Performance assessment and ranking of natural and recycled granular materials for road subbase layers by precision cyclic triaxial testing (EN 13286-7)

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ABSTRACT: The cyclic load triaxial test is a laboratory test that allows investigating the mechanical behaviour (resilient and permanent strains) of unbound granular materials used in subbase and capping layers of roads. The resilient modulus and permanent strains are required to assess material performance and serve as key input properties in modelling and designing roads.

This paper will present the investigation of resilient and permanent strains as specified by European standard EN 13286-7, for a limestone aggregate and recycled materials (one crushed concrete aggregate and two blended crushed waste aggregates) used in subbases and capping layers of road structures in Belgium. Method B (constant confining pressure) was used in most of the tests for resilient strains. The influence of water content was also analysed. Permanent strains were analysed after conditioning by 20,000 cycles of single-stage loading.

The paper will also present the results obtained on the limestone aggregate only in analysing resilient strains with both axial and confining cyclic loading – method A. The resilient moduli were deduced from the test results and compared to those obtained with method B.

The calibration of the LDT's (Local Deformation Transducer) in air proved to remain valid when they were used in water (variable confining pressure tests).

The natural and recycled materials were ranked starting from the characteristic values of resilient modulus and characteristic permanent axial strain. This ranking based on a mechanistic approach was compared with conventional ranking based on indicative properties determined in empirical tests.

This research work produced an excellent set of findings for the mechanical characterization of unbound subbase materials through the cyclic triaxial test, thus contributing to a more widespread and common use of recycled materials in geotechnical engineering.

KEY WORDS: Cyclic triaxial testing, unbound aggregates, recycling.

1 DESCRIPTION OF THE EQUIPMENT

The cyclic load triaxial test apparatus makes it possible to simulate in the laboratory the behaviour of unbound materials used in subbase and capping layers of road pavements under moving loads. Work by Corté (1994), Paute et al. (1994), Balay et al. (1998), Gomes Correia (1999) and Gomes Correia (2004) illustrated the use of this test to determine the resilient and permanent strains of as-dug granular materials while investigating the influence of parameters such as water content, dry density, or the method of compaction.

In this test, a cylindrical specimen is subjected to cyclically varied axial stresses (σ_1) and a confining pressure (σ_3). For a given stress state, the confining pressure either remains constant (CCP tests) or varies in phase with the axial stress cycles (VCP tests). CCP tests are performed with air as confining fluid. VCP tests require an incompressible confining fluid; deaerated water is used for that purpose.

The test allows defining, on the one hand, the resilient modulus required as an input in design calculations for road structures and, on the other hand, the permanent strains related to rutting. The cyclic triaxial test equipment presented in this paper was developed by CVR "Centro para a valorização de residuos" in Guimarães (Portugal). The equipment was described in Grégoire et al. (2009).

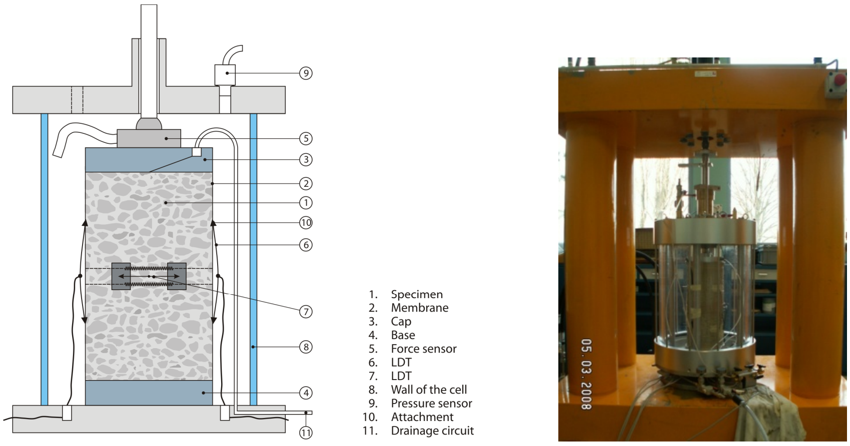

Figure1 – Setup and equipment for cyclic triaxial testing at BRRC

2 DEFORMATION MEASUREMENTS – USE OF LDTS IN WATER

Standard EN 13286-7 does not specify what type of deformation sensor (linear variable displacement transducer, hall effect deformation transducer, local deformation transducer (LDT), etc.) should be used. On the other hand, it requires the use of at least two transducers for axial deformations and at least one transducer for radial deformation.

For our research, we chose to use LDTs for measuring resilient deformations, because there are quite convenient for granular materials and do not require the installation of studs in the specimen. Moreover, LDTs are capable of measuring deformations smaller than 10^{-5} and have good resolution for strains up to 2 % (Goto et al., 1991; Hoque et al., 1997).

LDTs consist of four strain gauges forming a full Wheatstone bridge, glued to a thin flexible strip of phosphor bronze (Goto et al., 1991; Hoque et al., 1997) with a low coefficient of thermal expansion. Four LDT sensors are attached to the specimen: three to measure axial strains and the fourth to measure radial strain.

In conditioning the specimens (20,000 cycles) for the VCP tests, the LDTs were not used. LDTs can lose their water resistance when the stress levels and the number of cycles are high (as it is the case during the conditioning process). In that case we used a linear transducer. This is an external transducer measuring the movement of the piston. It has no direct contact with the specimen. This transducer was also used to measure permanent strains.

After conditioning for the VCP tests, the triaxial cell was emptied, the LDTs were installed and the cell was filled again with water.

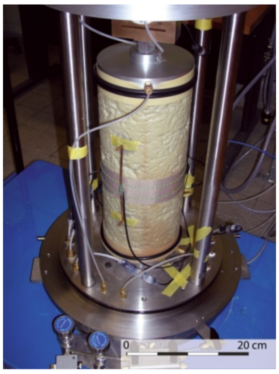

Figure 2: LDTs installed on a specimen

Calibrations by the Belgian Road Research Centre were made by means of a device fitted with a micrometer having a resolution of 10 microns and a range of 25 mm. The micrometer was used to check the movements of the LDTs. The axial LDTs were calibrated at intervals of 0.1 mm over a relative displacement of the attachments of 4 mm – corresponding with a strain of 2 % –, both in loading and release. The radial LDTs were calibrated at intervals of 0.1 mm for a relative displacement of the attachments of 2 mm, in both loading and release. For each LDT position data was captured for some ten seconds, to define a mean voltage. A second-degree polynomial describing the “distance between attachments / voltage” relation was defined for each calibration. The hysteresis between the curves in loading and release was small. The successive calibrations demonstrated good repeatability of “distance between attachments / voltage” curves.

These calibrations were performed in air. Tests were performed to check if the calibration remained valid when the LDTs were used in water (VCP test). Three vertical LDTs were attached to a specimen. 10,000 cycles were applied (constant confining pressure of 70 kPa and a deviatoric stress with a maximum of 340 kPa), to stabilize the permanent deformations. Then, under a constant confining pressure of 70 kPa, five stress levels were applied to the specimen (deviatoric stress with a maximum of 115, 150, 200, 280, and 340 kPa) – one hundred cycles per level. The vertical strains were recorded. Then the cell was filled with water, and the same stress levels were applied to the specimen. The cell was emptied and the stress levels were applied again to the specimen in air.

The voltages and the strains (calculated using the calibration in air) were compared. Very small variations between the curves were observed, but they were not due to the change of confining fluid. They also appeared between the two curves measured in air. We did not observe any shift in voltage with the change of fluid. This was an important conclusion. It meant that the calibration of LDTs in air remained valid when the LDTs were used in water.

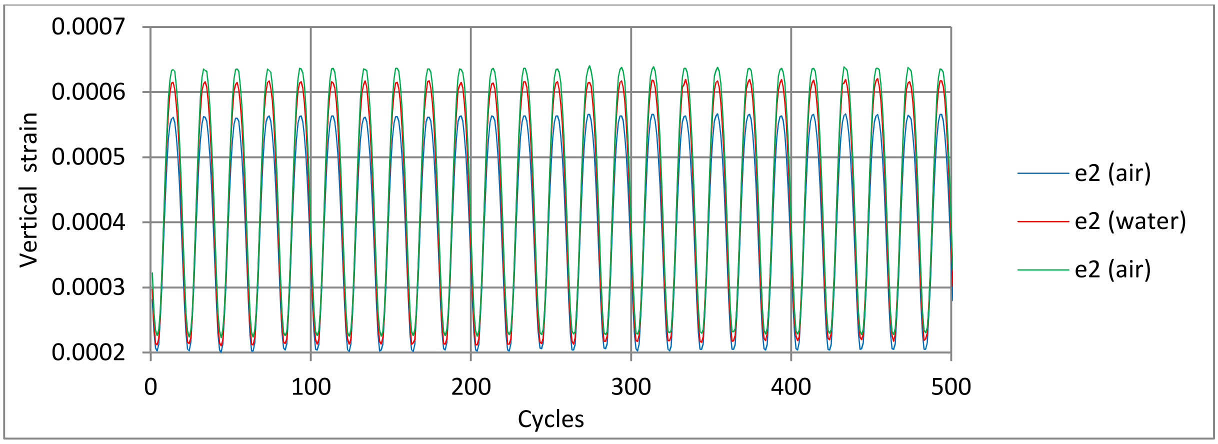

Figure 3: Comparison of LDTs used in air and in water (σ_3=70 kPa – σ_d = 115 kPa)

3 MATERIALS TESTED

The object of the tests was to characterize the resilient behaviour of a reference material commonly used in subbase layers or capping layers of Belgian roads and that of recycled materials, for comparison. The permanent strains were analysed at the end of the conditioning process (after 20,000 cycles). The reference material was a 0/20-mm sized limestone aggregate. The recycled materials were one crushed concrete aggregate and two blended crushed waste aggregates, all 0/32 mm in size. Results obtained on steel slags as presented in an earlier paper (Grégoire et al., 2009) will not be discussed here.

These materials are available in Belgium and are allowed in subbase or capping layers, under certain conditions. Figure 4 shows their particle size distributions.

For the investigation of resilient behaviour, CCP and VCP tests were performed at two different stress levels (high stress level (HSL) and low stress level (LSL)) as defined in European standard EN 13286-7.

Table 1: Properties of tested materials

	Fines content	**Passing 2 mm**	**W_{mpo}**	**ρ_{mpo}**	**Micro Deval (EN 1097-1)**	**LA (EN 1097-2)**
Limestone 0/20	7.4 %	25.9 %	5.5 %	2300 kg/m^3	17.5 %	18 %
Crushed concrete aggregate (0/32)	5.3 %	28.7 %	10 %	2010 kg/m^3	23.5 %	26 %
Blended aggregate 8824 (0/32)	5.5 %	42.3	12 %	1980 kg/m^3	41 %	-
Blended aggregate 8830 (0/32)	11 %	26	10 % - 12 % (not clear)	1985 kg/m^3	50 %	44 %

In the table, W_{mpo} is the optimum content of modified Proctor; ρ_{mpo} is the maximum dry density of modifed Proctor. The fines content is the passing at the sieve of 63 microns. Concerning blended aggregates, the Micro Deval and Los Angeles coefficients were only measured on the sample 8830 but it can be assumed that those of the 8824 would be quite similar.

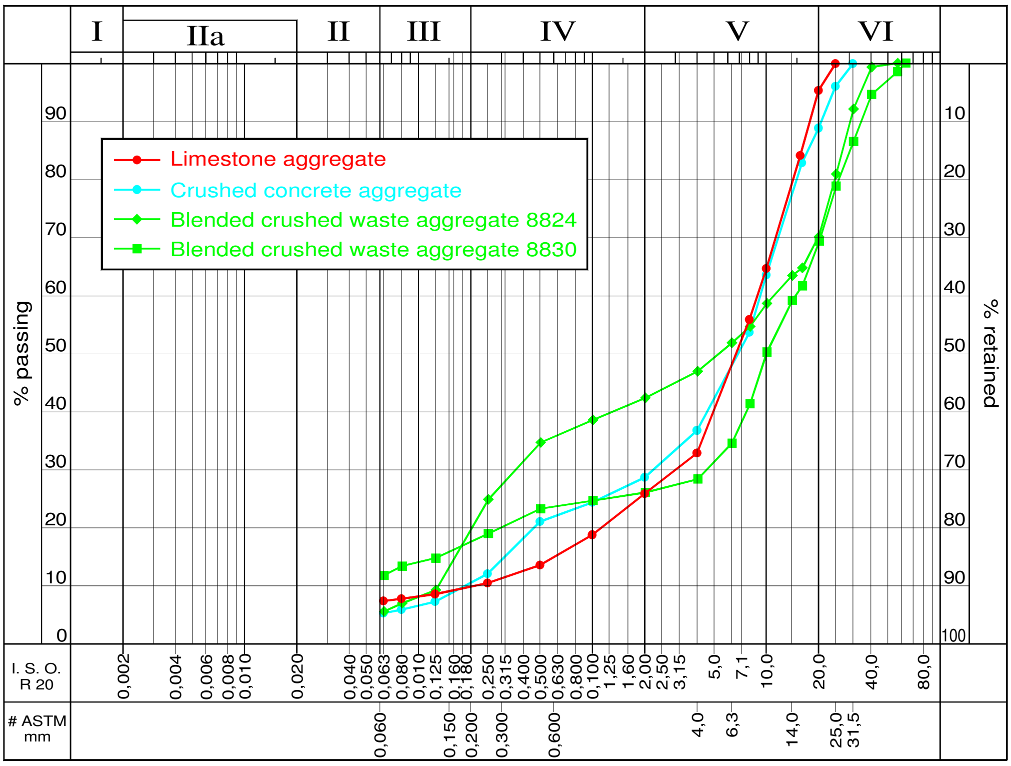

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Figure 4: Particle size distributions of the tested materials

4 PREPARATION OF SPECIMENS

After homogenization and oven drying, each material was separated into four or five particle size fractions with a view to manufacturing specimens of equal particle size distribution for testing.

This step was skipped for the blended aggregates, i.e., they were homogenized and dried, but not separated into four or five particle size fractions.

For the limestone aggregate, water was added and the fractions were mixed just before the specimen was compacted. For the recycled materials, which were liable to absorb water, the mixtures were prepared one day before compaction and stored in hermetically sealed bags.

The specimens were compacted with a vibrating hammer (EN 13286-51), in six layers at optimum density. Optimum density and water content were determined by modified Proctor testing.

After compaction, the mould was removed and a membrane encased the specimen during the test.

5 CONDITIONING

Conditioning (20,000 cycles, as required by standard EN 13286-7) was applied to the specimen, in order to stabilize the permanent strains. The results of the conditioning process were used to analyse permanent strain after 20,000 cycles. Table 2 summarizes the stress levels used in conditioning (EN 13286-7) for the CCP and VCP tests. σ_3 and σ_d were defined as the confining pressure and the deviatoric stress, respectively.

Table 2: Stress levels used for conditioning (in kPa)

VCP test	$\sigma_{3\,min}$	$\sigma_{3\,max}$	$\sigma_{d\,min}$	$\sigma_{d\,max}$
High stress level	10	110	0	600
Low stress level	10	110	0	300
CCP test	σ_3		$\sigma_{d\,min}$	$\sigma_{d\,max}$
High stress level	70		0	340
Low stress level	70		0	200

The analysis of permanent strains at the end of conditioning was based on characteristic permanent strain (ε_1^c), which characterizes resistance to permanent deformation. This parameter has been defined in standard EN 13286-7 as the difference between axial permanent strain at the end of conditioning – after 20,000 cycles – and axial permanent strain after 100 cycles:

$$\varepsilon_1^c = \varepsilon_1^p(20000) - \varepsilon_1^p(100) \qquad (1)$$

and is used as a basis for the ranking of materials concerning permanent deformations.

6.1 CCP tests

The CCP tests were performed on the four materials at the high and low stress levels. The specimens were compacted at ρ_{mpo} and w_{pmo}. Blended aggregate 8830 was tested at two water contents (10 and 12 %). The specimen of blended aggregate 8830 with 12 % of water was tested at the low stress level only.

The tests yielded characteristic permanent strains lower than 25e-4 (HSL and LSL tests), except for the limestone and blended aggregate 8824. The characteristic permanent strains of these materials was lower than 60e-4. The behaviour of the blended aggregate was influenced by its water content: higher water content resulted in a higher characteristic permanent strain. The limestone was tested twice at the low stress level. Both results were lower than 25e-4.

Blended aggregate 8824 developed the highest permanent strains at the high stress level, but blended aggregate 8830 was not tested with a water content of 12 % at the high stress level for comparison.

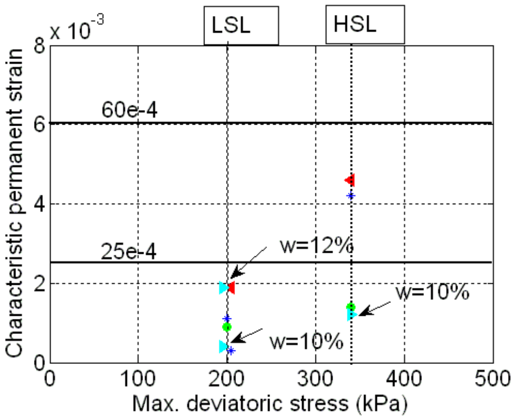

Figure 5: Characteristic permanent strains found in CCP tests

(* limestone / ● concrete aggregate / ◀ blended aggregate 8824 / ▶ blended aggregate 8830)

6.2 VCP tests

Characteristic permanent strains were also calculated from VCP tests. These were performed at HSL and LSL. For blended aggregate 8830 it was not possible to complete a HSL test owing to perforation of the membrane caused by high pressure and particle shape. The specimens were compacted at ρ_{OPM} and w_{OPM}. Blended aggregate 8830 was tested at w = 12 % only.

At the high stress level only the crushed concrete aggregate had a characteristic permanent strain corresponding to class C2 (< 60e-4). The strains developed by the other materials were too high.

At the low stress level the limestone, blended aggregate 8830 (one of the two specimens tested) and the crushed concrete aggregate exhibited characteristic permanent strains lower than 25e-4.

The characteristic strain of the crushed concrete aggregate increased with water content and with decreasing density.

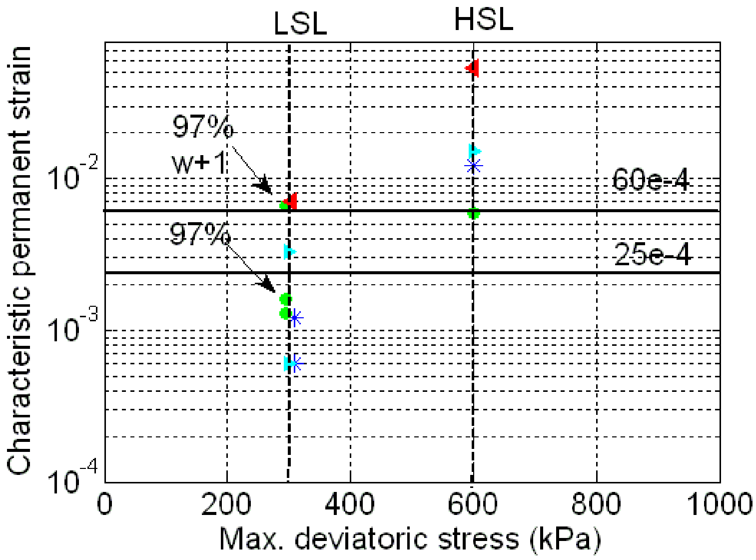

Figure 6: Characteristic permanent strains found in VCP tests (* limestone / ● concrete aggregate / ◀ blended aggregate 8824 / ▶ blended aggregate 8830)

6 RESILIENT BEHAVIOUR

To investigate resilient deformations, various stress paths were applied successively with one hundred cycles per stress path, according to method B (constant confining pressure) of the European standard (EN 13286-7).

The resilient modulus was calculated as:

$$M_r = \Delta q / \Delta \varepsilon_1^r \qquad (2)$$

where q was the deviatoric stress (or σ_d) as defined in equation (3) and ε_1^r the resilient axial strain.

$$q = (\sigma_1 - \sigma_3) \qquad (3)$$

Figure 7 represents the resilient modulus versus vertical stress σ_1 for the tested materials.

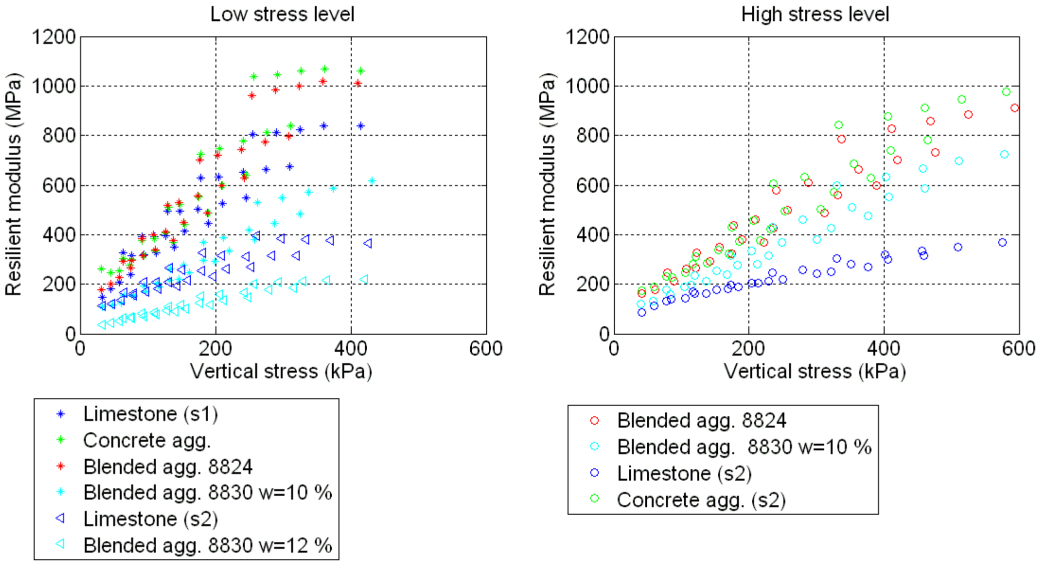

Figure 7: Resilient modulus calculated from CCP tests (LSL and HSL).

The crushed concrete aggregate exhibited the highest resilient modulus, both at the high and the low stress level. Blended aggregate 8824 also yielded high moduli.

The effect of water content was studied for blended aggregate 8830: higher water content produced a decrease in modulus.

Two tests (s_1 and s_2) were performed on the limestone (LSL) under the same conditions. The results were quite different. The second test seems to be more reliable, as the results were similar to the results of the HSL tests. This shows that it can be useful to perform a test several times under the same conditions.

The resilient modulus was analysed for a reference stress state, to calculate a characteristic elastic modulus (EN 13286-7, annex C; p = 250 kPa and q = 500 kPa corresponding to σ_1= 583 kPa). This characteristic resilient modulus was determined by interpolation from the results obtained at the high stress level, except where mentioned (the reference stress state is not the series of stress levels for the test).

The materials could be ranked by analysing their characteristic permanent strain and characteristic resilient modulus (Coronado et al., 2011). The result is summarized in table 3.

The crushed concrete aggregate was ranked as C1. Blended aggregate 8824 was rated as class C2, owing to a higher characteristic permanent strain. Blended aggregate 8830 was labelled as C2 at w = 12 % and C1 at w = 10 %. The limestone was classified as C2.

Table 3: Ranking of the analysed materials (based on CCP tests)

Materials	**E_c HSL results**	**ε_{1c} HSL results**	**E_c LSL results**	**ε_{1c} LSL results**	**Ranking based on E_c and characteristic permanent strain**
Crushed concrete aggregate	950 MPa	14e-4			C1
Blended aggregate 8824	950 MPa	46e-4			C2
Blended aggregate 8830	700 MPa (w = 10 %)	12e-4			C1
Blended aggregate 8830			300 MPa (w =12 %)	19e-4 (w=12 %)	
Limestone aggregate	400 MPa	42e-4			C2

Remark: the European standard suggests to do the classification for VCP tests, at a water content w= w_{mpo} -2 % and a dry density $\rho_d=0.97 \times \rho_{mpo}$. We choose $w_{mpo,}$ because of weather condition in Belgium.

The resilient behaviour of the limestone was analysed in VCP tests, at high and low stress levels. The resilient modulus was calculated as (EN 13286-7):

$$Mr = \frac{\sigma_1^{r\,2} + \sigma_1^{r}.\sigma_3^{r} - 2\sigma_3^{r\,2}}{\sigma_1^{r}\varepsilon_1 + \sigma_3^{r}\varepsilon_1 - 2\sigma_3^{r}\varepsilon_3} \quad where \ \sigma_1^{r} = \sigma_{1\max} - \sigma_{1\min} \qquad (4)$$

$$\sigma_3^{r} = \sigma_{3\max} - \sigma_{3\min}$$

The results are presented in Figure 8, in comparison with the moduli calculated from the results of CCP tests. For the limestone aggregate (HSL tests) the resilient moduli calculated from CCP tests are similar to those calculated from VCP tests. The resilient moduli calculated from the results of the VCP test at the low stress level are slightly lower.

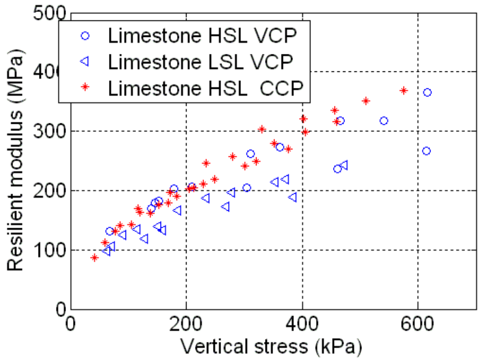

Figure 8: Resilient modulus calculated from VCP tests for the limestone (LSL and HSL)

7 CONCLUSION

Cyclic load triaxial tests were performed on a reference limestone and several recycled materials (crushed concrete aggregate and two blended crushed waste aggregates) used in Belgium. The limestone was tested both in CCP and VCP mode.

The characteristic resilient modulus and the characteristic permanent strain were analysed with a view to ranking the materials according to the European standard. At optimum water content, the tested crushed concrete aggregate (with continu grading size) performed better than the other materials tested (high modulus and low permanent deformation). However, the values of the mechanical properties (Los Angeles and Micro Deval coefficients) of the crushed concrete aggregate were slightly higher (i.e., worse) than for the limestone. Blended aggregate 8824 also exhibited a high modulus, but the permanent deformations were much higher. With a water content of 10 %, blended aggregate 8830 also exhibited a high modulus (a little bit smaller than blended aggregate 8824) and exhibited low permanent deformations. The reference limestone has medium resilient modulus and higher permanent deformations.

The tests performed on the limestone revealed a good correlation between the results of the CCP tests and the VCP tests. This remains to be checked for the other materials in further analyses.

Finally, some tests proved the reliability of LDTs in water.

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