrete is cast and it has hardened, a so called carbonation process is initiated. Carbonation of concrete is a process that continues throughout the entire life cycle of concrete structures when carbon dioxide enters concrete. During its life cycle, concrete can be estimated to absorb roughly one third of the emissions produced during its production. When concrete is crushed for recycling processes, the area of concrete exposed to air is multiplied and hence also the carbonation reaction accelerates. These effects have not yet been addressed within LCA modelling of C&DW management (Butera et. al 2015). Carbonation and CO2 uptake are essential processes in an ongoing discussion about anthropogenic, climate change because mitigation of anthropogenic climate change may also be achieved by increasing the capacity of carbon sinks.

Ageing and carbonation of cementitious C&DW during storage may affect leaching of the materials (e.g., Mulugeta et al., 2011). Carbonation can change the leaching properties of oxyanions (Butera et. al 2015). This is not an issue in all cases but the possibility should be recognized. The change in leaching properties of oxyanions depends on the environment and soil properties and needs further studies.

Figure 3. Simplified allocation of the virgin aggregate (natural aggregate) and recycled concrete aggregate processes. (Modified, Stripple 2001).

2.5 *Case studies*

A sustainable approach to material consumption and emissions begins with design and planning that seeks to reuse and incorporate existing materials on site as much as practically possible. Achieving emission reductions in the near future is important to mitigate anthropogenic climate change (IPCC 2014). Geotechnical aspects are of primary importance from the planning and design stages of an infrastructure construction project (Correia 2015). Thus, geotechnical solutions affecting consumption and transportation of materials enable direct and immediate greenhouse gas (GHG) reductions.

Resource efficient and environmentally superior infrastructure construction practices have been studied in various cases in Helsinki, Finland (Känkänen et al. 2014; Säynäjoki 2016). These case studies demonstrate that planning and design solutions, as well as intelligent material choices, can result in remarkable reduction in use of natural resources and in CO_2 emissions. In a street project in Helsinki West Harbour (Jätkäsaari), transportation of virgin rock material represented over 85 % of transportation CO_2 emissions, yet a more than 70 % reduction in emissions was achieved by re-cycling materials at the construction site and thereby minimizing transportation distances. In a public park project in Helsinki (the Ida Aalberg Park), almost 60 % reduction in transportation emissions was achieved by re-cycling and transporting materials from construction sites, which situated close to the project area.

Kivikko road & Ring Road I interchange project in Helsinki has been used as a case study to calculate reduced CO_2 emissions in construction process by replacing virgin aggregate (natural aggregate) with recycled crushed concrete (CCA). Preliminary calculation results show that approximately 50 % of total emissions of road construction project can be avoided by using recycled crushed concrete instead of virgin aggregate. Virgin concrete (and more precisely cement) manufacturing is highly CO_2 intensive (Josa et al. 2007) and transportation represents remarkable part of the emissions in a construction project (Butera et. al 2015).

3 CONCLUSION

The intent of this paper was to present the environmental aspects of utilising crushed concrete aggregate in earthworks. Construction and demolition waste (C&DW) is one of the major waste types produced by modern society,and depletion of natural aggregates is the main environmental impact in construction. Additionally airborne emissions generating from energy consumption and transportations are major consequences from construction activities, contributing approximately 20 to 25 % to global carbon emissions and thus significantly to anthropogenic climate change.

By reusing and recycling crushed concrete aggregate, the following impacts are achieved:

- significant quantities of valuable non-renewable natural rock material can be saved
- considerable savings in transport costs is achieved
- particle emissions into the atmosphere are reduced

When natural aggregates are replaced with recycled crushed concrete, all environmental impacts will be decreased; the net benefit shall be found to increase with increasing transportation distance for the materials

Emission reductions in the near future are important to achieve in order to mitigate anthropogenic climate change. Emission reductions also have effect on health, as road transport and diesel vehicles are major contributors to various health problems worldwide. Geotechnical aspects are of primary importance from the planning and design stages of an infrastructure construction project. Thus, geotechnical solutions affecting consumption and transportation of materials enable direct and immediate GHG reductions and also reducing health problems caused by particle emissions. To tackle these matters it is important to involve the environmental design aspects in earlier stages of design and give the decision-makers tools to make justified decision over environmental values and sustainable options.

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