Assessment concept for the sustainable use of secondary aggregates in concrete

T. Herbst¹, K. Rübner¹, B. Meng¹, and B. Hauer²

¹ BAM Federal Institute for Materials Research and Testing, Berlin, Germany
² Research Institute of the German Cement Industry (FIZ), Düsseldorf, Germany
(present address: Georg Simon Ohm University of Applied Sciences, Nuremberg, Germany)

ABSTRACT: Nowadays there are several applications of mineral recycling materials and residues. At present an assessment method for the use of secondary raw materials, which considers sustainability aspects, does not exist. In the framework of the German DAfStb/BMBF research project “Sustainable Building with Concrete” an assessment concept was developed. It includes the following four assessment steps: I. Basic considerations, II. Advantages for sustainable construction, III. Alternative paths for application, and IV. Sensitivity analysis. The concept was developed on the basis of recycled concrete aggregates, which are already used according to German standards. Afterwards, it was applied and verified by the evaluation of the utilisation of municipal solid waste incinerator bottom ashes.

1 INTRODUCTION

German and European regulations demand waste management system to reduce the waste volume stored in landfills, to save natural resources and to enhance sustainable development by recycling of various residues. There are several applications of mineral recycling materials and residues already. Although, such materials are often used in low-grade applications (road constructions e.g.), there are already standardised residues and recycling products (fly ash, silica fume and recycled concretes or bricks), which are used in the production of high-grade concretes and other mineral building materials. Secondary materials are used as raw materials or secondary fuels in the production of cement clinker, substitutes for cement clinker materials, concrete additives as well as aggregates.

At present an assessment method for the use of secondary raw materials, which considers sustainability aspects, does not exist. In the framework of the German DAfStb/BMBF research project “Sustainable Building with Concrete” (FKZ 0330780B) a concept to assess the applicability of secondary materials as aggregates in concrete was developed. (Hauer et al 2011, Herbst et al 2010)

2 ASSESSMENT CONCEPT

The assessment concept is schematically shown in Figure 1. According to this framework, the basic technical and legal requirements for using secondary aggregates have to be evaluated first (step I). If the materials are basically suitable for the use in concrete the ecological and economic advantages and disadvantages for sustainable construction can be examined (step II). In step III, alternative paths for application, like road construction, embanking or landfilling, have to be examined. Finally, a sensitivity analysis (step IV) should be conducted. It considers
the change of boundary conditions as well as regional differences. The assessment concept was developed on the basis of recycled concrete aggregates, which have already been used according to German standards. Afterwards, it was applied and verified by the evaluation of municipal solid waste incinerator bottom ashes (referred to MSWI bottom ashes) (Herbst et al 2010, Rübner et al 2010).

Figure 1. Concept for the assessment of secondary aggregates in concrete.

3 RECYCLED CONCRETE AGGREGATES
Recycled aggregates are obtained by processing (washing and grading) of inorganic mineral construction materials from demolition of buildings in structural and civil engineering sector. Generally, such crushed concrete can be used as aggregates in the production of new concrete.
By that a new closed loop for recycling of processed demolition materials from building construction is created. Therefore, natural resources can be conserved and waste deposited in landfills can be reduced (Weil et al 2003, Weil and Jeske 2005).

3.1 Basic considerations (step I)

3.1.1 Technical requirements

According to Figure 1, basic technical and legal requirements have to be evaluated first (step I). Demolition materials are usually heterogeneous. Therefore, the material composition of such aggregates (cement-bonded, mineral, ceramic, bituminous, and glassy components) has to be analysed first. In addition, the chemical composition is very important. The main focus is concrete-damaging components. These are chlorides, sulphates, organics, fines, aluminium metal, and waste glass. Furthermore, mechanical and physical properties have to be examined. These properties are porosity, water absorption, grain shape, bulk density, strength, frost resistance, etc. Overall, it has to be noted that frequently an extensive processing of recycling materials is required for the application of such materials.

For the above mentioned technical properties there are certain requirements in German regulations, standards, and directives. Accordingly, recycled concrete aggregates meet the basic technical requirements for concrete aggregates and are suitable for the use as aggregates in concrete. (Herbst et al 2010)

3.1.2 Environmental compatibility

In addition to technical requirements, environmental properties are also very important - particularly with regard to emissions into air, soil and ground water. General principles for a harmless recycling, special regulations for sampling, methods for analysis and its evaluation are specified in a set of German rules. Harmful quantities of inorganic and/or organic substances in recycled concrete aggregates are determined by leaching tests and solid matter analyses. The quantities are limited by specified maximum values. Furthermore, recycled materials are classified specifically using categories depending on their leaching properties.

Based on harmlessness of basic construction material and a closed-loop recycling, the environmental compatibility of crushed concrete and the recycled concrete aggregates can be assumed. According to German regulations, recycled concrete aggregates meet the basic environmental standards for recycled materials. Thus, concrete with recycled concrete aggregates are not harmful to the environment. (Maultzsch et al 2003, Weil 2004)

3.2 Advantages for sustainable construction (step II)

If a secondary material is basically suitable for the use in concrete ecological and economic advantages and disadvantages for sustainable construction can be examined (step II). In doing so, differences between the provision of primary and secondary raw materials are studied. Parameters, like energy consumption, material resources, emissions, and other environmental aspects, are discussed for the complete process chain including early steps. Furthermore, the influences of using secondary aggregates on the production process of concrete must be considered. (Herbst et al 2010, Rübner et al 2010)

3.2.1 Influences on the provision of secondary aggregates

The necessary prerequisite for a high grade recycling of crushed concrete materials is a sufficient homogeneity. Depending on material composition of the demolition material, this implies generally an extensive and specific processing (separating/sorting, crushing, grading). A controlled dismantling, a pure collection and storage on the demolition site and processing plant as well as a receiving control have positive effects on the quality of recycled concrete aggregates. Therefore, collaboration of demolition and processing companies regarding disposal
and utilization concepts is very important for useful, adequate, and cost effective actions. (Aßbrock 2000, Salkowski 2000)

The study of differences between the provision of primary and secondary raw materials requires information about the exploitation/production, processing and transport of the materials (e.g. costs and energy consumption). Hardly any average data are available for Germany. However, studies (Weil et al 2003, Weil 2004) indicated that the provision of recycled aggregates is more energy-intensive than the exploitation of sand and gravel. Gravels and sands are available in most parts of Germany. Thereby, distances for transport can be kept short, and roads can be relieved from heavy trucks. In addition, gravel and sand can be found frequently near big rivers and can be transported very environmentally friendly by ship. All these circumstances have positive effects on the ecological assessment of concrete produced with sand and gravel. However, in areas with low regional availability of gravel and sand, logistical effort for recycled aggregates can be lower than for gravel and sand. (Hauer et al 2011, Herbst et al 2010)

In particular cases, the logistical effort for the provision of recycled aggregates can be quite different. This is related to the differing transport distances from demolition sites to processing plants, within the plant (conveyor belts, grab excavators and suction excavators, ships, bicycle loaders) as well as from the processing plant to the user. In Germany, 1806 of 2148 recycling plants processed pure, non-mixed demolition waste in 2004 (Statistisches Bundesamt 2006). Therefore, area-wide supply of recycled aggregates was possible depending on material demand and quality. (Hauer et al 2011, Herbst et al 2010)

3.2.2 Influences on the production process of concrete

Selected influences on the production process of concrete and its properties are summarised in Table 1. The lower strength and higher permeability of concretes with recycled aggregates limit their application, but they do not exclude the application. The DAfStb-Guideline (DAfStb 2004) applies to the pure use of recycled aggregates of type 1 and 2 according to DIN 4226-100 for the production of concrete according to DIN EN 206-1 and DIN 1045-2. Depending on the quality of material the guideline considers the influences on concrete properties by limiting the quantities used. In addition, extended concrete tests are required. Observing these limitations recycled aggregates can be used as primary aggregates equivalently.

The result of life cycle assessments of concretes with recycled aggregates is influenced by processing and logistical efforts as well as by changes in production of concrete. In a series of studies (Eyerer and Reinhardt 2000, Hauer et al 2007, Weil 2004) technically equivalent concretes with recycled aggregates and only primary aggregates were compared. Generally, saving primary aggregates by recycled aggregates is offset by increased consumption of primary energy, global warming potential, and acidification potential. But, depending on the boundary conditions the results can be different. (Herbst et al 2010)
Table 1. Selected influences on the production process of concrete (Hauer et al 2010, Herbst et al 2010)

<table>
<thead>
<tr>
<th>Property</th>
<th>Effect</th>
<th>Counteractive measures</th>
</tr>
</thead>
<tbody>
<tr>
<td>edged grain shape and rough grain surface of recycled aggregates due to concrete crushing</td>
<td>worse workability of fresh concrete</td>
<td>higher volume of fluid phase paste (e.g. fly ash, cement, rock flour) or concrete plasticisers</td>
</tr>
<tr>
<td>high porosity and low bulk density of recycled aggregates due to high amount of hardened cement paste</td>
<td>increased water absorption of aggregates and fresh concrete, worse workability of fresh concrete</td>
<td>pre-wetting of recycled aggregates, higher water dosing, concrete plasticisers</td>
</tr>
<tr>
<td>high amount of hardened cement paste</td>
<td>lower bulk densities of fresh and hardened concrete</td>
<td>-</td>
</tr>
<tr>
<td>increased water absorption, lower compressive strength of recycled aggregates, higher volume of fluid phase paste</td>
<td>lower compressive strength and tensile strength of hardened concrete</td>
<td>higher amount of cement or fly ash</td>
</tr>
<tr>
<td>higher water-cement ratio and higher volume of fluid phase paste</td>
<td>higher moisture transport due to higher volume of capillary pores and higher amount of major capillary pore diameters</td>
<td>application in dry environment</td>
</tr>
<tr>
<td>basic material: alkali-sensitive constituents in aggregates and alkali content of hardened concrete</td>
<td>alkali-silica reaction under moist conditions</td>
<td></td>
</tr>
</tbody>
</table>

3.3 Alternative paths for application (step III)

Even if the evaluated secondary material is suitable for the application in concrete, an alternative application can make a better ecological and/or economic sense. Therefore, alternative paths for application have to be examined in step III. Until now, recycled aggregates are principally applied in earth and road construction (e.g. bearing layer, frost protection layer, foundation material, embankment, drainage layer, filling material). Furthermore, these materials are also used in horticulture and scenery construction (e.g. drainage layers for green roofs, planting substrates, sports field construction). Each path of application has its own technical requirements. This has to be considered in this assessment step, too. (Bundesgütegemeinschaft Recycling-Baustoffe 2009, Salkowski 2000, Weil 2004)

A study (Weil 2004) examined the effects of an increased close-loop recycling within the structural construction area on mineral material flows in the whole construction sector. According to his study production of concrete from recycled aggregates for building construction would divert these aggregates from potential use in earth construction. Thus, saving resources in structural construction would be counter-balanced by a lack of materials in the civil engineering sector. Overall, there would be no saving of primary aggregates. However, with regard to the future increase in volume of recycled aggregates and possible changing boundary conditions, the application of recycled aggregates in concrete remains relevant. (Herbst et al 2010)
3.4 Sensitivity analysis (step IV)

Effects of changing boundary conditions as well as regional differences on the outcome of the assessment are identified by a sensitivity analysis (step IV). Some critical parameters and boundary conditions are listed below:

- available volume of recycled aggregates (future demolition wastes), application capacities and supply/demand
- regional boundary conditions (gravel pit areas, distribution of recycling plants, logistics)
- quality of materials (new processing techniques, new construction techniques, increased control in demolition)
- stricter regulations for earth works and road constructions (diverting of material flows into the structural construction sector)

These effects have to be assessed from case to case. (Hauer et al 2011, Herbst et al 2010)

4 MSWI BOTTOM ASHES

Municipal solid waste incinerator bottom ash (referred to MSWI bottom ash) is a residue of the controlled combustion of domestic waste and municipal solid waste (300 kg of ash per one ton of waste) (Römpp 2009). An application of MSWI bottom ashes requires extensive processing and storage for several months. In Germany today, such processed bottom ashes are mainly used in bearing layers of roads or parking lots in the public or private sector, sound embankments as well as landfills (Reichelt and Pfang-Stotz 2002, Römpf 2009, Z wahr 2005). Due to the high content of mineral components as well as its chemical and physical characteristics, MSWI bottom ashes have the potential to be used as aggregates in concrete (Hauer et al 2007, Herbst et al 2010). But in contrast to earth and road construction, the alternative application in concrete construction is subject to stricter legal and technical requirements. In a series of projects (Müller and Rübner 2006, Rübner et al 2007, Rübner et al 2008), processed and aged municipal solid waste incinerator bottom ashes have been studied in regards to their potential application as aggregates in concrete. However, the ashes contained too large quantities of chlorides, sulphates, organics, fines, aluminium metal, and waste glass. These components cause damage in concrete and complicate the recycling process. Thus, adequate processing is an essential precondition.

According to the assessment concept (steps I, II, III, and IV) described in chapter 2 and 3, application of MSWI bottom ashes as aggregates in concrete was evaluated. The assessment considers material properties of MSWI bottom ashes, technical properties of concretes produced, and an analysis of ecological impact of their provision (Herbst et al 2010). Based on the results of this sustainability assessment, the following conclusions can be drawn: Concrete with a good workability and normal compressive strength can be produced easily with MSWI bottom ashes as aggregates (from 2 to 32 mm particle size). Its properties are similar to concrete made with recycled crushed concrete aggregates. However, damage in concrete can only be avoided by intensive and extensive treatments of the MSWI bottom ashes to minimise and remove the harmful components. The quality of the bottom ashes could be improved by the following additional treatments: sieving and washing for fines, organic chlorides and, sulphates, opto-mechanical separation for waste glass, and magnetic induction tomography sensors for metals or lye treatment for aluminium metal. If by-products (metals e.g.) of such ash treatments are not taken into account, the provision of MSWI bottom ashes as aggregates in concrete will be more costly in ecological and economic terms than the provision of natural aggregates. For completing the studies, the analysis of ecological impact will be extended to the concrete production. Here, the comparability of the concrete properties (strength, consistency) has to be considered specially. That could lead to modifications of concrete mix design (e.g., increased cement content for concretes produced with MSWI bottom ash as aggregates). Finally, effects of changing boundary conditions and regional differences as well as other unconsidered effects on the assessment result have to be identified and examined from case to case by sensitivity analyses. (Hauer et al 2010, Hauer et al 2011, Herbst et al 2010, Rübner et al 2010)
CONCLUSION

In the framework of the German DAFStb/BMBF research project “Sustainable Building with Concrete”, a sub-project evaluated the potential of secondary materials as concrete aggregates. A concept to assess the applicability of secondary materials as aggregates in concrete, which considers sustainability aspects, was developed. Today, recycled concrete aggregates are already used according to German standards. Using recycled concrete aggregates as an example, the four assessment steps were explained. At first, basic technical and legal requirements on the use of secondary aggregates have to be evaluated (step I). Depending on the basic suitability of the material, the ecological and economic advantages and disadvantages for the sustainable construction can be examined (step II). In step III, alternative paths for application have to be examined. Finally, a sensitivity analysis (step IV) identifies the effects of changing boundary conditions as well as regional differences.

Application of this assessment concept to new potential secondary materials was shown by the evaluation of MSWI bottom ashes, which have not been used as concrete aggregates before.

REFERENCES


Bundesgütegemeinschaft R ecycling-Baustoffe e. V. (2009), w w w.recycling-bau.de/abfall.htm ( Februar 2011) (in German)

DAfStb-Richtlinie (2004) "Beton na ch DIN E N 2 06-1 und D IN l 045-2 m it rezyklierten Gesteinskörnungen nach DIN 4226-100 - Teil 1: Anforderungen an den Beton für die Bemessung nach DIN 1045 -1". D ezember 2 004. D utschecer Ausschuss für S tahlbeton - DAfStb i m DIN De utsches Institut für N ormung e.V. (Ed.), (in German)


Rübner, K., Jakubcová, P. and Herbst, T. (2010) „Saving Natural Resources by Material Recycling“, In: P roceedings o f t he c onference C entreal E urope towards S ustainable B uilding 2010 ( CESB 10) ,


