UNBOUND CRUSHED CONCRETE IN HIGH VOLUME ROADS – A FIELD AND LABORATORY STUDY

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ABSTRACT

In Norway, recycled concrete aggregate has recently 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. 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.

The paper discusses these field-lab contradictions with reference to a field trial at highway E6 south of Trondheim where crushed concrete was used as sub-base layer in a pavement designed for rather heavy traffic (ADT > 10000).

Several field and laboratory tests have been conducted before, during and after construction, and the paper is focusing on comparing field tests with both empirical (traditional) and functional (new) laboratory tests, including a large-scale cyclic triaxial test apparatus.

The road was constructed 2003-2004, and will be followed up by frequent bearing capacity (FWD), rutting and evenness (IRI) measurements. Preliminary registrations show very promising results for all these parameters.

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

1 INTRODUCTION

In Norway, recycled concrete aggregate has recently 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.

Late autumn 2003 two test sections with unbound crushed concrete 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.

2 TEST SECTIONS

The E6 highway is the “backbone” of the Norwegian road network, stretching 2580 km from south-east to the very north of Norway. At this specific site at Melhus, the road is designed for an annual daily traffic ADT = 12.500. The standard construction for the new road is 15 cm of asphalt on top of 65-85 cm crushed rock materials as shown in Figure 1. On the test sections, shown in Figure 2, the construction was modified by replacing the 45-65 cm crushed rock sub-base with a crushed concrete sub-base of the same thickness. This implies that the bearing capacities of these materials were assumed to be equivalent.

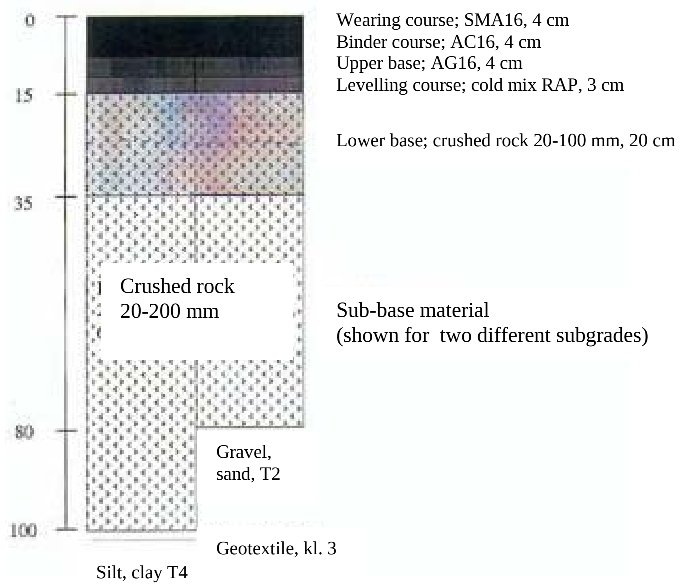

Figure 1: Pavement construction at E6 Melhus, layer details

In order to compare the two alternative crushed concrete materials, two adjacent test sections á 80 m were constructed, as shown in Figure 2. For practical (engineering) studies, one side was compacted with a lightweight roller (6 tons) and the other side with a heavy roller (15 tons).

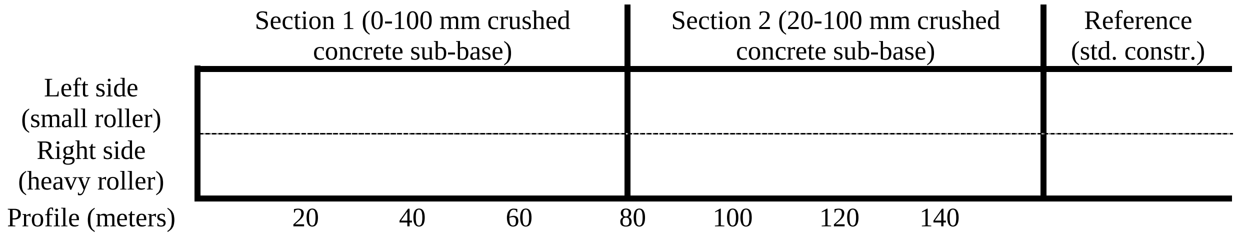

Figure 2: Test sections, E6 Melhus

3 MATERIALS

The origin of the 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.

Figure 4: Material production; crushing and separation of reinforcement bars

Figure 5: Material production; sieving and transport

After dumping on the test site, the materials were sprinkled with water before compaction in two layers á ca 30 cm (Figure 6).

Figure 6: Sprinkling of crushed concrete materials is recommended before paving and compaction

4 FIELD INVESTIGATIONS

Norwegian experience with recycled concrete aggregate as road material is still limited. However, some field projects carried out in the recent years in Norway have revealed good functional properties and proven suitability og recycled concrete aggregate as road copnstruction material (Aurstad and Hoff, 2002). An important part of the E6 Melhus project has been to gain further practical experience regarding handling, workability and compaction properties (compared to traditional crushed rock materials).

The following in-situ measurements/registrations were conducted by Statens vegvesen/Public Road Administration (Dahlhaug, 2004):

- Density/compaction effects (comparing small vs. heavy roller); levelling, visual evaluation, disintegration, sieve analyses
- Bearing capacity; plate bearing tests, FWD measurements

After compaction, the in situ dry densities were detected as shown in Figure 7. These values were to be used as input to the laboratory tests that followed.

Figure 7: In place detection of density/unit weight (sand replacement method)

Some learning could be gained almost instantly, while other developments have been observed this year (2005):

Workability: The contractor on site (Mesta) had no previous experience with these materials and was somewhat 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!

Figure 8: Remaining steel bars may cause a lot of trouble

Compaction: A detailed program was worked out including levelling and plate bearing tests for every two passes of the rollers (up to 10 passes). Material samples were also collected for sieve analyses.

The results revealed no immediate adventages of using the heavy compactor, no significant differences between left and right side (Figure 2) were recorded. For section 2 with the coarser 20-100 mm material, max density (after 10 passes) was in fact obtained with the small 6 tons roller.

Evenness: IRI measurements two years after construction (October 2005) showed a very smooth and high quality surface over the test sections (IRI = 0,68).

Bearing capacity: Plate bearing and FWD tests have been conducted on the test sections and on a reference section with standard pavement construction (Figures 1 and 2). 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 section with crushed rock material were more or less equivalent regarding bearing capacity. More interesting results could be observed in summer 2005, 1½ year after construction. As shown in Table 1 the crushed concrete layers then revealed substantially higher E-moduli than the crushed rock material, which was at the same level as after construction.

Most dramatic are the results for the dense 0-100 mm concrete material. Those values have increased radically. Hardening effects in unbound crushed concrete layers have been reported in many projects the recent years, and then also clearly demonstrated here.

Table 1: Sub-base stiffnesses at E6 Melhus (back-calculated E-moduli from FWD measurements, April 2005)

	E-modulus (MPa)		
	Left side	Right side	Average
Section 1 (0-100 mm crushed concrete)	904	875	889
Section 2 (20-100 mm crushed concrete)	344	275	310
Reference section (20-200 mm crushed rock)	171	145	158

These measurements will also 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.

5 LABORATORY INVESTIGATIONS

There is still some way to go to make alternative materials fully accepted. 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 parallell to the field investigations. Both traditional (empirical) and new performance-based (functional) test methods were performed;

- 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
- Repeated load triaxial test

5.1 Basic characterisation

Grading: Particle size distributions for the two crushed concrete materials are shown in Figure 9. Bold lines show the medium curves (also used as target curves for the triaxial tests, see 5.3). The curves comply with grading requirements for granular sub-base materials in the Norwegian specifications (Handbook 018, 2005).

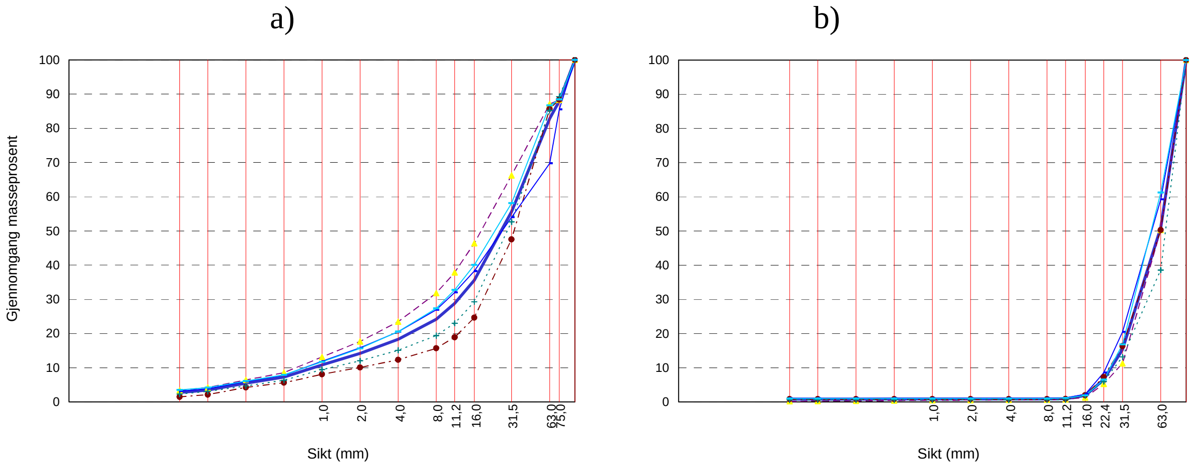

Figure 9: Crushed concrete before compaction; 0-100 mm (a) and 20-100 mm (b)

Curves for material samples taken on the road after compaction are shown in Figure 10.

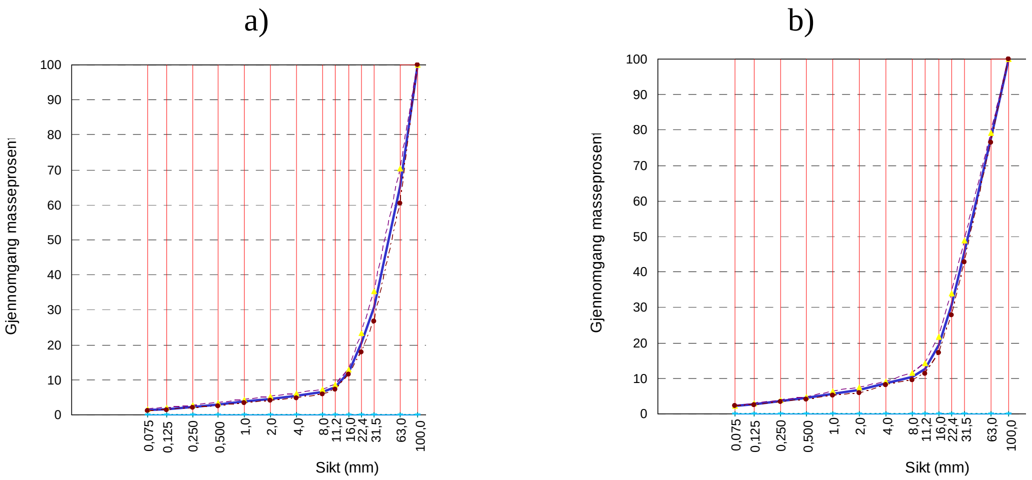

Figure 10: Crushed concrete (20-100 mm) after compaction; 10 passes of heavy weight (a) and light weight (b) roller

By comparing Figures 9b) and 10, the crushing and fragmentation of the coarser material during construction can be estimated. As mentioned, no significant differences in compaction effects were observed between the two rollers.

Water absorption: Due to the porosity, these aggregates will in some cases behave quite differently from natural materials. Hence, water absorption is an important parameter for materials as crushed concrete. Some precautions are recommended in order to avoid fragmentation, such as water sprinkling (Figure 6). Data for the Melhus materials are shown in Table 2.

Table 2: Water absorption and densities, crushed concrete E6 Melhus

Test fraction	Particle density, apparent (g/cm^3)	Particle density, oven dry (g/cm^3)	Particle density, surface dry (g/cm^3)	Water absorption (%)
0,075 - 4 mm	2,76	2,40	2,53	5,5
4 – 31,5 mm	2,78	2,51	2,61	3,9

Compaction characteristics: The fact that ca 5 % of water will be absorbed by the aggregate, substantially increases the optimum water content for efficient field and laboratory compaction. The optimum water content was detected both by traditional impact method (Modified Proctor) and by use of Gyratory compactor. The results are shown in Table 3. Some differences can be observed, the gyratory procedure seems to give a more efficient compaction than the impact procedure (Proctor).

Table 3: Compaction characteristics, crushed concrete E6 Melhus

	Test fraction	Max dry density (g/cm^3)	w opt (%)
Modified Proctor	0-19 mm	1,98	14,0
Gyratory compactor[1]	0-19 mm	2,14	9,5

[1] Diam 150 mm, 400 kPa, gyratory angle 1 °, 50 cycles, specimen size 6500 g

5.2 Mechanical strength

Resistance to fragmentation: Both impact test (Norwegian procedure), Los Angeles test and crushing test using Gyratory compactor have been conducted. CBR tests were carried out on the 0-19 mm fraction of the 0-100 mm material. The results are summerized in Table 4.

Table 4: Mechanical strength, crushed concrete E6 Melhus

	Test fraction	Test results	Requirements (granular sub-base)	Remarks
Norwegian impact test	8-11 mm	Impact value: $s_8 = 50$ Shape index: f = 1,38	$s_8 < 60$ f < 1,60	OK! (These req. are in new spec. replaced by Los Angeles req.)
Los Angeles	10-14 mm 31,5-50 mm	LA = 27,3 LA = 25,7	LA < 40 (35)	OK!
Gyratory compactor[1]	0-20 mm 10-20 mm		No req.	
CBR	0-19 mm	$CBR_{0,1} = 95$ $CBR_{0,2} = 125$	No req.	

[1] See separate discussion

Gyratory compactor: An ICT 150 Gyratory compactor test program was set up for the Melhus materials, in accordance with the recommendations from the ALT-MAT project, which concluded that more emphasis should be put on performance-related test methods such as cyclic load triaxial tests and gyratory compaction (Reid, 2000). Due to sample size limitations, the field materials had do be down-scaled to lab-test fractions 0-20 mm and 10-20 mm ("dense-graded" and "open-graded" respectively). The following parameters were considered to be of special interest;

- effects of grading (0-20 mm vs. 10-20 mm)
- effects of water addition (dry vs. w_{opt})

- effects of compaction effort (50 vs. 250 revolutions/cycles)

For each specimen the increase in density and shear resistance during compaction was recorded. Finally, the particle size distribution curves were compared (before vs. after compaction). The following conclusions could be drawn:

- Grading: Only minor generation of fines (< 1,6 mm) was observed during the test, between 1-2 % for both materials. Crushing of the open-graded material mainly took place in the coarser part (changes on sieves 10 and 16 mm). On the dense-graded material hardly any crushing of the coarser particles could be observed.
- Effects of water: High density levels were most easily achieved for the wet samples (better workability). No substantial differences in crushing were observed between wet and dry samples at 50 cycles. When moving from 50 to 250 cycles, more crushing was observed in the dry samples (particulary the open-graded material).
- Compaction levels: The major compaction took place during 0-50 cycles. Only 3-5 % increase in density was observed when continuing the compaction from 50 to 250 cycles, while the crushing increased considerably. Thus, high compaction efforts are questionable (also in accordance with the field observations).

So far, no criteria have been established in Norway for this type of investigation, making this work an introductory approach. Further studies have to be done on more materials before gyratory results can be used to evaluate functional properties of granular alternative materials.

5.3 Functional properties

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. The following performance-based procedure has been conducted on the Melhus materials;
Cyclic triaxial test (large scale, d = 300 mm, h = 600 mm).

Apparatus:
The testing apparatus, test procedure, sample preparation procedure etc is developed by NTNU/SINTEF in Trondheim (Skoglund, 2002). This equipment allows for testing materials with particle size up to about 60 mm. The apparatus is shown in Figure 11.
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*".

For the two Melhus materials, particles > 63 mm were sorted out and replaced with 30-63 mm material, giving the following test fractions;

- 0-63 mm (dense-graded)
- 20-63 mm (open-graded)

Only the part > 63 mm differs these from the materials used on the road.

Field densities and water contents were measured in situ after compaction (Figure 7). These became the target values when compacting specimens for triaxial tests in the lab. Two parallel samples of each fraction were tested. As can be seen from Table 5, the twin samples were almost identical.

Table 5: Specimens for large-scale triaxial tests, crushed concrete E6 Melhus

Sample	Density (kg/dm^3)	Water content (%)
DG 1 (0-63 mm)	2,17	7,8
DG 2 (0-63 mm)	2,16	7,8
OG 1 (20-63 mm)	1,81	4,9
OG 2 (20-63 mm)	1,82	4,9

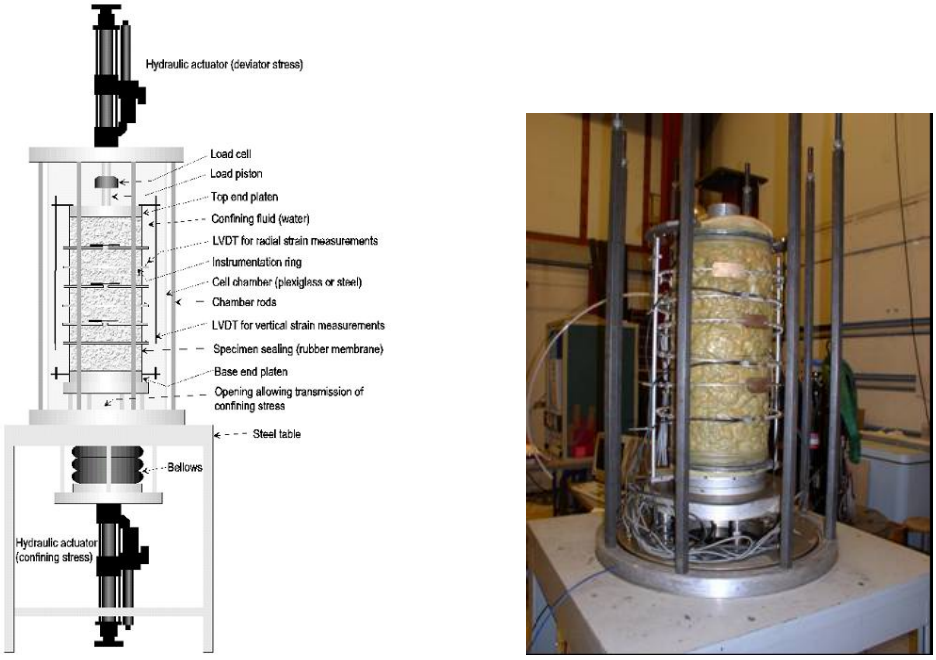

Figure 11: Large-scale triaxial test apparatus at NTNU/SINTEF with mounted specimen of crushed concrete from E6 Melhus

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* as shown in Figure 12.

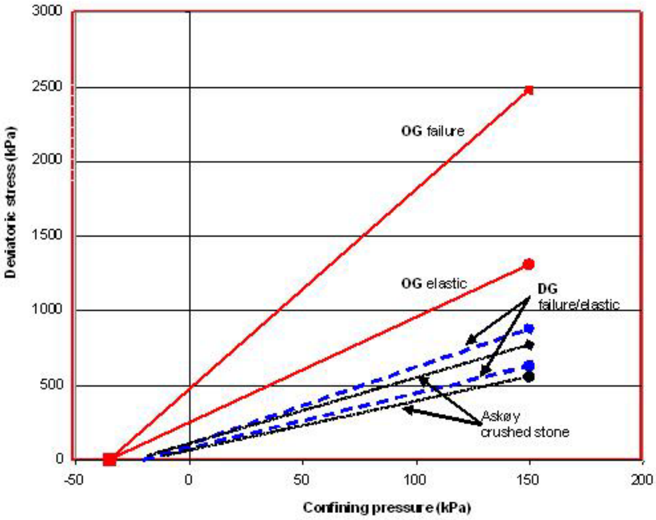

Figure 12: Resistance to permanent deformations, crushed concrete E6 Melhus

The results are summarized in Table 6.

Table 6: Results from cyclic load triaxial tests, crushed concrete E6 Melhus

Sample	E-modulus [1] (MPa)	Elastic angle Sin(ρ)	Failure angle Sin(ϕ)
DG 1 (0-63 mm)	350	0,63	> 0,70
DG 2 (0-63 mm)	450	0,67	> 0,75
OG 1 (20-63 mm)	400	0,50[2]	0,65[2]
OG 2 (20-63 mm)	650	0,78	> 0,87
Reference; Askøy crushed rock [3]	450	0,50	0,65

[1] *mean stress 200 kPa* [2] *questionable values* [3] *(Hoff, 2004)*

Stiffness:
The stiffness of the crushed concrete is higher than normal values for Norwegian unbound crushed rock materials. The open-graded (OG) samples reveal slightly higher values than the dense-graded (DG) samples.

Deformation properties:
Both failure and elastic angles are high (especially for OG) compared to natural granular base and sub-base materials. The results indicate that the crushed concrete materials should have very good properties regarding bearing capacity and stability (permanent deformation resistance).

Crushing/fragmentation during the triaxial test:
The triaxial test specimens were sieved after testing and the grading curves compared to the initial curves before testing as shown in Figure 13.

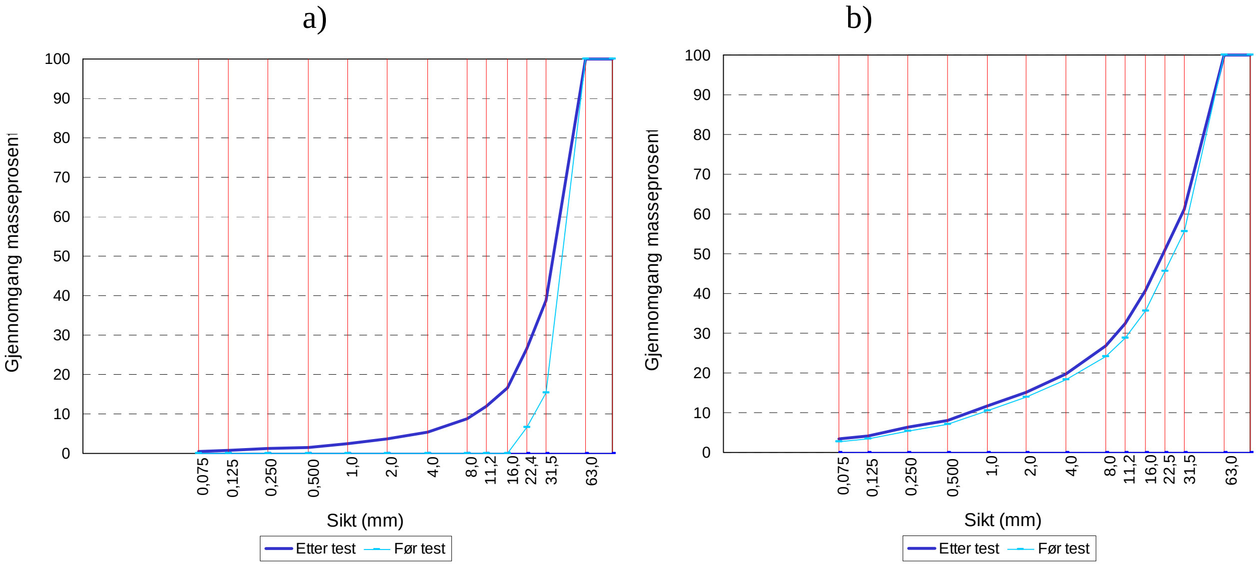

Figure 13: Grading curves before (thin) vs. after (bold) triaxial tests, samples OG1 (a) and DG1 (b)

When comparing Figure 13 to samples taken from field (Figure 10) we see that the curves for the open-graded material are almost identical. The materials seem to have had same crushing during field compaction as in the triaxial testing procedure. Thus, with the same densities and same water contents, the laboratory results should give a representative picture of the material properties in field.

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 (late 2003). Two test sections were established in order to compare the fractions 0-100 mm (dense-graded) and 20-100 mm (open-graded). Both materials came from the same source; 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.). Another objective was to link field and laboratory behaviour. An extensive laboratory program was carried out including both empirical and performance-based tests.

The main conclusions are as follows:

Laboratory results

Mechanical strength: The current material was of very good quality; both Los Angeles values and impact values satisfy the requirements set up for base and sub-base materials of crushed stone. Water absorption tests show that approximately 5 % water may 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. Fragmentation tests by use of gyratory compactor reveal that crushing mainly occurs within the coarser particles, only minor increases in fines are detected. *(The effects of crushed concrete fines on frost heave/ frost susceptibility are to be investigated in a separate study.)*

Shear strength: CBR-tests reveal good bearing capacity/shear strength, CBR = 120-130.

Triaxial tests: Elastic stiffness and deformation resistance was investigated by use of a large-scale dynamic triaxial test apparatus. The specimens were compacted with same water content and to same density as in field. 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).

Stiffness: The results reveal 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).

Deformation: Both elastic and failure angles were higher than for natural/ordinary materials (here also the open-graded specimens got the highest values). This implies high stability and good permanent deformation resistance.

Relations to field: Laboratory compaction tests by gyratory compactor showed minor increase in density levels when exceeding 50 cycles, while crushing of the materials accelerated. This corresponds well with what was observed in field, only small effects were detected by using a heavy roller (15 tons) instead of a 6 tons roller. In that respect, the behaviour of crushed concrete materials seems to be substantially different from crushed asphalt or crushed rock, and should be emphasised when working with these materials.

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.

Field behaviour

Bearing capacity: FWD measurements on the road 1½ year after construction have shown substantial increase in 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 800-900 MPa.

Evenness: Laser measurements on the road 1½ year after construction reveal very satisfying surface conditions; IRI = 0,5-1,0.

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 14: New E6 Melhus, autumn 2004

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