Unbound crushed concrete in high volume roads – Evaluation of field behavior and structural performance

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ABSTRACT: In Norway, recycled concrete aggregates were introduced in design codes for road construction in 2005, including material specifications. Until then, utilisation of these materials was limited due to the fact that the mechanical properties of the aggregates in many cases did not comply with the specifications concerning mechanical strength. However, a number of field projects have revealed good functional properties (proven suitability), showing that traditional test methods for mechanical properties are clearly not suitable for this kind of materials. A proper evaluation should be based on performance-related (functional) tests.

The paper discusses some of these field-lab contradictions with reference to a field trial at highway E6 south of Trondheim where recycled crushed concrete aggregates (RCA) has been used as sub-base layer since 2003 in a pavement designed for rather heavy traffic (Annual Daily Traffic > 10000).

Several field and laboratory tests were conducted before, during and after construction. In the laboratory, both empirical (traditional) and functional (new) tests were run, including use of a large-scale cyclic triaxial test apparatus. The triaxial tests showed very promising material properties, and also in field the materials behaved very well during laying and compaction.

Since then the structural performance and the surface characteristics have been followed up frequently, including FWD measurements with backcalculated layer stiffnesses, rutting and evenness (IRI) measurements. The registrations so far show very promising results.

These data and results, both from the field and laboratory investigations, have given valuable inputs to new Norwegian pavement design standards and has already encouraged further use of recycled/ secondary materials in Norway.

The work has been conducted as a part of a 4-year “Norwegian Roads Recycling R&D Program” of the Norwegian Public Roads Administration. The main objective of this program has been to facilitate more frequent and environmentally safe applications of recycled materials in road construction.

1 INTRODUCTION

In Norway, recycled concrete aggregate has recently (2005) been introduced in design codes for road construction, including material specifications. A number of field projects have revealed good functional properties (proven suitability), despite the fact that the mechanical properties of the materials in many cases do not comply with specifications concerning mechanical strength. Many traditional test methods for mechanical properties are clearly not suitable for this kind of materials. A proper evaluation should therefore be based on performance-related, functional tests (Reid 2000, Aurstad and Hoff, 2002).

Late autumn 2003 two test sections with unbound crushed concrete aggregates as sub-base layer were constructed as part of a new Highway E6 at Melhus, 20 km south of Trondheim, Norway. Two different concrete materials/fractions were tried out; 0-100 mm and 20-100 mm. A number of field measurements were conducted, both during and after construction, in order to gain further practical experience with these kinds of materials. Parallel to the field investigations, an extensive laboratory program was carried out on the same materials.

Since then the structural performance and the surface characteristics have been followed up frequently, including FWD measurements (with backcalculation of layer stiffnesses), rutting and evenness (IRI) measurements etc. The results from the registrations so far are summerized in this paper.

2 TEST SECTIONS

The E6 highway is the “backbone” of the Norwegian road network, stretching 2600 km from south-east to the very north of Norway. At this specific site at Melhus, the road is designed for ca 12.500 vehicles/day (annual daily traffic ADT = 12.500). The standard construction for this new road according to Norwegian design guides (Handbook 018) is 15 cm of asphalt on top of 65-85 cm crushed rock materials (dependant on subgrade) as shown in Figure 1.

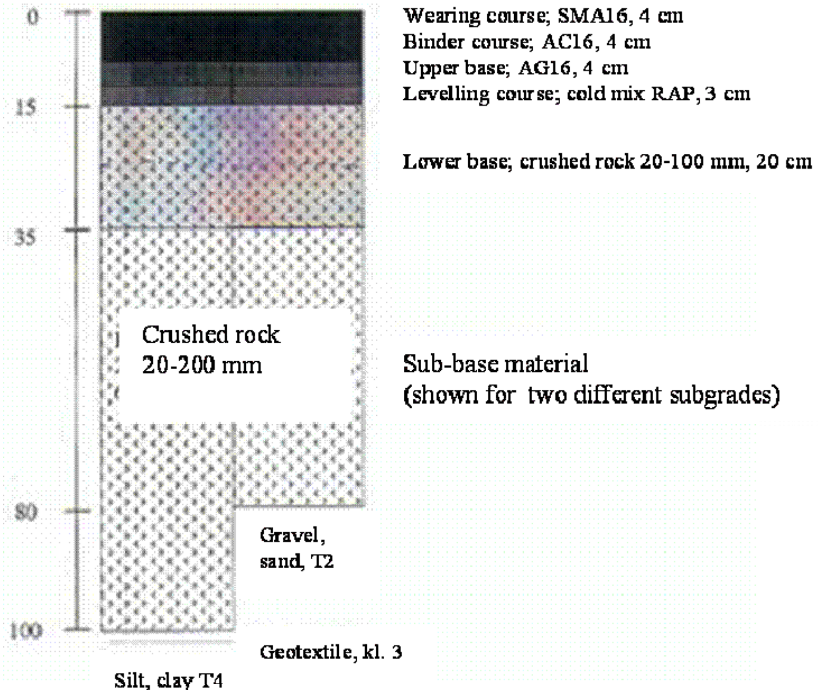


Figure 1. Pavement construction at E6 Melhus, layer details (shown for two different subgrades)

In order to compare the two alternative crushed concrete materials, two adjacent sections á 80 m were constructed on the test site, as shown in Figure 2. On these test sections the standard construction was modified by replacing the crushed rock sub-base (see Figure 1) with crushed concrete sub-bases of the same thickness. That is, the bearing capacities of these materials were assumed to be equivalent.

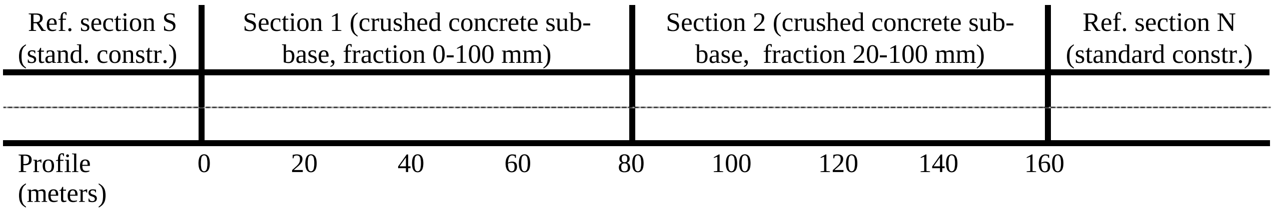


Figure 2. Test sections, E6 Melhus

3 MATERIALS

The origin of these alternative sub-base materials was discarded pre-fabricated element concrete, as shown in Figure 3.

Figure 3. Element concrete stockpile

The concrete elements were crushed in a mobile crushing mill which also separated (most of) the reinforcement. The crushed materials were then fractionated into the two required products, 0-100 mm and 20-100 mm (Aurstad et al 2005). After transportation to the test site, the materials were sprinkled with water before compaction in two layers á ca 30 cm (Figure 4).

Figure 4. Sprinkling of the crushed concrete materials was recommended before paving and compaction

Some knowledge could be gained almost instantly:
Workability: The contractor on this job had no previous experience with recycled materials and was rather sceptical. This caused discussions regarding procedures, type of rollers, need of water sprinkling etc. The effect of abundant water addition was soon clearly demonstrated, both visually and by levelling and plate bearing measurements. The materials performed very well during laying and compaction and only minor crushing and disintegration was observed. The workers were certainly positively surprised by the behaviour of the materials.
Contaminants: The importance of “clean”, well-sorted materials was also clearly demonstrated; during the first two hours of construction work three truck tires were punctured by remaining reinforcement steel bars!

The compaction was closely monitored with levelling and plate bearing tests for every two passes of the roller (up to 10 passes). Material samples were collected before and after compaction for sieve analyses.
After compaction, the in situ dry densities were detected as shown in Figure 5. These values were to be used as input parameters to the laboratory tests that followed.

Figure 5. In place detection of density/unit weight (sand replacement method)

Particle size distributions for the two crushed concrete materials are shown in Figure 6. Bold lines show the medium curves (also used as target curves for the triaxial tests, see 4.1). The curves comply with grading requirements for granular sub-base materials in the Norwegian specifications.

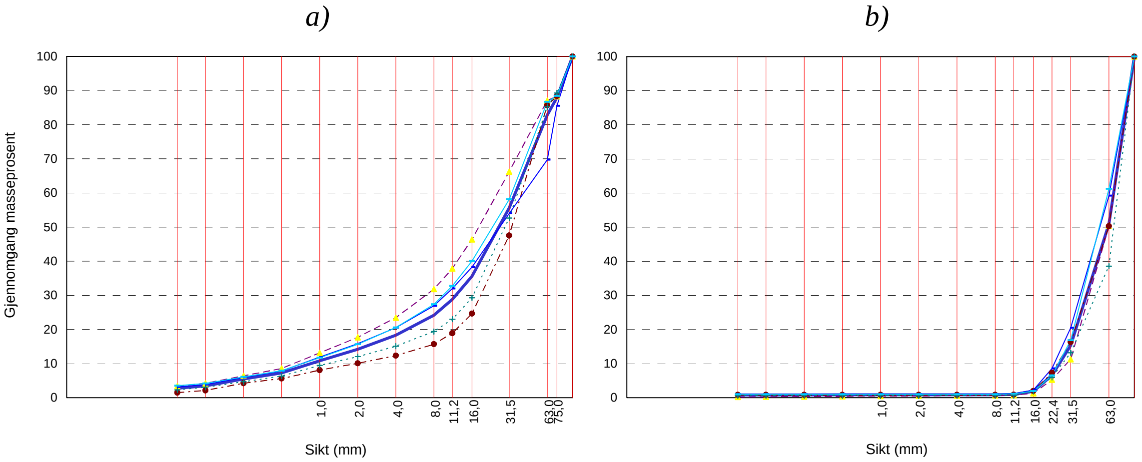


Figure 6. Crushed concrete before compaction; 0-100 mm (a) and 20-100 mm (b)

4 LABORATORY INVESTIGATIONS

4.1 Test methods

There is still some way to go to make alternative materials fully accepted, also in Norway. Partly this has to do with the fact that the materials are rejected in traditional lab tests, and do not in all cases comply with specifications concerning mechanical strength. At least some of the traditional test methods for mechanical properties are clearly not suitable for this kind of materials.

To get a picture of this for the Melhus materials, a laboratory program was carried out using both traditional (empirical) and new performance-based (functional) test methods.

The “traditional” investigations were:

- Grading (sieve analyses); samples taken before and after field compaction
- Density and water absorption
- Laboratory compaction characteristics; Modified Proctor and Gyratory compaction
- Resistance to fragmentation; Impact test, Los Angeles, Gyratory compaction
- CBR

The “performance-based” investigations were based on triaxial tests:

In order to make laboratory investigations relevant and comparable to field conditions, the materials should be tested as layers rather than as particles. Also the applied test loadings should be comparable to real traffic. Figure 7 shows the cyclic triaxial test apparatus developed by

NTNU/SINTEF in Trondheim, which has been used for testing of different granular materials in Norway the recent years, including the Melhus RCA materials.
This equipment allows for rather large scale sylindrical samples (d = 300 mm, h = 600 mm), thus materials with particle size up to about 60 mm can be tested (Skoglund 2002, Hoff 2004).

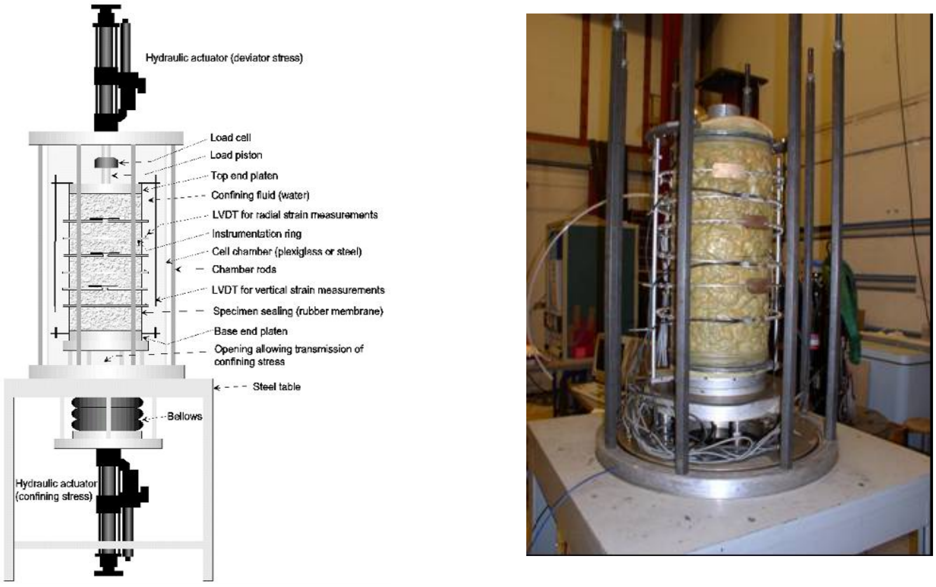
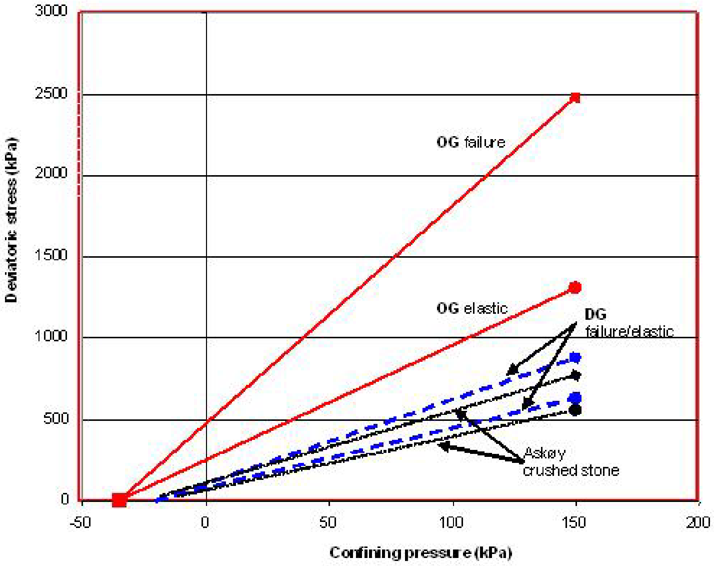


Figure 7. Large-scale triaxial test apparatus with mounted specimen of crushed concrete aggregate from E6 Melhus

The tests were carried out in accordance with EN 13286-7 “Unbound and hydraulically bound mixtures Part 7: Cyclic load triaxial test for unbound mixtures”. The specimens were compacted with same water content and to same density as measured in field (Figure 5). Open-graded and dense-graded material were compared by down-scaling the field materials from 0-100 mm/20-100 mm to 0-63 mm/20-63 mm. The testing was performed at stress levels equivalent to the sub-base conditions in field (on a road with heavy traffic).
From repeated load triaxial tests both elastic stiffness and resistance to permanent deformations can be derived. The elastic stiffness is expressed by E-modulus for a given mean stress level, while the deformation properties are expressed by elastic and failure angles, see Figure 8.



OG: Open-graded (20-60 mm)
DG: Dense-graded (0-60 mm)
Askøy: Reference crushed stone mat. (high quality)

Figure 8. Resistance to permanent deformations, crushed concrete E6 Melhus

4.2 Test results

In short, the laboratory investigations led to the following conclusions:

Mechanical strength: The material was of very good quality; both Los Angeles values (LA = 25-27) and impact values satisfy the Norwegian requirements set up for base and sub-base materials of crushed stone.

Water absorption tests showed that approximately 5 % water might be absorbed due to the porosity. This should be compensated by abundant water addition to improve workability and compactability and also reduce crushing and disintegration during construction. (This was clearly demonstrated in field during laying of the test sections.)

Fragmentation tests by use of gyratory compactor revealed that crushing mainly occured within the coarser particles, only minor increases in fines were detected.

Shear strength: CBR tests were carried out on the 0-19 mm fraction of the 0-100 mm material. The results revealed good bearing capacity/shear strength; CBR = 120-130.

Triaxial tests: Elastic stiffness and deformation resistance was investigated by use of the large-scale dynamic triaxial test apparatus.

Stiffness: The results revealed high elastic stiffness values compared to ordinary gravel or crushed rock materials; E = 350-650 MPa, with highest values for the open-graded 20-60 mm material (OG in Figure 8).

Deformation: Both elastic and failure angles were higher than for natural/ordinary materials. This implies that the crushed concrete materials should have very good properties regarding bearing capacity and stability (permanent deformation resistance).

(Here also the open-graded specimens (OG in Figure 8) got higher initial values than the dense-graded (DG). This picture seems to change as time goes by, see 5.1-5.2).

Relations to field: Sieve analyses showed that the triaxial test procedure gave a similar disintegration of the materials as the laying and compaction in field. Thus, with the same densities and water contents, the stiffness and deformation results from the lab testings should give a relevant picture of the in situ properties and hence an indication of the long term performance.

The immediate expectations after these initial lab testings were therefore that these recycled concrete materials should perform well as sub-base layers, also with traffic levels as high as on E6 Melhus (Aurstad et al 2006). But of course, many are anxious to see the real long term performance of the road.

5 FIELD INVESTIGATIONS, LONG-TERM PERFORMANCE

After construction of the E6 highway at Melhus in 2003, the road has been followed up with frequent field measurements and registrations. This Melhus project opened for (quite) extensive use of secondary materials. Thus both crushed asphalt, crushed concrete and light-weight foamglass materials have been utilised in the construction. Special emphasis however has been put on the test sections with recycled concrete aggregates.

As described, these materials behaved very well in the construction phase. And the laboratory tests also indicated good material quality and engineering properties. However, before “new” materials can be included in design guides and material standards etc, some proven durability and long-term field performance has to be demonstrated and documented.

The following measurements and registrations have been conducted on the test sections the past years:

- Plate bearing tests (mainly as compaction control, during and right after construction)
- FWD measurements
- Calculated axle load capacities (based on FWD data)
- Backcalculated construction layer stiffnesses (based on FWD data)
- Rutting (transversal evenness), ALFRED high speed profilometer
- Longitudinal evenness (IRI), ALFRED high speed profilometer

5.1 Bearing capacity, axle loads

Bearing capacity on Norwegian roads are often reported as "allowable axle loads" (in tons), a measure calculated from FWD data. Normally these registrations are done in spring (thawing period), that is in the weakest periods of the construction.

Figure 9 shows the latest results from FWD measurements on the E6 Melhus road. Norwegian roads are normally designed for a bearing capacity of 10 tons. The results reveal substantial higher bearing capacity on the test sections with RCA, compared with the standard reference constructions (both north (N) and south (S) of the test site). The section with RCA sub-base material fraction 0-100 mm seems to have the highest values.

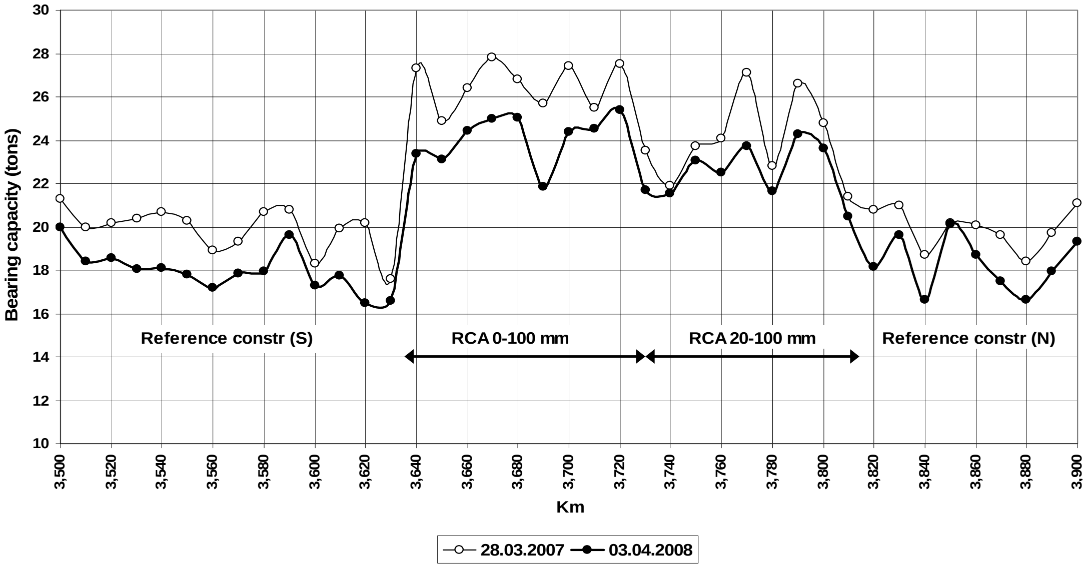


Figure 9. E6 Melhus; bearing capacity, thawing period (allowable axle loads, tons)

5.2 Bearing capacity, backcalculated sub-base moduli

From the FWD registrations, the E-moduli of each construction layer on the road have been backcalculated from the recorded deflections using linear elastic models. Figure 10 shows some of the 2005 and 2008 results for the sub-base materials. The different sections/ materials can be identified from the profiles (same as in Figure 9). The average values are summerized in Table 1.

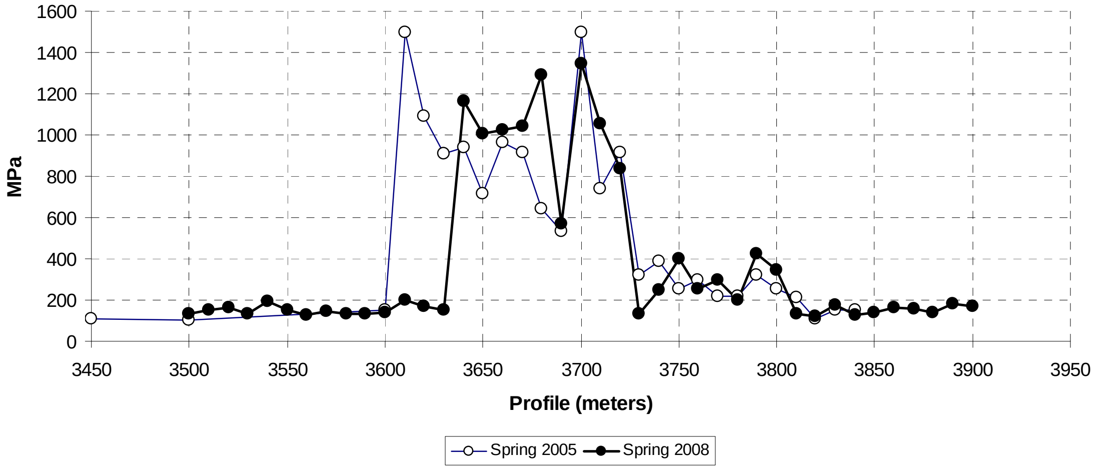


Figure 10. Sub-base stiffnesses at E6 Melhus (backcalculated E-moduli from FWD measurements)

Table 1. Sub-base stiffnesses at E6 Melhus (backcalculated E-moduli from FWD measurements)

	E-modulus (MPa)					
	2005			2008		
	Left line	Right line	*Average*	Left line	Right line	*Average*
Section 1 (RCA 0-100 mm)	904	875	*889*	1339	1037	*1188*
Section 2 (RCA 20-100 mm)	344	275	*310*	437	270	*354*
Reference sections (crushed rock 20-200 mm)	158	133	*145*	151	172	*161*

The first results (based on FWD measurements performed on pavement surface immediate after construction) showed that the test sections with crushed concrete and the reference sections with crushed rock material were more or less equivalent (E = 150 MPa). Since then, as shown in Table 1 and Figure 10, the crushed concrete layers have developed substantially higher E-moduli than the crushed rock material, which still is at about the same level as after construction. Most evident are the results for the dense 0-100 mm concrete material, that is the material containing fines.

Hardening effects in unbound crushed concrete layers have been reported in many projects the recent years, and then also clearly demonstrated here.

5.3 Road evenness

The surface condition of the Norwegian road network is closely monitored. Both longitudinal and transversal evenness (rutting) is measured at least once a year (national and county roads), combined with photos for every 50 m (Ferne, 2008). These data are stored in a National Road Data Bank and are used for different purposes; statistics, overall and detailed budgeting, pavement management etc. Insufficient bearing capacity in the sub-base may lead to deformations, therefore monitoring of rutting and also longitudinal evenness (IRI) is of special interest on roads with alternative materials/technical solutions, such as E6 Melhus.

Evenness data for E6 Melhus is shown in Figure 11 and Figure 12.

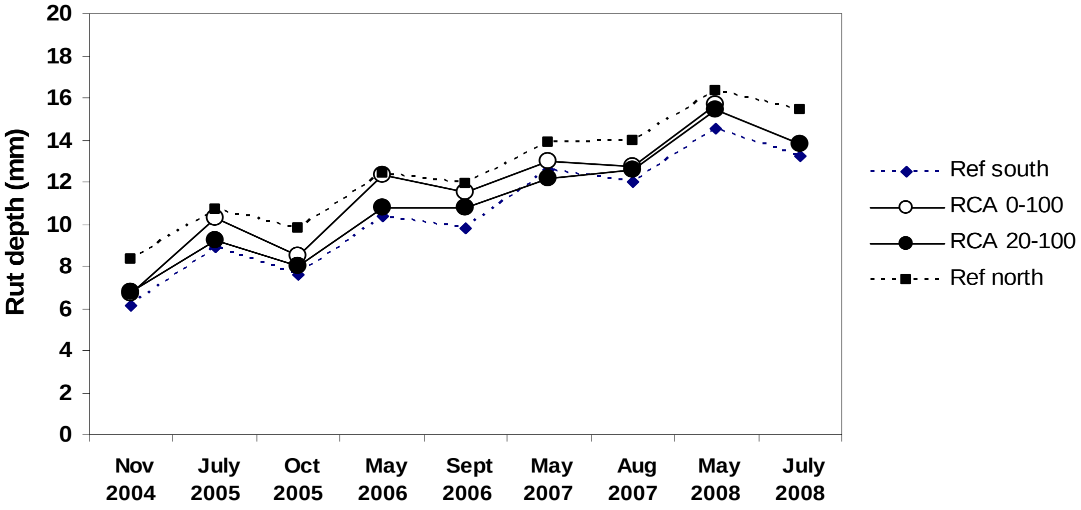


Figure 11. Rutting (transversal evenness), measured by ALFRED device

Threshold (“trigger”) rut depth value for maintanence/repaving on high volume pavements in Norway is 25 mm. Hence, no dramatic development can be observed on the test sections. The rutting on the alternative constructions is equal to the reference constructions. The major part of these ruts comes from the winter season (there is quite extensive pavement surface wear from studded winter tyres in Norway).

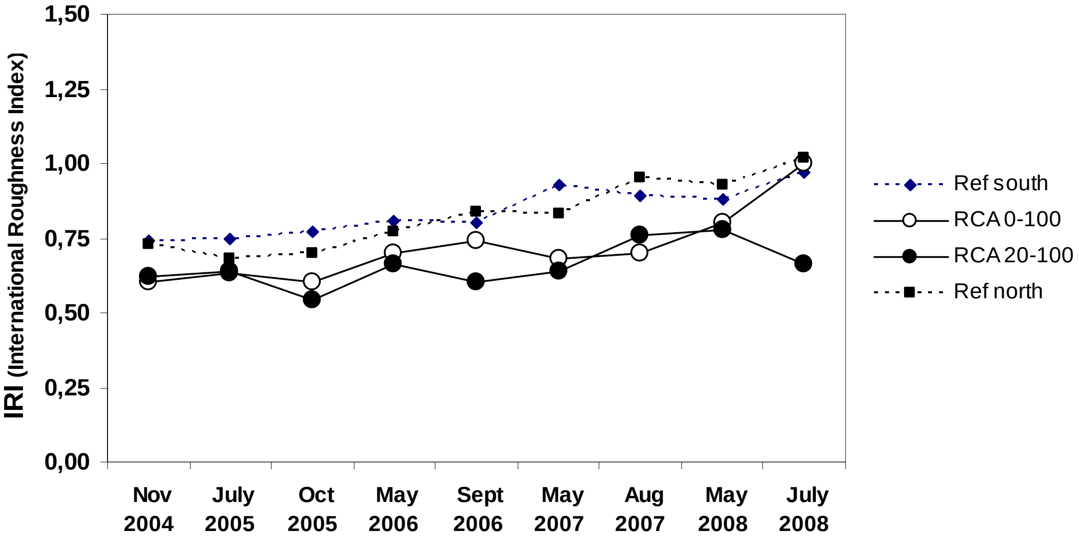


Figure 12. Longitudenal evenness (IRI), measured by ALFRED device

Threshold ("trigger") IRI value for maintanence/repaving on high volume pavements in Norway is IRI = 4.0. All values in Figure 12 are far below (better than) this level. And the sections with RCA are in fact the most even parts.

6 SUMMARY AND CONCLUSIONS

On a new highway E6 south of Trondheim, Norway, unbound crushed concrete has been tried out as alternative sub-base material. Two test sections were established in 2003 in order to compare the fractions 0-100 mm (dense-graded) and 20-100 mm (open-graded) RCA. Both materials came from the same source; a stockpile of discarded new element concrete.

During construction the material properties in situ were studied by different kinds of measurements; levelling, plate bearing tests and FWD tests. One of the objectives was to gain more practical experience with these materials (handling, workability, compaction etc.).

It was demonstrated that these materials can behave very well during construction, given that some precautions are taken (good separation from reinforcement, sufficient water addition, careful laying and compaction etc.). Another objective was to link field and laboratory behaviour. An extensive laboratory program was carried out including both empirical and performance-based tests. The performance-based laboratory investigations showed very promising values, especially the stiffness and deformation results from the large-scale triaxial device were positive.

During the years after construction, field measurements have been repeated frequently to monitor the long-term behaviour of the constructions. Any detection of hardening effects in the crushed concrete layers has been of special interest for the follow-up programme.

The main conclusions are as follows (after 5 years of field monitoring):

Bearing capacity: FWD measurements after construction have shown substantial increase in bearing capacity and stiffness on the crushed concrete sections. This is most evident on the section with 0-100 mm material, where backcalculations give crushed concrete E-moduli in the order of 900-1400 MPa.

Evenness: Ultrasonic and laser measurements on the road have so far revealed very satisfying surface conditions. IRI measurements show a very smooth and high quality surface over the test sections; IRI = 0,5-1,0. Also regarding rutting no differences can be observed between the RCA sections and the reference sections. (NB! The major contributor to the rutting on these pavements is studded winter tyre wear, which is a surface mechanism.)

These measurements will be repeated frequently to monitor the long-term behaviour of the constructions. Any further hardening effects will hopefully be detected by the follow-up programme.

According to the results from this project, recycled crushed concrete material should perform excellent as unbound sub-base layer in roads, even with traffic levels as high as on E6 Melhus.

Figure 13. New E6 Melhus, autumn 2003 and summer 2008

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