Recycled Aggregates a Viable Alternative for the Norwegian Building and Construction Industry

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ABSTRACT
The recycling of construction and demolition (C&D) waste is still conducted at a relatively low level in Norway. The building and construction industry, however, have recently published action a plan by which no more than 30% of C&D waste will be placed in landfills by the year 2005. Even though this is relatively low compared to other European countries, it is still an ambitious goal. As a result, the recycling of heavy C&D waste, as well as the use of recycled aggregate, has received considerable attention in Norway over the last few years.

Nationally, high quality and relatively low cost natural aggregates are found in abundance. At the same time, Norway is a scarcely populated nation in which a significant portion of C&D waste is generated in rural areas. Thus, in many parts of the country, the C&D waste volumes are too low and too irregular to make industrialized recycling economically feasible. Consequently, the recycling levels accomplished in other European countries are not environmentally or economically justifiable in Norway. In more urban parts of the country, however, the supply of natural aggregate is limited, and large volumes of C&D waste are rapidly filling landfills. Ambitious environmental policies and a general change of attitude towards the use of primary raw materials have, however, proven to be important motivations for the recycling of C&D waste.

Recycled aggregate has been commercially available in Norway in the Oslo region since 1996. In the last five years, a significant effort has been made to provide technical documentation, initiate reference projects, and include recycled aggregates as an alternative to natural aggregates in relevant codes and standards. The national EcoBuild program has funded the three-year R&D project, RESIBA (1999-2002). The main objective of the RESIBA-project was to provide technical documentation and promote the use of recycled aggregates for various applications. This paper will focus on the most important end results from the RESIBA-project, including a proposed system for quality control for recycled aggregates, as well as the guidelines for use of recycled aggregate published at the conclusion of the RESIBA-project.

Furthermore, this paper will provide a brief overview of the current strategy and policy of the Norwegian authorities and the building and construction industry, in trying to increase the levels of C&D waste recycling. This includes a presentation of an on-going four year R&D program funded by the Norwegian Road Authorities which looked at various recycled materials, including recycled aggregate, specifically for road construction.

1. INTRODUCTION

The Norwegian building and construction industry generates approximately 1.5 mill. tons of construction and demolition waste (C&D-waste) per year. An estimated 70 % (1.1 mill. tons per year) is concrete and masonry ruble (Statistics Norway ,1999). Since the mid-90s the recycling, reuse and reduction of C&D-waste have received increasing attention in Norway. EcoBuild (1998 – 2002), a development program initiated to increase environmental efficiency of the building and construction industry, has been important in this development. The EcoBuild-program has funded several R&D projects related to C&D-waste.

In 2001, the Norwegian building and construction industry - in cooperation with the EcoBuild-program - published a national action plan for C&D-waste, (BNL, 2001). The plan presents several ambitious objectives and a list of 27 explicit actions related to environmentally harmful substances, waste reduction, industrial recycling, and knowledge and information. With respect to recycling specifically, the industry's target is to reduce the amount of C&D-waste landfilled annually to no more than 30 % by 2005. This is a ambitious goal considering recycling is still not standard practice in Norway. Rough estimates indicate current levels of recycling and reuse to be around 20 %. Lack of reliable C&D-waste statistics makes it difficult to measure the current amount of C&D-waste being recycled.

The motivation for recycling, reuse and reduction of C&D-waste has been quite different as compared to other European countries. Norway is a scarcely populated nation with only 4,5 mill. inhabitants spread out over vast areas. At the same time, there is good access to primary raw materials, such as large natural aggregate reservoirs. The Norwegian authorities have, however, set the following objectives in relation to C&D-waste: the reduced consumption of primary raw materials, the controlled handling of hazardous waste, and the reduction of waste landfilled in order to increase the life-span of existing landfills. Still, it is important to recognize that levels of recycling close to 100 % are unlikely to be economically and environmentally feasible in Norway.

The main focus of the Norwegian recycling effort has been on the concrete and masonry ruble, as it makes up the largest portion of all waste generated. Recycled concrete aggregate (RCA) from concrete and masonry ruble has been documented and used successfully in other countries for many years, (Mehus et. al., 2000). Thus in 1998, BA Gjenvinning, a commercial recycling facility for production of RCA from heavy C&D-waste (concrete and masonry ruble) opened for business in Oslo. However, despite selling at a price of 10-40 % that of natural aggregate, lack of sufficient technical documentation and reference projects soon proved to be yet another obstacle to the use of RCA in Norway.

2. RESIBA

2.1 Objective and organization

The Norwegian research and development project RESIBA – Recycled Aggregates for Construction and Building (1999-2002) - aimed to make RCA a competitive product for various applications within the Norwegian building and construction industry. The main objective of RESIBA was to encourage the long-term use of RCA by:

- Disseminating new knowledge and results obtained in the RESIBA-project through systematic documentation and demonstration projects using RCA.
- Actively applying existing knowledge and experience on recycled building materials from various other projects, both nationally and internationally.

EcoBuild funded the RESIBA-project together with the project partners. The RESIBA-project included key representatives from customers, producers to the public and research sector.

2.2 Work packages

The project was divided into three work packages:

- **Work package 1 (WP1): Declaration and quality control**
  The aim was to produce a proposed certification system with parameters and routines for the quality control of RCA. In order to establish such a certification system, the technical background material describing and documenting the main properties and possible environmental influences of the product had to be available.
- **Work package 2 (WP2): Demonstration projects**
  The aim was to evaluate the use of RCA in already completed construction projects, and to launch various demonstration projects investigating the use of RCA in roads, trenches and different types of concrete structures.
- **Work package 3 (WP3): Dissemination of results**
  The aim was to make knowledge and experience from the project widely available through a project web site, technical reports, articles, papers, seminars, courses etc.

3. CERTIFICATION SYSTEM FOR RECYCLED AGGREGATE

As a part of WP1 of the RESIBA-project, a certification system for RCA was proposed, (Karlsen et. al., 2002a and 2002b). The proposed system was based on a similar certification system for natural aggregate, a Dutch certification system for RCA, in addition to European standardisation in general. The proposed certification system is based on the requirements for the production control system and includes documentation of the following main elements:

– Routines for the receiving of concrete and masonry rubble
– Routines for the production of RCA
– Routines for the testing and documentation of RCA

The producer is required to declare typical material properties, including acceptable/expected variation in material properties for the various RCA products made at the plant. The proposed certification system provides requirements with respect to test methods and minimum test frequency (see Table 1). The required testing and documentation shown in Table 1 separates between RCA for unbound (trenches and road base) and bound (concrete) applications. The certified producer is required to test and document the various RCA products according to Table 1 and notify customers if the test results are outside the declared maximum acceptable variation. In addition, a system for the classification of RCA based on material composition and use in unbound or bound applications is also introduced (see Table 2).

As of 2003, certification of RCA producers based on the system proposed by the RESIBA-project is being issued by the Norwegian certification agency Kontrollrådet for betongprodukter, (2002). This same agency is responsible for updating and revising the certification system for RCA when needed.

This certification system has also been adopted for the testing and documentation of RCA produced on-site, as, for example, at the ongoing demolition site of the former airport just outside Oslo, (Sylte, 2002). In addition, the Norwegian Public Roads Administration (NPRA), in co-operation with RCA producers, is currently evaluating the system for the testing and documentation of RCA. The main objective of this evaluation is to get an indication of the typical variations in material properties. Furthermore, the objective is to evaluate the validity of the various test methods, such as the Los Angeles method, when used for evaluating RCA.

Table 1. Test methods and minimum test frequency, (Karlsen et. al., 2002b)

Property to be tested	**Test method**	**Tested by (type of lab.)**	**Test frequency at continuous production**	
			Products for bound applications (concrete)	**Products for unbound applications**
Particle size distribution	EN 933-1	L [1]	Once every week or min. every 2000 tons	
Content of fines (< 0,063 mm for materials < 19 mm)	EN 933-1	L [1]	Once every week or min. every 2000 tons	
Content of mat.<0,020 mm for materials < 19 mm	NPRA - 14.434	L [1]	-	When required
Material constituents	prEN 933-11	L [1]	Once every week or min. every 2000 tons	
Organic materials [5]	EN 1744-1	L [1]	Once every week or min. every 3000 tons	-
Shape - Flakiness index (of materials > 8 mm)	EN 933-3	L/C/E [2]	Once every month	
Mechanical properties (Los Angles)	EN 1097-2	L/C/E [2]	-	Once every two weeks or min. every 10 000 tons
Density	EN 1097-6	L/C/E [2]	Once every two weeks or min. every 10 000 tons	
Water absorption	EN 1097-6	L/C/E [2]	Once every two weeks or min. every 10 000 tons	
Chloride content [5]	EN 1744-1	L/C/E [2]	Once every two weeks or min. every 10 000 tons	When required
Sulfur-containing compounds	EN 1744-1	L/C/E [2]	When required	When required
Chemical analysis [4] (Leaching test)	EN 1744-3	A [3]	-	Once every two weeks or min. every 10 000 tons

[1] Should be tested at the production site to allow for adjustment of production according to the results [2] Can be tested either locally, or at a central or an external laboratory [3] Should be tested either by a third party approved or accredited laboratory [4] Alternative methods might be accepted [5] The test frequency might be reduced by 50 % if pre-evaluation of the building is carried out according to Publication no. 26, (Norwegian Concrete Association, 1999)

Table 2. Classification of recycled aggregate. Constituents calculated as percentage by mass unless specified, (Karlsen et. al., 2002b)

	Type 1 "Crushed concrete"		**Type 2 "Mixed materials"**	
	A - Bound use	**B – Unbound use**	**A – Bound use**	**B – Unbound use**
Main material:				
Crushed concrete and/or natural aggregate	> 94 %		-	
Crushed concrete, crushed masonry and natural aggregate			> 90 % [1]	
Other granular material:				
Crushed masonry	< 5 %	< 5 %	-	-
Crushed asphalt	< 1 %	< 5 %	< 1 %	< 5 %
Non-mineral content:				
Wood, paper, metals, insulation materials*), organic materials**), plastics, glass, rubber, others	< 1 %		< 2,5 %	
*) Insulation materials	< 0,1 v. % [2]		< 0,5 v. % [2]	
**) Organic materials	< 0,1 v. % [2]		< 0,5 v. % [2]	
Density – oven dry [3]	> 2000 kg/m^3		> 1500 kg/m^3	
- saturated surface dry [3]	> 2100 kg/m^3		> 1800 kg/m^3	
Water absorption	< 10 %		< 20 %	

[1] For applications with material property requirements other than material constituents it is recommended to keep the percentage of concrete and/or natural aggregate at minimum of 80 %

[2] The content of organic materials and isolation materials should be calculated on based on volume

[3] To be tested according to EN 1097-6. The requirement should be fulfilled by at least one of the two.

4. RESIBA DEMONSTRATION PROSJECTS

4.1 Unbound use of recycled aggregates

A wide range of demonstration projects using RCA for various bound and unbound applications was initiated as a part of the RESIBA-project. As experience has shown in other countries, unbound application in road and highway construction is expected to be the most common and most profitable.

4.1.1 Roads and parking lots

In August 2000 the Oslo Public Roads Administration opened a new motorway through the Svartdal tunnel. A 50 m test section was established outside of the tunnel using approximately 600 tons of RCA 38-120 mm as sub-base. The thickness of the sub-base layer was approximately 0,9 m. In addition, a 20 m reference section was established using natural aggregates in the subbase layer. Plate loading tests were performed, measuring the modulus of elasticity of the two sections. Finally, the two sections are currently monitored measuring the rut depth and longitudinal evenness (International Roughness Index) of the road surface.

As expected, the initial modulus of elasticity was significantly lower for the test section consisting of RCA. The average E2-value (second loading) and the relationship E2/E1 of the RCA subbase was 106 MPa and 2,4 respectively, compared to 204 MPa and 2,0 for the reference section. The recommended values for subbase layers are $E2 \geq 150$ MPa and $E2/E1 \leq 2,5$, (NPRA, 1999) . However, after two and a half years of heavy traffic, the ongoing monitoring of the road surface does not indicate any significant difference between two sections, and there are no signs of the premature deterioration of the test section.

During the winter of 2000, the Oslo Public Roads Administration built a new pedestrian/cycle path using RCA as both the subbase and base layer for two 50 m test sections. In addition, a 50 m reference section was created. Again plate loading tests were performed, measuring the modulus of elasticity. The results reflected the same trend as the Svartdal tunnel.

Completed in 1999, Oslo Sporveier's (Oslo Public Transportation) new tramline over Gaustadbekkdalen in Oslo, included the use of approximately 4000 m^3 of RCA 38-120 mm as base material (0,4 - 1,4 m deep) on top of a lightweight filling. The project has been monitored by RESIBA, measuring deformation of the RCA base layer. After approximately two years, there is no significant difference in deformation between the various parts of the filling exposed to three different loading conditions (pedestrians, cars, and trams). The RCA base layer is also exposed to freeze-thaw action, but after almost three winter seasons, there are no signs of premature deterioration. All projects are presented by Myhre et. al. (2003).

4.1.2 Trenches and backfills

Full-scale laboratory testing conducted by the Norwegian Building Research Institute (NBI) indicated that RCA would function well as backfill materials in the pipe zone of utility trenches. This testing included extensive material documentation, in addition to functional characteristics such as:

- Load distribution - measured as deformation of flexible pipes
- Permeability - using Darcy's law modified for turbulent flow
- Stability - measured as deformation due to:
    - Washout of fines due to high volume water drainage
    - Crushing and deformation due to compaction and subsequent washout of fines
    - Crushing and deformation due to mechanical loading (simulated traffic load) and subsequent washout of fines

Natural aggregate was used as reference material for the purpose of comparison. In general, the functional characteristics for RCA were similar to those of natural aggregate. Some results are presented in Table 3.

Table 3. Results from full-scale laboratory testing, (Mehus et. al., 2002)

	RCA Type 1B*) 10-20 mm	RCA Type 2B*) 10-20 mm	Natural aggregate 8-12 mm
Particle density, ρ_{ssd} (g/cm^3)	2,49	2,43	2,84
Bulk density, ρ_b (g/cm^3) (non compacted/compacted)	1,26/1,37	1,23/1,31	1,41/1,59
Voids (%)**) (non compacted/compacted)	49/45	49/46	50/43
Permeability, k (m/s) 10^{-3} ***) (non compacted/compacted)	130/107	128/112	104/86

*) See table 1 for classification. **) Based on surface dry particle density. ***) Based on Darcy's law modified with a non-linear factor, φ = 0,65, for turbulent flow

The results presented in Table 3 show that RCA, 10-20 mm has even better drainage characteristics (permeability) than natural aggregate, 8-12 mm, which is frequently used as backfill material for utility trenches. Furthermore, the results show that the RCA bulk density ρ_b is significantly lower than natural aggregate.

Full-scale testing with repetitive mechanical loading (10 load steps) simulating heavy traffic load resulted in deformation of the PVC pipe embedded in RCA (8-12 mm) in the same range as when using natural aggregate (8-12 mm), (Mehus et. al. 2002).

Initial washout of fines due to high volume water drainage was significantly higher for RCA compared to natural aggregate. However, the washout was reduced to an insignificant level after a short period of time and did not cause any deformations. Mechanical loading (simulating traffic load) of RCA showed that the recycled material yielded a constant but somewhat higher deformation at a constant high load level when compared to natural aggregate, (Mehus et. al., 2002).

In a demonstration project, Asker municipality used about 1000 tons of RCA (10-20 mm) as backfill in a 600 m utility trench for water and gas drainage from a landfill, (Mehus et al., 2002) and (Ingebriktsvold, Mehus 2000). The project has been closely monitored measuring deformation at various levels and locations along the trench. The results show no significant difference in deformation between RCA and reference sections using natural aggregate.

4.1.3 Economic feasibility for unbound applications of RCA

Currently in Norway, the cost of RCA compared to natural aggregate is less than 50%. The number of suppliers, however, is limited and transportation to the construction site becomes an important factor for the actual cost . Also the bulk density of RCA compared to natural aggregate is significantly lower (see Table 3). This allows for a higher volume of aggregate to be transported on each truck. One truckload will, consequently, fill up a larger volume at the construction site. Thus, the cost of the RCA compared to natural aggregate is reduced even more. Unbound use of RCA as road base and as backfill in utility trenches does not generate any extra cost due to more elaborate handling procedures on site. Disregarding transportation cost, the use of RCA for unbound applications will be a significantly cheaper alternative.

4.2 Bound use of recycled aggregates

4.2.1 Concrete

As part of a demonstration project, the contractor, Veidekke ASA, incorporated the use of RCA in the construction of a new parking garage at Fornebu outside Oslo. For this project, 20 % of the coarse aggregate in the concrete foundations was replaced by RCA, (Lahus et. al., 2002a and 2002b). The concrete production and the casting were successful, and the laboratory test results show that the concrete met the material properties as specified. Laboratory testing of concrete consisting of 100 % RCA have also yielded positive results.

In another demonstration project, a new high school of approximately 13 000 m^2 just outside Oslo is currently being built by Akershus County Municipality. Construction started the summer of 2001, and the school will be ready for use by students by the fall of 2003. The decision to include the use of RCA at an early stage allowed recycled aggregates to be included as the main alternative in the bidding documents for the contractor. The use of RCA in the new building has been conducted in close cooperation with the design engineer, the contractor, the RCA supplier, and the concrete ready mix plant.

For this project, 35 % of the coarse aggregate was replaced with 10-20 mm RCA, Type1A (see Table 1) for the cast in place concrete (C35) in all foundations and 50 % of the basement walls and columns. The remaining walls and columns of the basement was cast using 100 % natural aggregates to allow for a comparison between the two concrete mixes. Extensive testing of both aggregates' properties, fresh concrete properties and hardened concrete properties were carried out. The testing of hardened concrete included compressive strength, density, modulus of elasticity, freeze-thaw durability, and shrinkage.

To reduce the risk of any future complications, concrete with RCA was not used for sections of the structure exposed to freeze thaw action. Test results later showed, however, that the concrete with 35 % coarse RCA had excellent freeze thaw resistance, (Mehus, Hauck, 2003), (Lahus et al., 2002a). Hardened concrete properties were comparable, and concrete production and casting was carried out without any problems. The use of 35 % RCA did not cause any noticeable increase in cracking.

4.2.2 Shotcrete

One of the world’s first uses of shotcrete incorporating RCA can be found at Oslo Sporveier's new tramline over Gaustadbekkdalen in Oslo, completed in 1999, (Farstad, Hauck, 2001), (Hauck, Farstad, 2001), (Lahus et al., 2002a). The vertical sides of an EPS lightweight filling is protected by 100 m^3 of shotcrete where up to 20 % of the sand, 0-4 mm was replaced by RCA. The contractor, Veidekke, successfully conducted the spraying, and the shotcrete met the material properties specified. Testing included determination of fresh shotcrete properties, mechanical properties, and durability characteristics. After four years of exposure to freeze-thaw action, the shotcrete does not show any signs of premature deterioration.

4.2.3 Building blocks

RCA has also been incorporated in the production of building blocks. Optiroc AS has produced Leca masonry sound insulation blocks using 30 % RCA, 4-10 mm. Laboratory testing demonstrates that all specifications for the Leca masonry sound insulation blocks were met, (Lahus et al., 2002a). RCA is now included as a part of the regular production of Leca masonry sound insulation blocks.

4.2.4 Economic feasibility for bound applications of RCA

Currently, the only commercial bound application of RCA in the Norwegian building and construction industry is the production of Leca masonry sound insulation blocks.

Despite positive results with respect to technical testing, production at the ready-mix plant, and handling at the construction site, production of regular concrete with RCA has not been made commercially available. The most important reason being that up until now only parts of the coarse aggregate have been replaced by RCA in demonstration projects. Consequently, any ready-mix plant using RCA will have to store and handle an additional type of aggregate. Most concrete ready-mix plants do not have extra aggregate bins, thus, making this virtually impossible. The relatively low cost for RCA does not compensate for the investment costs and increased handling cost associated with the use of RCA.

In general, the use of RCA for bound applications is unlikely to become a significant area of use in the Norwegian B&C-industry. However, the realisation that RCA can be used for bound application has been important for the reputation of RCA as a viable building material.

5. GUIDELINES

A clear aim of the RESIBA-project was to ensure the dissemination of results. A variety of papers, articles and detailed technical results are presented and discussed in depth in a series of seven project reports. In addition, a summary of the results and recommendations from the RESIBA-project are presented in a 20 page information brochure, entitled *Guidelines for the use of RCA*. These guidelines are not intended to provide detailed design specifications for consultants, but rather general orientation with easily accessible information about the most important areas of use for RCA in the Norwegian construction industry. The guidelines are available from the RESIBA website (www.byggforsk.no/prosjekter/RESIBA). The overall purpose of the guidelines is to increase the general awareness of RCA as a viable alternative to natural aggregates for a wide range of applications; subsequently, increasing the use of RCA in the Norwegian construction industry.

6. STANDARDS AND REGULATIONS

Norwegian design guidelines for highway construction is currently being revised by the NPRA. The new edition is expected to be published in 2003, and will incorporate results from the RESIBA-project. The new design guidelines will allow for the use of RCA as base material in road construction and backfill in utility trenches. Any producer supplying RCA for road construction purposes will be required to be certified or document the products according to the proposed system for certification from the RESIBA-project (see chapter 3). Requirements with respect to the material properties will be the same as the requirements used for natural aggregate. This is expected to be an important document in facilitating the increased use of RCA for unbound applications.

On a local level, the RESIBA project has initiated change as well. The city of Oslo has local standards and regulations related to the construction of utility trenches. These regulations are also being revised and will allow for RCA to be used as backfill material in utility trenches in Oslo, provided the producer is either certified or documents the recycled aggregate according to the proposed system for declaration from RESIBA (see Chapter 3).

In 1999, the Norwegian Concrete Association published recommendations for material documentation and design of concrete structures using recycled aggregate (NCA, 1999). According to the national application document of EN 206-1, it is required to follow this publication when using RCA in concrete structures (2002). It is expected that the NCA publication will be revised to incorporate results from national projects, such as RESIBA, as well as various international R&D work.

Thus, a first generation framework of regulations and design guidelines controlling the use of RCA in construction will be in place in Norway in the near future. This framework is expected to contribute to an increase in recycling and the use of RCA throughout the country. There are, however, several areas that will require further development and investigation before a complete framework is in place.

7. ONGOING RESEARCH

Following the RESIBA-project, the Norwegian Public Roads Administration (NPRA) have initiated a four-year (2002-2005) €2. mill. R&D program focusing on waste management, recycling, and reuse in the road construction sector in general (NPRA, 2002). This program will include other recycled materials such as asphalt, foamed glass, and tire cuts, in addition to recycled aggregate. An important part of the program addresses issues related to the possible environmental impact of recycled materials, (Engelsen et. al., 2003).

The part of the R&D program handling RCA (WP3) focus on unbound application of RCA as road base. The objective of WP3 is to provide suggestions for the revision of NPRA design manuals and regulations related to road construction, in order to fully establish RCA as an independent road construction material with material property requirements, test methods, etc. Modifying test methods to better suit for the documentation of RCA, such as testing methods for mechanical properties and freeze thaw resistance, will be emphasized. Furthermore, WP3 activities include evaluation of the proposed certification system from RESIBA and documentation of long-term durability characteristics for RCA.

8. CONCLUSION

The RESIBA-project has successfully documented that RCA is a viable alternative to natural aggregates for a wide range of applications. As in most other countries, unbound applications such as road and utility trenches, is expected to be the most important area of use. In general, the technical results in relation to RCA from various laboratory tests and demonstration projects conducted by RESIBA are positive overall.

A first generation framework of regulations and design guidelines controlling the use of RCA in construction will be in place in Norway in the near future. The process of further developing the regulation and design guidelines is ongoing.

The most significant challenge in the near future will be to increase the volumes of concrete and masonry delivered at recycling facilities throughout the country. Apart from the most densely populated areas around the 3-4 largest cities, separate recycling plants will not be able to operate continuously or to be economically feasible. Thus, alternative solutions are needed. One possible alternative would be to organize the delivery of concrete and masonry rubble to quarries already producing and selling natural aggregate. RCA would then be merely a supplement to the natural aggregate and only available occasionally.

In addition, better waste statistics are needed. To ensure further development, the recycling industry must be able to engage in future plans based on waste statistics and models, which provide a prognosis for the years to come. Investments in recycling facilities is currently relatively high risk, especially considering the supply of raw materials (rubble) is uncertain, and no available methods currently exists for making a prognosis of the future waste flow.

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