Sustainable evaluation - concepts to assess the applicability of secondary aggregates in concrete

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Summary

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 (referred to MSWI bottom ashes). [1, 2, 3]

Keywords: sustainable building, sustainability aspects, secondary materials, secondary aggregates in concrete, energy and material resources, assessment concept

1. Introduction

German and European regulations demand a 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. Nowadays there are already several applications of mineral recycling materials and residues. However, such materials are often used in low-grade applications (road constructions e.g.). Nevertheless, 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.

Up to the present an assessment method for the use of secondary raw materials, which considers sustainability aspects, did 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. [1, 2, 3]

2. Assessment concept

The assessment concept is schematically shown in Figure 1. According to this framework, the basic technical and legal requirements on the use of 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 the sustainable construction can be examined (step II). In step III, alternative application paths, 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. [2, 3, 4]

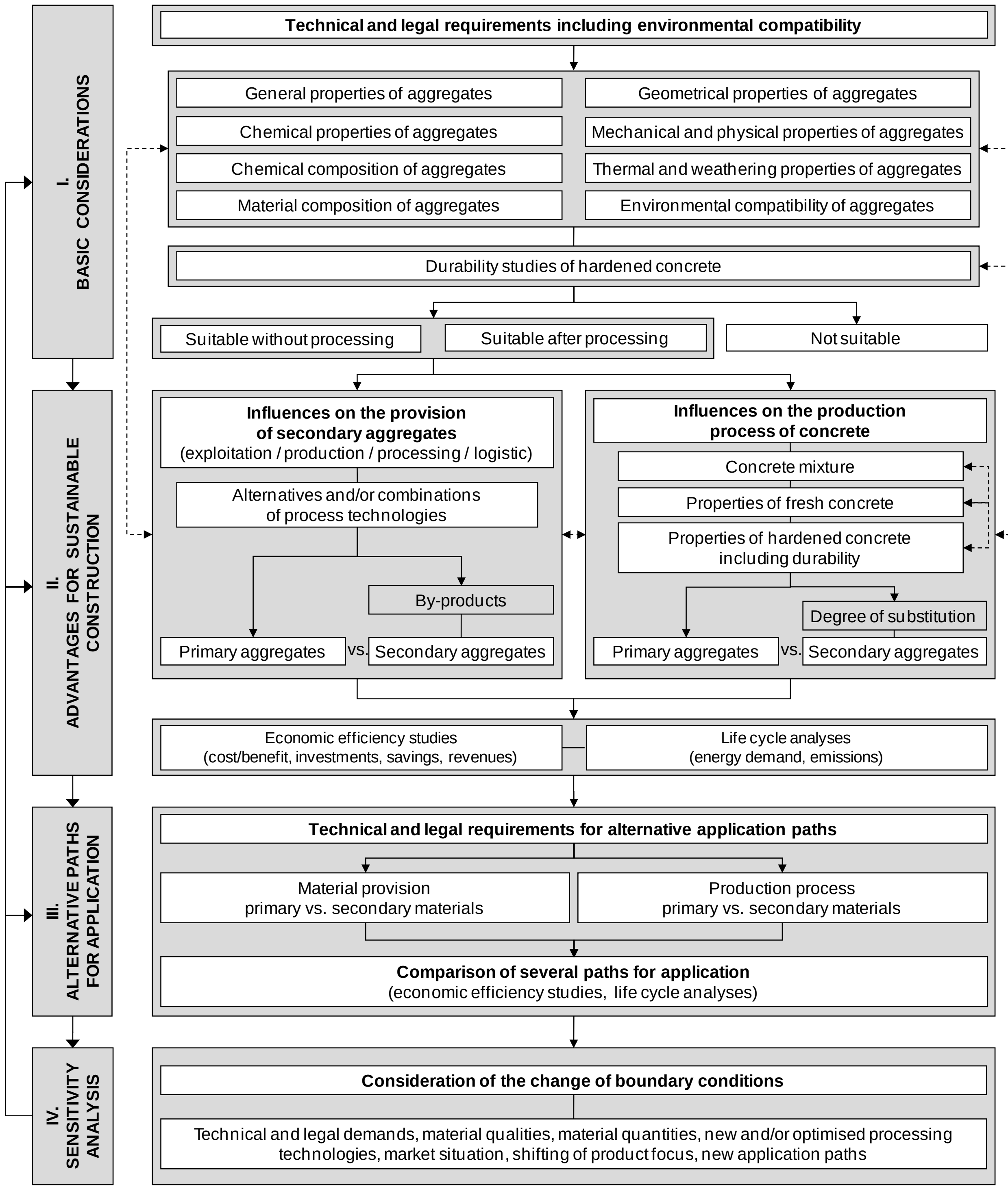

Fig. 1 Concept for the assessment of secondary aggregates in concrete [3]

The assessment 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 municipal solid waste incinerator bottom ashes. [2, 3, 4]

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. Principally, such crushed concrete can be used as aggregates in the production of new concrete. This results in a close-loop recycling for demolition wastes within the structural engineering sector. Thereby natural resources can be conserved and waste deposited in landfill can be reduced [3, 5, 6].

3.1 Basic considerations (step I)

3.1.1 Technical demands

According to Figure 1, the 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, the 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 enables 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. [2, 3]

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 the 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 in specific 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 requirements for recycled materials. Thus, concretes with recycled concrete aggregates are not harmful to the environment. [3, 7, 8]

3.2 Advantages for the sustainable construction (step II)

If a secondary material is basically suitable for the use in concrete the environmental 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 pre-stages. Furthermore, the influences of using of secondary aggregates on the production process of concrete must be considered. [2, 3, 4]

3.2.1 Influences on the provision of secondary aggregates

The necessary prerequisite for a high grade recycling of crushed concrete materials is a suffcient 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 demolition site and processing plant as well as a receiving control have positive effects on the quality of recycled concrete aggregates. Therefore, the collaboration of demolition and processing companies regarding disposal and utilization concepts is very important for useful, adequate, and cost effective actions. [3, 9, 10]

The study of differences between the provision of primary and secondary raw materials requires information about the exploitation/production, processing and transports of the materials (e.g. costs and energy consumption). Hardly any average data are available for Germany. However, studies [5, 8] 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 the roads can be relieved from heavy load traffic. Moreover, gravels and sands can be found frequently near big rivers and can be transported very environmentally friendly by ship. All these circumstances have positive effects on the environmental assessment of concrete produced with sands and gravels. However, in areas with low regional availability of gravels and sands, logistical effort for recycled aggregates could be lower than for gravels and sands. [1, 2, 3]

In particular cases, the logistical effort for the provision of recycled aggregates can be quite different. This is related to the differing distances for transport from demolition sites to processing plant, within the plant (conveyer belts, grab excavators and suction excavators, ship, 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 [11]. Therefore, area-wide supply of recycled aggregates was possible depending on material demand and quality. [1, 2, 3]

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 but not exclude their application. The DAfStb-Guideline [12] 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. Considering 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 [8, 13, 14] 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. [2, 3]

3.3 Alternative paths for application (step III)

Even if the evaluated secondary material is suitable for the application in concrete, an alternative application may make a better environmental 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, landfilling). Furthermore, these materials are also used in horticulture and scenery construction (e.g. drainage layer for green roofs, planting substrates, sports field construction). Each path for application has its own technical requirements. This has to be considered in this assessment step, too. [8, 10, 16]

A study [8] examined the effect of an increased close-loop recycling within the structural construction area on mineral material flows in the whole construction sector. According to this study, the production of recycling concrete could divert the flow of materials of recycled aggregates for earth and road construction into the building construction. Thus, saving resources in building constructions would be counter-balanced by a lack of materials in the earth and road constructions. Overall, there would be no saving of primary aggregates. However, with regard to the future increase volume of recycled aggregates and possible changing boundary conditions, the application of recycled aggregates in concrete remains relevant. [2, 3]

Table 1 Selected influences on the production process of concrete [2, 3, 15]

Properties of recycled aggregates and modifications of concrete mixture	*Effect*	*Counteractive measures*
edged grain shape and rough grain surface of recycled aggregates due to concrete crushing	worse workability of fresh concrete	higher volume of fluid phase paste (e.g. fly ash, cement, rock flour) or concrete plasticisers
high porosity and low bulk density of recycled aggregates due to high amount of hardened cement paste	increased water absorption of aggregates and fresh concrete, worse workability of fresh concrete	pre-wetting of recycled aggregates, higher water dosing, concrete plasticisers
	lower bulk densities of fresh and hardened concrete	-
high amount of hardened cement paste of recycled aggregates	higher shrinkage deformations	small concrete sections
increased water absorption, lower compressive strength of recycled aggregates, higher volume of fluid phase paste	lower compressive strength and tensile strength of hardened concrete	higher amount of cement or fly ash
higher water-cement ratio and higher volume of fluid phase paste	higher moisture transport due to higher volume of capillary pores and higher amount of major capillary pore diameters	application in dry environment
basic material (used concrete): alkali-sensitive constituents in aggregates and alkali content of hard-ened concrete	alkali-silica reaction under moist conditions	

3.4 Sensitivity analysis (step IV)

Effects of changing boundary conditions as well as regional differences on the assessment result 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 building constructions)

These effects have to be assessed from case to case. [1, 2, 3]

4. MSWI bottom ash

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) [17]. 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 [17, 18, 19]. 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 [1, 2, 3, 14]. But in contrast to earth and road construction, the alternative application in concrete constructions is subject to stricter legal and technical requirements. In a series of projects [20, 21, 22], processed and aged municipal solid waste incinerator bottom ashes have been studied in terms of possible application as aggregates in concrete. However, the ashes contain too large quantities of chlorides, sulphates, organics, fines, aluminium metal, and waste glass. These components cause damage in concrete and complicate the recycling. Thus, adequate processing is an essential precondition [3].

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 environmental impact of their provision [1, 2, 3]. 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 concretes 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.

*Table 2 Comparative life cycle analysis *) for the provision of 1 ton of concrete aggregates from processed MSWI bottom ash, recycled aggregates as well as natural aggregates (gravel and sand) [1, 24]*

Impact categories	Unit	1 ton aggregates from MSWI bottom ash	1 ton recycled aggregates [13]	1 ton gravel and sand [13]
Primary energy nonrenewable	MJ	213	84,2	34,4
Primary energy renewable	MJ	10,4	0,16	0,4
Global Warming Potential	kg of CO_2 eq.	13,7	5,9	2,0
Ozone Depletion Potential	kg of R11 eq.	2,2E-6	no data	no data
Acidification Potential	kg of SO_2 eq.	2,3E-2	5,7E-2	1,1E-2
Nutrification Potential	kg of PO_4 eq.	1,8E-3	9,0E-3	2,0E-3
Photochemical Ozone Creation Potential	kg of C_2H_4 eq.	1,6E-3	8,0E-3	1,0E-3

*) not taken into account:

- any other environmental impacts and partial distribution of environmental impacts on other possible marketable by-products (waste glass, metals e.g.)
- potential operational changes of the waste incinerator due to the return of limited quantities of materials from the ash processing

As part of the sustainability assessment for MSWI bottom ashes, the energetic and environmental impacts of the processing steps „sieving and washing“ as well as „opto-mechanical glass separation“ were exemplary analysed [1, 2, 23, 24]. Therefore, primary energy as well as five generally accepted impact categories of a life cycle assessment (LCA) were chosen as impact indicators [13, 25]. The exemplary comparison of the LCA results with existing data [13] for recycled aggregates as well as natural aggregates (gravel and sand) is shown in table 2 [1, 2, 24]. Accordingly, the provision of MSWI bottom ashes as aggregates in concrete will be more costly in ecological (as well as economic) terms than the provision of natural and recycled aggregates.

For completing, the analysis of environmental impacts has to 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. [1, 2, 3, 4, 15]

5. Conclusion

In the framework of the German DAfStb/BMBF research project “Sustainable Building with Concrete”, a sub-project provided the application 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. Presenting recycled concrete aggregates as an example, the four assessment steps were explained. At first, the 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 environmental and economic advantages and disadvantages for the sustainable construction can be examined (step II). In step III, alternative application paths have to be examined. Finally, a sensitivity analysis (step IV) identifies the effects of changing boundary conditions as well as regional differences.
Applicability 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 [1, 2, 3].

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