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The Effects of Grading Scale on Repeated Load Triaxial Test Results

FREDRICK LEKARP[a*] and ULF ISACSSON[b†]

[a]*Swedish National Road Administration, Construction and Maintenance, Business and Engineering Development, Box 4018, SE-171 04 Solna, Sweden and* [b]*Professor, Division of Highway Engineering, Royal Institute of Technology, SE-100 44, Stockholm, Sweden*

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The present paper attempts to explore the impact of grading scale, or changes in maximum particle size of graded aggregates, on triaxial test results. The study is based on a series of repeated load triaxial tests on three unbound granular materials at different grading scales. The experimental results show clearly that the structural response observed depends on the maximum grain size used in the triaxial specimen. The reduction of grading scale is shown to have a significant impact on both resilient and permanent strain responses of the materials tested. However, the nature and the extent of this impact are complex and inconsistent when different materials are compared. It is therefore recommended that triaxial testing of granular materials be performed at natural gradings.

Keywords: Triaxial testing, Grading scale, Maximum Particle Size

INTRODUCTION

In flexible pavements, especially when unsurfaced or thinly surfaced, granular layers play a significant structural role in the overall performance of the pavement. During construction, the granular layers carry the construction traffic and provide a foundation for the higher pavement layers. In the finished pavement, the contribution of the granular layers to the structural performance of the pavement continues by spreading the traffic loads applied to the pavement surface. In order to establish more rational pavement design and construction criteria, it is essential that the response of granular layers under traffic loading be thoroughly understood and taken into consideration.

Current knowledge concerning the granular materials employed in pavement structures is limited. In recent decades, substantial research effort has been devoted to the study of the behavior of such materials. Different types of testing equipment have been developed for in situ trials and laboratory experiments. In this regard, it is probably fair to say that, at least for research purposes, repeated load triaxial testing, although not without its limitations, has found most favor. Over the years, many universities and research laboratories around the world have adopted this type

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[*] Email: fredrick.lekarp@vv.se
[†] Email: isacsson@ce.kth.se

of test. Nevertheless, several aspects of triaxial testing are still being discussed and need further development. One of the basic issues that need further investigation is the required specimen size. This is particularly important in the case of coarse-grained aggregates, since insufficient specimen size could lead to erroneous conclusions about the overall response of the material. It is generally believed that the size of a triaxial specimen is dependent on the maximum particle size of the aggregate to be tested. Consequently, large particles are often removed from coarse-grained aggregates in order to reduce the specimen size required. Yet, very few studies have been conducted in the past to investigate whether this affects the structural properties of the material.

The present paper attempts to investigate the effects of grading scale (that is, changes in the maximum particle size of graded aggregates) on triaxial test results through a literature survey and laboratory experiments. First, a brief review of a few studies found in the literature is presented. Then, the review is supplemented by a series of repeated load triaxial tests on three types of unbound granular materials at different grading scales. The various changes in the resilient and permanent strain behavior due to the change in maximum grain size are presented and discussed. The aim of this investigation is to find possible common trends that could be extended to granular materials in general.

LITERATURE REVIEW

In laboratory tests, in which the actual size of the original pavement structure is reduced, the specimen must be large enough so as not to have any influence on the recorded response. For triaxial testing of granular materials, earlier studies have shown that the size of the triaxial specimen is to be considered in relation to the maximum particle size of the aggregate to be tested. In this sense, an insufficient ratio of specimen diameter to maximum grain size is said to influence the material's response significantly.

Marachi el al. (1969) studied the monotonic shear strength of well-graded aggregates in a triaxial apparatus. Higher values of strength were observed in specimens in which the ratio between the specimen diameter and the nominal size of the aggregate was less than 7. The nominal size of a material was defined as the sieve at which 70%, by weight, of the material passed through. Vallerga et al. (1975) suggested that a specimen diameter of 3–4 times maximum particle size is required. In the repeated load triaxial testing procedure outlined by TRB (1975), a minimum ratio of 4–5 times was recommended. The standard specification released by AASHTO (1986) prescribed a minimum specimen diameter of 6 times the largest grain size. In addition, the literature available suggests that the height of a triaxial specimen needs to be at least twice its diameter (Dehlen 1969, Taylor 1971, TRB 1975, AASHTO 1986).

Although a few large-scale triaxial testing facilities are currently available, these tests are most commonly conducted using specimen diameters of 300 mm, 150 mm or even less. This creates a significant technical restriction in testing coarse-grained aggregates. One fairly widespread approach in dealing with the specimen size requirements is to test coarse-grained materials in so-called scaled-down gradings. In this way, the maximum particle size is reduced in order to keep the ratio of specimen diameter to maximum grain size at or above the generally used value of 5. However, the impact of such interference with material grading on the test results is yet to be fully explored.

The significance of grading scale was studied by Donbavand (1987), who performed repeated load triaxial tests on 150x300 mm specimens of crushed granite and carboniferous limestone in a dry condition. For each material, specimens with different maximum particle sizes (11 mm, 16 mm, 22 mm, 30 mm and 40 mm) were prepared by sieving and remixing the material. For the granite, the volumetric and shear stiffness properties were shown to be directly proportional to the maximum particle size. It was suggested that this mode of action could be the effect of the change in the number of particles within a specimen. By scaling down the grading, the number of grains within the specimen is increased, thus providing an increased number of possible sites for movement to take place. A reduced grading scale would therefore lead to increased deformation and lower stiffness. This justification did not match the response of the limestone, in which the grading scale had virtually no impact on volumetric behavior and only a slight influence on the shear response. Donbavand also investigated the resistance to permanent deformation, using constant confining pressure of 50 kPa and cyclic deviator stress of 0–200 kPa, and noted that the stiffer specimens, with larger particles, yielded larger permanent strain values. This was said to be attributed to particle crushing, since large particles generally show a greater tendency to break up than smaller ones. In total, Donbavand concluded that the grading scale produced a significant impact on material response, but this was very difficult to quantify.

Thom (1988) investigated two aspects of scale in triaxial testing; the grading scale given by the maximum particle size, and the scale of the specimen given by its diameter. He conducted tests at four different grading scales using three different specimen sizes. The resilient stiffness was shown to decrease with decreasing aggregate size, but remained unaffected by the specimen size. According to Thom, the only effect of specimen size on resilient properties is the considerable scatter seen in the results when the ratio of specimen diameter to maximum grain size is too small. Shear strength was found to decrease with decreasing particle size, but the test results revealed that the ratio of specimen diameter to maximum grain size was more important than the aggregate size alone. Higher shear strengths were recorded as this ratio was reduced. The relative resistance to permanent strain development remained basically unaffected by the maximum grain size alone, but no conclusions could be drawn when the permanent strain was plotted against the ratio of specimen to grain size.

The effects of material downscaling were also studied by Sweere (1990) in a series of resilient triaxial tests using two specimen sizes of 400x800 mm and 150x300 mm. The crushed masonry and crushed concrete included in the study were tested initially at the original grading of 0/40 using the larger specimen size. The grading was then scaled down to 0/19 and the tests were repeated with the smaller specimen size, at the same values of moisture content and dry density as for the initial trials. Sweere focused in his investigation on the changes in material stiffness properties and reported that the results were not consistent with respect to specimen size effects. For the crushed masonry, higher resilient moduli were found with the 150 mm specimen diameter. For the crushed concrete, on the other hand, the specimen size had a negligible impact on the resilient modulus. He then concluded that the maximum grain size of the aggregate, or the size of specimen used, does have an influence on the resilient properties measured during triaxial testing, but this influence cannot be determined with certainty. Sweere further suggested that it would be possible to use small-scale triaxial testing for classification of materials into categories of stiffness properties. For a detailed study of the stress-strain behavior of coarse-grained aggregates, however, large triaxial specimens would be needed.

From the studies outlined above, it seems rather clear that the grading scale certainly influences the response of the aggregate being tested. However, the nature and the extent of this influence seem very complex and difficult to determine.

EXPERIMENTAL

In order to explore further the impact of grading scale on triaxial test results, a series of repeated load triaxial tests were conducted on a number of unbound granular materials.

The tests were mainly focused on investigating the changes occurring in the resilient response as a result of the reduction of maximum particle size in the specimen. However, data were also collected on the relative resistance of the materials to permanent deformation by conducting permanent strain tests on specimens already subjected to the resilient test series. The tests were all performed in a drained condition so as to avoid excess pore pressure during the tests.

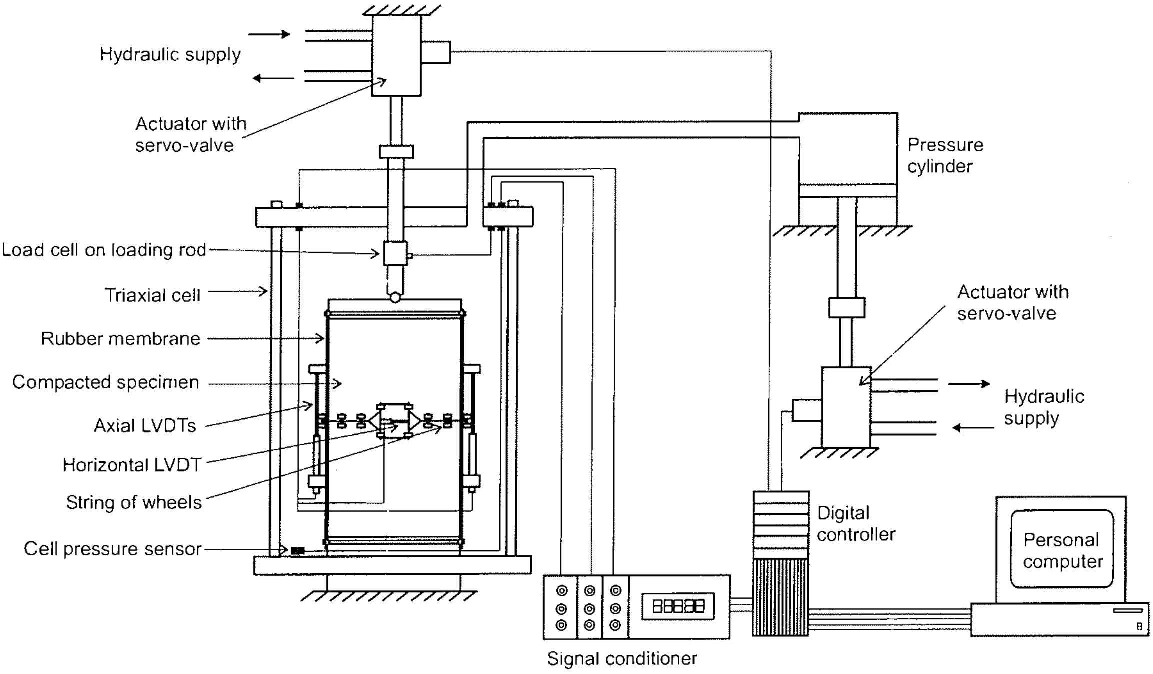


FIGURE 1 Schematic illustration of the large-scale triaxial apparatus used in the investigation

Triaxial Testing Equipment and Specimen Preparation

In the present investigation, a large repeated load triaxial testing facility with 500x1000 mm specimen size was employed. This equipment has been developed recently at the Highway Engineering Division of the Royal Institute of Technology in Stockholm, Sweden. Both the equipment and specimen preparation have been described in detail elsewhere (Lekarp and Isacsson 2000). A brief description is given below.

The schematic representation of the principal components of the triaxial testing equipment is given in Figure 1. The loading system uses servo-controlled hydraulic actuators to apply repeated deviatoric and confining stresses to the specimen placed inside a triaxial pressure cell. The axial load is generated by a 250 kN actuator capable of applying a repeated deviator stress of up to about 1300 kPa to 500U mm diameter specimens. The axial load is monitored by a load cell inside the triaxial cell. The feedback signal from the load is compared with the load command signal by the electronic control system, after which an error signal is relayed to the servo-valve on the actuator so as to adjust the load applied to that required. The confining pressure is applied through the silicone oil surrounding the specimen in the triaxial cell. The applied fluid pressure is governed by a 50 kN servo-controlled hydraulic actuator, operating a 320 mm diameter pressure cylinder, which is connected to the triaxial cell by a flexible hydraulic tube. The loading system is capable of applying constant or variable confining pressures of up to 600 kPa to the specimen. The level of confining stress is controlled by the output signal from a pressure sensor inside the cell, in a similar manner to that of the axial load.

During a repeated load triaxial test, the specimen undergoes both vertical and radial deformations. Here, the response of the specimen is monitored by on-sample instrumentation positioned remotely from

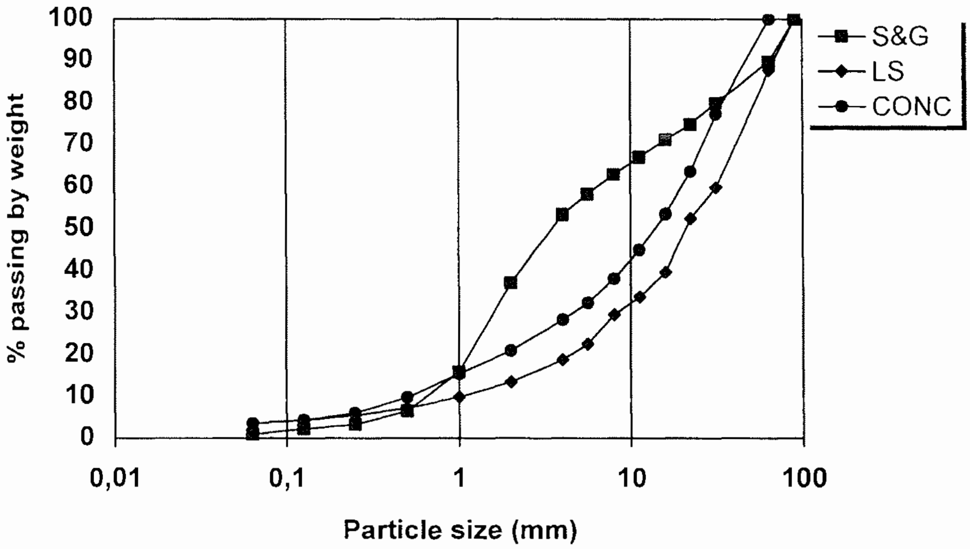


FIGURE 2 Particle size distributions for the tested materials

the ends of the specimen to avoid end-effects. The axial deformation is measured for the central 600 mm portion of the specimen's height by three LVDTs placed equally spaced around the circumference of the specimen. Each LVDT measures the relative vertical movement of the specimen between two "locating anchors" fitted into the body of the specimen after compaction is completed. For monitoring lateral deformation, a "string of wheels" is wrapped around the specimen at the middle of its height and held together by two springs. Any lateral movement of the specimen is measured by the LVDT, which is kept between the two ends of the siring of the wheels.

The specimen is compacted in 10 layers with a vibrating hammer in a split mold covered on the inside by a rubber membrane. This membrane is used to hold the specimen when the compaction mold is removed. As the membrane usually suffers damage during the compaction process, a second membrane is put over the first one after removal of the compaction mold in order to protect the specimen from the surrounding oil. The need for inclusion of a correction factor due to the influence of membrane stiffness on recorded data has been previously investigated (Lekarp and Isacsson 2000) and found not necessary.

The specimen is fitted at its ends with loading platens, around which the membranes are clamped to ensure a proper seal. Each loading platen is provided with three drainage connections from porous discs embedded in the body of the platen around its central part.

Materials

Three different types of unbound aggregates were included in this study with the expectation that any common trends found are also likely to apply to other granular materials. The materials consisted of the following (all locations are in Sweden):

- Crushed Limestone (LS) from Hejdeby quarry, Gotland
- Crushed Concrete (CONC) from deposit, Frosunda Vik
- Sand and Gravel (S&G) from Åhls pit, Enköping

Accurate scaling of a graded granular material requires separation and recombining of all size fractions. In this study, the amount of aggregate needed for each triaxial specimen was almost 400 kilograms. The separation of different fractions by sieving would have been an extremely cumbersome and time-consuming procedure. LS was delivered in seven separate fractions (0/4, 4/8, 8/11, 11/16, 16/32, 32/63 and 63/90, where each fraction is named by its lower and upper grain size boundaries in millimeters) which were mixed to produce the required grading curves. CONC and S&G, on the other hand, were delivered at one combined grading (0/63 for CONC and 0/90 for S&G). The total amount of each of these two materials was manually mixed to overcome the segregation that takes place during transport. Different gradings were then accomplished by mixing, for LS, or sieving, for S&G and CONC. For LS and S&G, gradings of 0/90, 0/63, 0/32 and 0/16 were prepared. For CONC, however, only the last three gradings could be made. This method of scaling was deemed the only feasible way of handling several tons of test material, although it reduced, to some extent, the accuracy of the specimen preparation at least for S&G and CONC. However, the main objective of the present study is not a deep fundamental analysis of the material behavior, but rather to observe the general changes that occur in the response of the material as the grading scale is altered. It is. therefore, believed that the objectives of the study have not been compromised.

The particle size distributions of the materials at the highest grading scales (i.e. with the largest particle sizes) are given in Figure 2.

The values of optimum dry density (ODD) and optimum moisture content (OMC) were determined for each grading scale. The specimens were then manufactured to the same degree of compaction and moisture content relative to the optimum values. For determination of ODD and OMC, it was necessary to use the same technique for all the gradings. Normally, these parameters are derived experimentally by the Modified Proctor Compaction Test (SRA 1977). This method, however, is not applicable for aggregates coarser than 32 mm. Here, the values of ODD were obtained by compacting the materials in saturated condition using a vibrating table, according to the Swedish test standard (SRA 1988) applicable to gradings up to 0/90. The values of OMC for the 0/16 and 0/32 gradings were derived using the modified Proctor. The corresponding values of OMC for the coarser gradings were then calculated, in accordance with the Swedish standard (SS 1975), by

$$\mathrm{OMC} = \mathrm{OMC}_{0/32} \cdot (1 - \mathrm{r}) + \mathrm{w}_{>32} \cdot \mathrm{r} \qquad (1)$$

in which OMC is the optimum moisture content for the mixed aggregate with a grading larger than 0/32, $\mathrm{OMC}_{0/32}$ is the corresponding value for the 0/32 grading, $\mathrm{W}_{>32}$ is the amount of water absorption, in %, by the grains larger than 32 mm and r, $0 \leq \mathrm{r} \leq 1$, is the proportion of particles coarser than 32 mm.

A comparative study such as the one presented here may be conducted at any selected density and saturation level, as long as these are kept the same for all the specimens involved. In order to avoid excessive pore pressure during testing, moisture content of 60% OMC was chosen. The very first specimen, which was compacted to refusal, reached a density of 99% ODD. The same target density was therefore selected for all the other specimens too. The actual properties of the specimens are summarized in Table I.

In preparing the specimens, each layer was compacted with a certain degree of under-compaction, using the technique suggested by Ladd (1978). Based on this method, the level of under-compaction is highest for the first layer and is gradually reduced to zero for the top layer. Compensation is made for the under-compaction of each layer as it experiences additional compaction while the overlying layers are being compacted. In these tests, 5% under-compaction was chosen for the first layer. The suitability of such compaction technique was investigated and approved through a number of preliminary compaction tests in which the uniformity of the density in compacted specimens was verified by comparing the actual density of each layer with its target density, considering the degree of under-compaction. Figure 3 illustrates the density variations for two specimens (S&G 0/90 and CONC 0/63). As shown in the figure, the uniformity of the specimen density is fully acceptable, at least within the central portion where the response measurements are taken.

TABLE I Properties of materials tested

		Laboratory derived properties		*Sample properties*		
Material	*Grading*	*ODD (g/cm^3)*	*OMC (%)*	*DD (g/cm^3)*	*MC before testing (%)*	*MC after testing (%)*
CONC	0/63	1.95	7.4	1.93	4.4	3.9
	0/32	2.01	8.6	1.97	5.2	5.1
	0/16	1.97	10.5	1.93	6.3	6.3
LS	0/90	2.15	4.5	2.12	2.7	2.5
	0/63	2.16	5.0	2.13	3.0	2.6
	0/32	2.17	7.0	2.14	4.2	3.7
	0/16	2.20	6.9	2.17	4.1	3.9
S&G	0/90	2.10	4.4	2.07	2.6	1.6
	0/63	2.09	4.9	2.04	2.9	2.5
	0/32	2.01	5.4	1.98	3.2	2.6
	0/16	1.94	6.4	1.89	3.8	2.5

TABLE II Details of the resilient test program

Confining stress, σ_3 (kPa)		*Deviator stress, q (kPa)*		*Stress path q/p*	*Confining stress, σ_3 (kPa)*		*Deviator stress, q (kPa)*		*Stress path q/p*
min	*max*	*min*	*max*		*min*	*max*	*min*	*max*	
10	60	0	0	0	20	70	5	155	1.5
10	110	0	0	0	20	120	5	305	1.5
10	160	0	0	0	20	170	5	455	1.5
10	210	0	0	0	20	220	5	605	1.5
10	60	5	35	0.5	20	50	5	185	2.0
10	110	5	65	0.5	20	80	5	365	2.0
10	185	5	110	0.5	20	120	5	605	2.0
10	60	5	155	1.5	20	30	5	155	2.5
10	110	5	305	1.5	20	35	5	230	2.5
10	160	5	455	1.5	20	40	5	305	2.5
10	210	5	605	1.5	20	20	5	45	3.0
10	40	5	185	2.0	20	20	5	70	3.0
10	70	5	365	2.0	20	20	5	95	3.0
10	110	5	605	2.0	20	20	5	120	3.0
10	20	5	155	2.5	20	20	5	145	3.0
10	25	5	230	2.5	30	30	5	55	3.0
10	30	5	305	2.5	30	30	5	95	3.0
20	70	0	0	0	30	30	5	135	3.0
20	120	0	0	0	30	30	5	175	3.0
20	170	0	0	0	30	30	5	215	3.0
20	220	0	0	0	40	40	5	65	3.0
20	70	5	35	0.5	40	40	5	120	3.0
20	120	5	65	0.5	40	40	5	175	3.0
20	195	5	110	0.5	40	40	5	230	3.0
					40	40	5	285	3.0

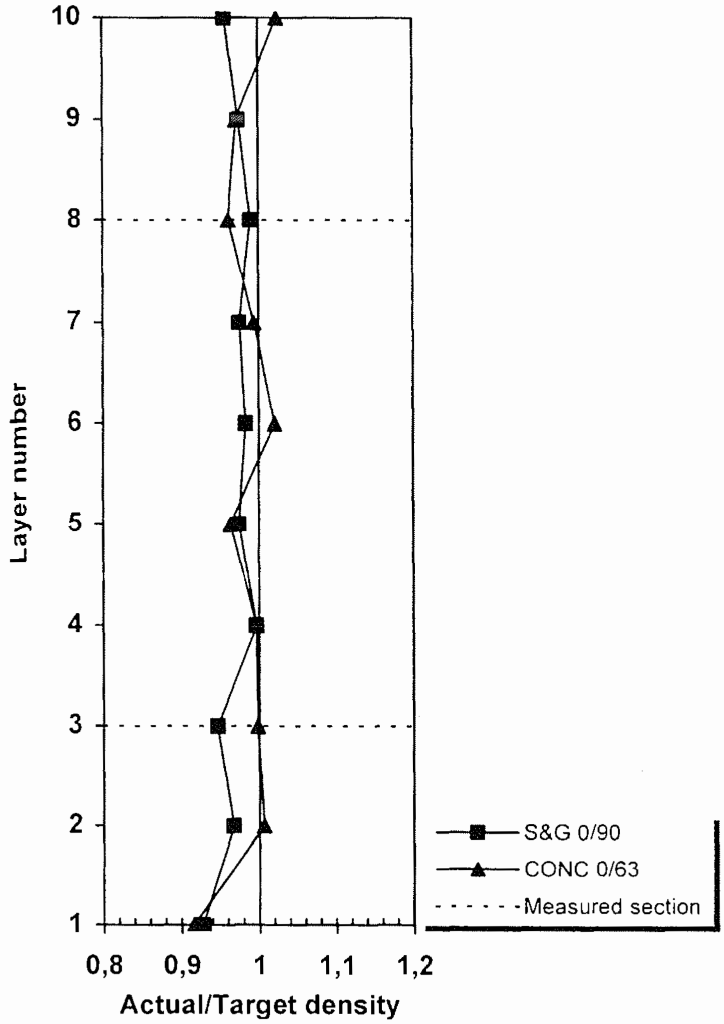


FIGURE 3 Examples of density variation in compacted specimens

Test Program

The main aim of the test program was to assess the resilient response of the materials at different grading scales. Prior to the resilient tests, each specimen was conditioned in order to stabilize the permanent strain in the material and obtain a practically resilient response. The conditioning was achieved through the application of 5000 sinusoidal load cycles, at a frequency of 1 Hz, in which the deviator stress was varied between 5 and 600 kPa and the confining pressure between 10 and 100 kPa. During conditioning, the strains were recorded for the first 20 cycles and for cycles 50, 100, 200, 400, 600, 800, 1000, 2000, 3000, 4000 and 5000.

The resilient test program consisted of the application of a series of different stress paths, with both constant and variable confining pressures. The stress paths are given in Table II and Figure 4. Using the

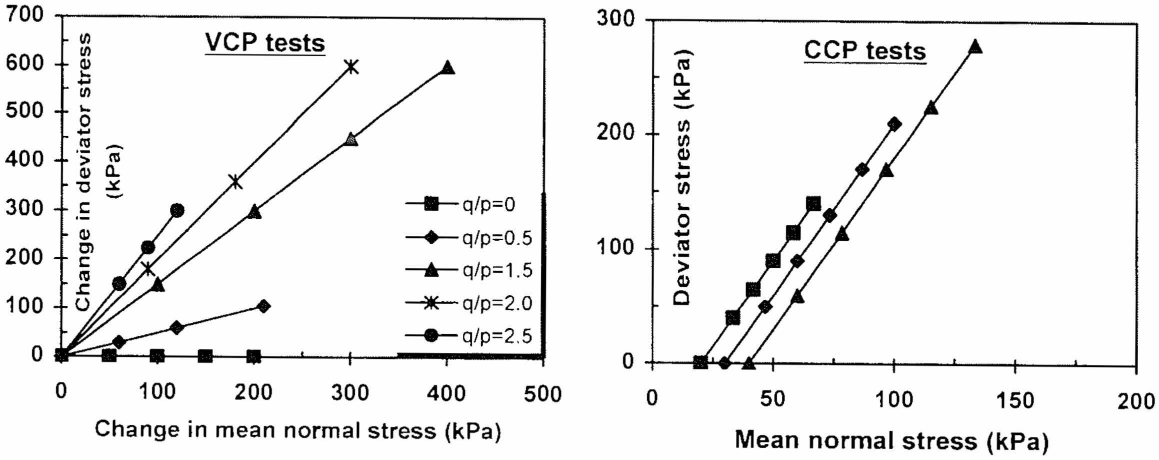


FIGURE 4 Loading pulses applied in the resilient test series

amplitudes of the applied stresses, each stress path is defined by the stress ratio q/p, where $q=\Delta(\sigma_1-\sigma_3)$, $p=\Delta(\sigma_1+2\sigma_3)/3$. Here Δ indicates "change in" and q, p, σ_1 and σ_3 are the deviator stress, the mean normal stress, and the major and minor principle stresses, respectively. The stress paths chosen are very similar to those proposed in the new European standard (CEN 1997). Each stress path was applied for 100 cycles as sinusoidal pulses at a frequency of 1 Hz. The strains were recorded during the final 5 loading cycles.

Following the resilient tests on each specimen, two consecutive permanent strain tests were performed. For these tests, the confining pressure was kept constant at 100 kPa, while the deviator stress was cycled, at the frequency of 10 Hz, between 5 and 600 kPa for the first test and between 5 and 700 kPa for the second one. The strains were recorded in a similar manner to that of the conditioning.

RESULTS OF TESTING AND DISCUSSION

Material Response during Conditioning

The impact of grading scale on the accumulation of permanent strain during conditioning is presented in Figure 5 for the three materials tested. A significant difference is seen in the figure between the responses of different materials. For LS, the accumulated permanent strain increases as the grading is changed from 0/90 to 0/63, but it drops for the lower gradings. For CONC, the strain increases with the change in grading from 0/63 to 0/32 and is not consistent with the pattern observed in LS. The response in S&G is different altogether as the accumulated permanent strain increases consistently with reduction of the grading scale. It is noteworthy that the accumulated permanent strains during the first few cycles are sometimes ignored (Lekarp et al. 2000) as these are considered to be due to bedding effects. These initial strains have not been excluded from the results shown in Figure 5, as they do not influence the response patterns observed.

The inconsistent outcome of the conditioning is perhaps the first indication of an inconclusive impact of grading scale on permanent strain development. This will be confirmed later in this paper when the results of the permanent strain tests are presented.

Results of Resilient Testing Program

In order to analyze the resilient response of the materials, the values of resilient modulus and Poisson's

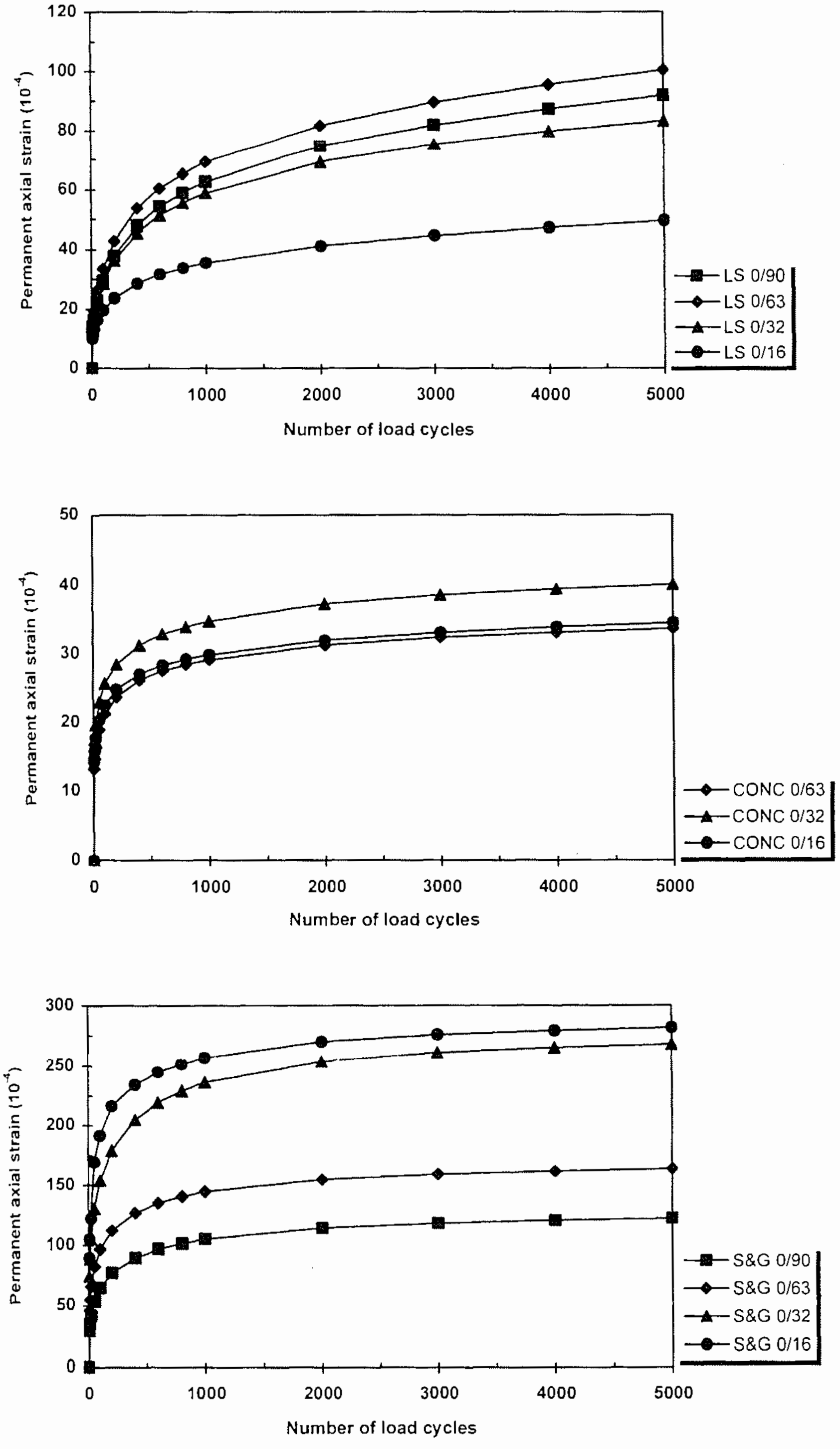


FIGURE 5 Effect of grading scale during conditioning

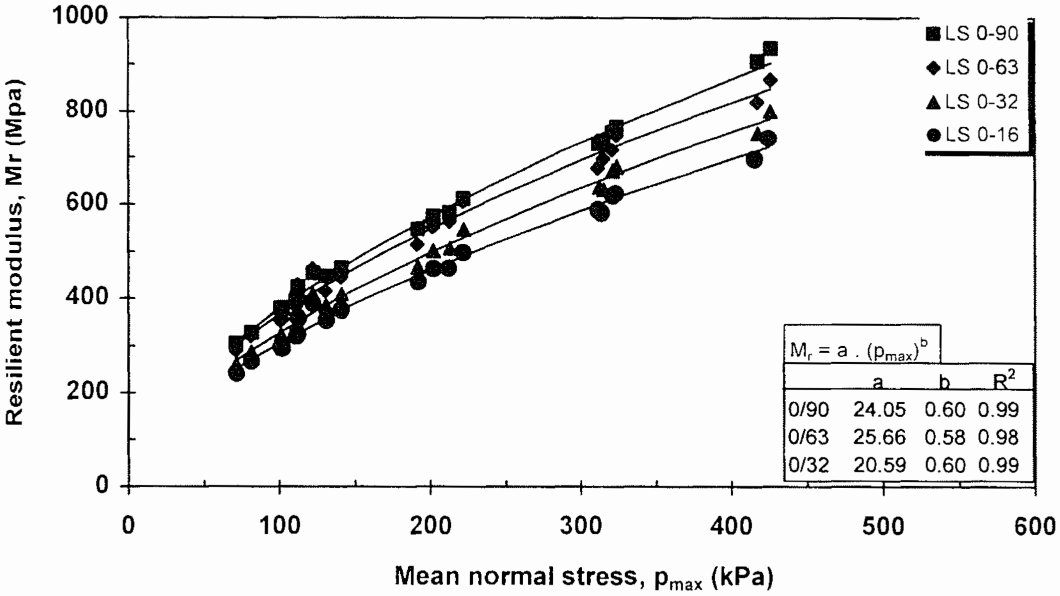
ratio were calculated according to Hooke's law. For repeated load triaxial tests with constant confining pressure (CCP), these parameters are defined by

$$M_r = \frac{\Delta(\sigma_1 - \sigma_3)}{\varepsilon_1} \qquad \nu = -\frac{\varepsilon_3}{\varepsilon_1} \tag{2}$$

in which M_r is resilient modulus, v is resilient Poisson's ratio, Δ indicates "change in" and σ_1, σ_3, ε_1 and ε_3 are major and minor principal stress and recoverable axial and horizontal strain, respectively. When variable confining pressure (VCP) is applied, the resilient parameters are derived according to the generalized Hooke's law by

$$\begin{aligned} M_r &= \frac{\Delta(\sigma_1 - \sigma_3)\Delta(\sigma_1 + 2\sigma_3)}{\varepsilon_1\Delta(\sigma_1 + \sigma_3) - 2\varepsilon_3\Delta\sigma_3} \\ \nu &= \frac{\Delta\sigma_1\varepsilon_3 - \Delta\sigma_3\varepsilon_1}{2\Delta\sigma_3\varepsilon_3 - \varepsilon_1\Delta(\sigma_1 + \sigma_3)} \end{aligned} \tag{3}$$

During the data analysis, it was noticed that the quality of the deformation measured at the very low stress state given by q/p=0.5 was poor and inconsistent. Some possible explanations can be given. In general, for the deformations to be detected by the sensors, the applied stresses must be large enough to overcome the movement and rearrangement of the particles within the specimen. At low stresses, the internal movements of the grains consume a large percentage of the energy input and the deformations detected become relatively much lower than they should be. The impact also varies with material type, since particle movement is different in different materials. It is also possible that the behavior of aggregates at low stresses is simply atypical of their behavior at higher stresses (e.g. due to partial contact and rearrangement non-linearities). A third possible reason for the poor quality of the data recorded at very low stresses may be that the sensitivity of the deformation transducers has been insufficient. Although the readings from the transducers showed no signs of low sensitivity, it is suggested that, for future experiments, the signal conditioning is enhanced at low stresses. For this investigation, however, it was decided to exclude the data obtained during the stress paths of q/p=0.5 from the analysis altogether.



$M_r = a \,.\, (p_{max})^b$

	a	b	R^2
0/90	24.05	0.60	0.99
0/63	25.66	0.58	0.98
0/32	20.59	0.60	0.99

FIGURE 6 Variation in resilient modulus with stresses in LS

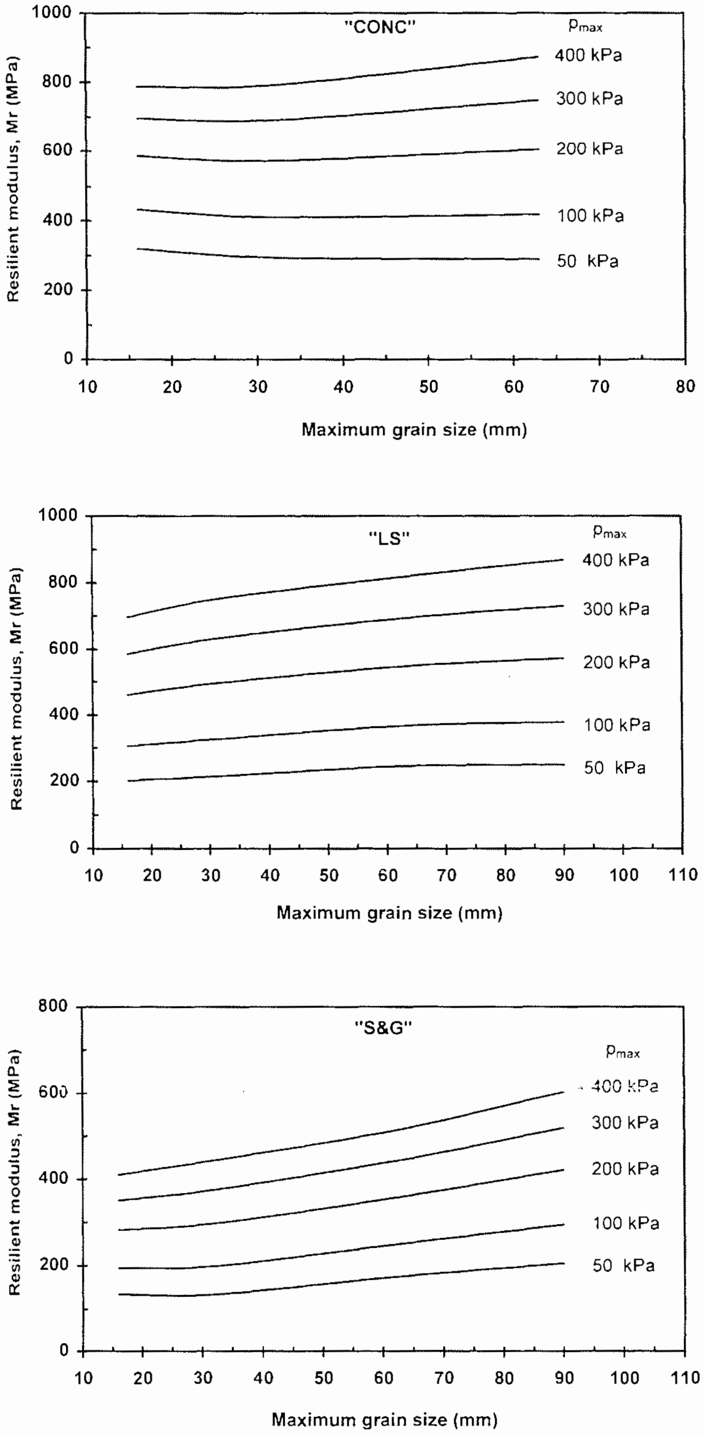


FIGURE 7 Resilient modulus versus maximum grain size at different stress levels

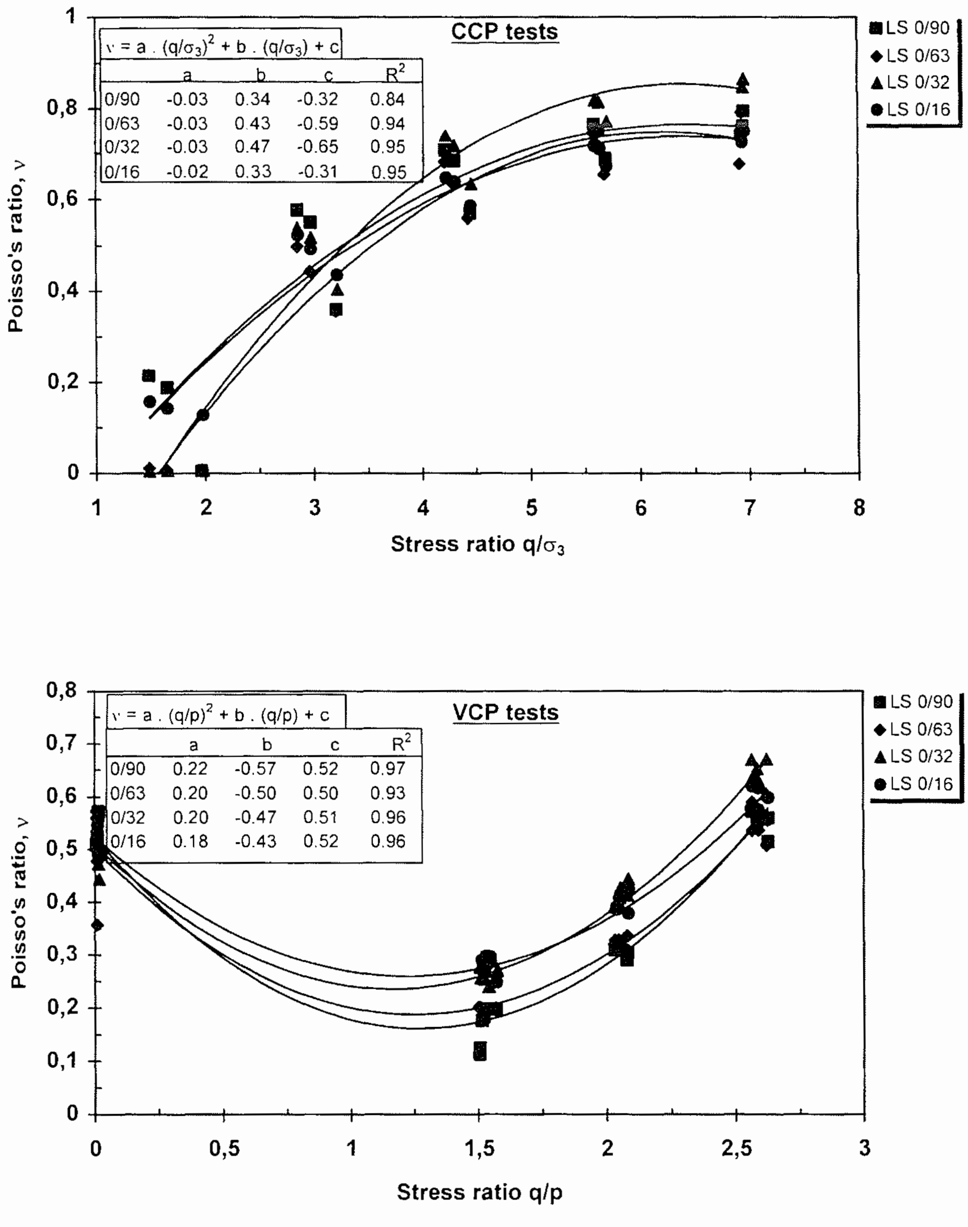
The stress dependence of the resilient modulus was best given when the moduli observed were plotted against the maximum mean normal stresses, p_{max}. A very similar pattern of behavior emerged from both the VCP and CCP tests, although the latter resulted in slightly lower moduli. For CONC, the influence of grading scale on the resilient modulus was negligible at low stresses. As the stresses increased, lower resilient moduli were shown by specimens that had lower maximum particle sizes. The modes of action in LS and S&G were similar to each other and the resilient modulus proved to decrease consistently with decreasing particle size. The general decrease in the resilient modulus and the low impact observed in CONC confirm previous findings, described earlier in this paper. The results obtained for LS are presented in Figure 6, in which the experimental data have been fitted to a power function to examine the type of relationship. The approximate variation in resilient modulus at different stresses with maximum particle size is shown in Figure 7 for all the materials tested.

The stress-dependent nature of the resilient Poisson's ratio is normally considered in relation to a stress ratio that represents the stresses in different directions. Here, the stress ratios q/p and q/σ_3, where σ_3 is constant, are used for the VCP and CCP tests, respectively. The analysis showed a completely different pattern of response for these two types of test. For the VCP tests, Poisson's ratio decreased initially with increasing stress ratio. This continued up to a stress ratio of about 1.5, after which it started to increase. For S&G, a large amount of resilient dilation (ν of about 0.8) was found for stress ratios of about 2.5. At these levels, slight dilation also occurred in LS. In both cases, some dilation also appeared at very low stress ratios. For these two aggregates, the reduction of maximum grain size seemed to have an increasing effect on Poisson's ratio. In other words, the grading scale had a larger impact on radial strains than on axial strains. This was not the case for CONC, in which Poisson's ratio was almost the same for all grading scales. In the CCP tests, the variation in Poisson's ratio with stresses was, in principle, the opposite to that of the VCP tests. Here, Poisson's ratio increased initially with increasing stress ratio, but seemed to decline as the stress ratio became higher than about 6.0. For stress ratios greater than 3.0, dilation was observed in most cases. For the CCP tests, the responses were very inconsistent between aggregate types and no conclusions could be drawn in regard to the effect of grading scale on Poisson's ratio. Figure 8 shows the results obtained for LS during both the CCP and VCP tests.

The variation in Poisson's ratio with the applied stresses during a CCP test is the direct result of changes in the deviator stress. Experimental studies in the past (e.g. Lo and Lee 1990, Semmelink and de Beer 1995, Zamhari 1998) have shown that granular materials exhibit anisotropic response, normally being stiffer vertically than horizontally. As the deviator stress increases during a CCP test, the radial strain grows at a higher pace than the axial strain, leading to an increase in Poisson's ratio.

For VCP tests, the understanding of the material response in different directions is more difficult, as both vertical and horizontal stresses are cycled, and the resilient Poisson's ratio is calculated using the influence of both stress components. Therefore, the variation in Poisson's ratio with stresses cannot be explained as simply as for CCP tests. However, a possible explanation can be given by comparing the material response at low and high stress ratios. Additional data presented elsewhere (Lekarp and Isacsson 2000) show that the materials investigated exhibit radial compression for stress ratios between 0 and 1.5, with the former producing the largest radial compression. As the stress ratio increases from 0 to 1.5, the decreasing radial compression (i.e. decreasing radial strain) together with increasing axial strain would result in declining Poisson's ratio. As the applied stress ratio increases beyond 1.5, the materials show radial extension (i.e. increasing radial strain). Due to the anisotropic behavior, the radial strain increases at a higher pace than the axial strain, leading to an increase in Poisson's ratio.

In order to summarize the impact of grading scale on the resilient properties, it was decided to normalize the responses at different gradings in relation to the response at the largest grading scale (i.e. with largest particle size). This was accomplished by calculating



$\nu = a \cdot (q/\sigma_3)^2 + b \cdot (q/\sigma_3) + c$

	a	b	c	R^2
0/90	-0.03	0.34	-0.32	0.84
0/63	-0.03	0.43	-0.59	0.94
0/32	-0.03	0.47	-0.65	0.95
0/16	-0.02	0.33	-0.31	0.95

$\nu = a \cdot (q/p)^2 + b \cdot (q/p) + c$

	a	b	c	R^2
0/90	0.22	-0.57	0.52	0.97
0/63	0.20	-0.50	0.50	0.93
0/32	0.20	-0.47	0.51	0.96
0/16	0.18	-0.43	0.52	0.96

FIGURE 8 Variation in Poisson's ratio with stresses in LS

the corresponding values from the curves fitted to the experimental results. The outcome of this comparison, based on the VCP tests, is given for all the three materials in Figure 9. The grading scale does not seem to have a large impact on the resilient modulus of CONC (less than 10%). The influence for the other two aggregates, however, is quite noticeable. The resilient modulus may fall by up to 20% in LS and 35% in S&G as a result of a reduced grading scale. The resilient Poisson's ratio in LS and S&G may

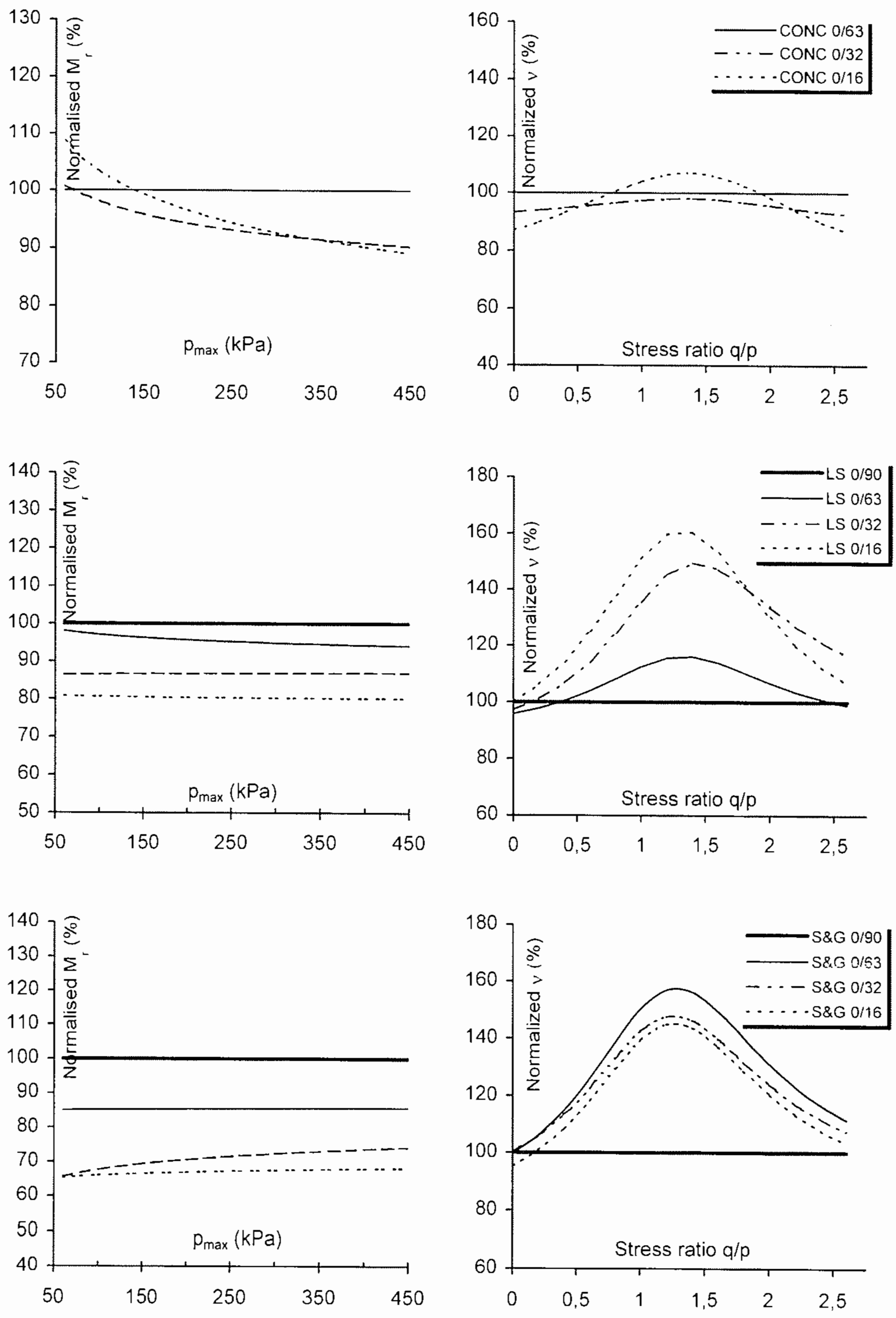


FIGURE 9 Normalized comparison of resilient parameters at different grading scales

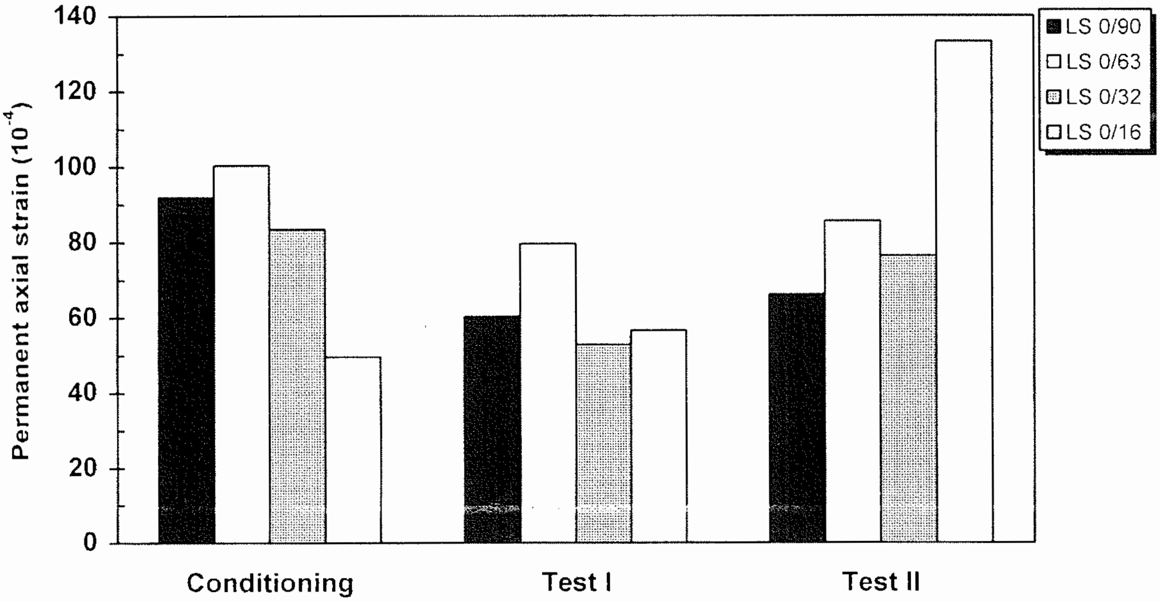


FIGURE 10 The effect of grading scale on permanent strain development in LS

increase significantly (up to 60%), whereas it changes only slightly in CONC. Furthermore, the pattern observed for the variation of Poisson's ratio is not the same for the three materials tested.

In total, the only general conclusion that could apply to all the three aggregates included in this investigation is that the reduction of the grading scale (i.e. the reduction of the maximum particle size) has a definite impact on the resilient properties. The extent of this impact can be as little and, perhaps, insignificant as in CONC, or as large and important as in S&G.

Results of Permanent Strain Tests

Accumulation of permanent deformation in granular materials is influenced markedly by stress history. Therefore, permanent strain tests are normally conducted using a new specimen for each set of stresses applied. In this investigation, however, the same specimens, already tested for resilient properties, were subjected to a set of two permanent strain tests. The objective of these tests was to perform a comparative study of the impact of grading scale on permanent strains recorded during triaxial testing. The measure used for this purpose was the total amount of accumulated permanent axial strain at the end of conditioning and each of the two permanent strain tests.

In general, the material responses at different grading scales proved to be very inconsistent and no distinguishable patterns could be extracted. An example of the results obtained is shown in Figure 10. The impact of grading scale on resistance of the materials to permanent strain seems significant, even for CONC, but is very complex in nature.

CONCLUSIONS

A series of repeated load triaxial tests has been performed on LS, CONC and S&G at the gradings 0/90, 0/63, 0/32 and 0/16. Based on the experimental results, the following conclusions can be drawn:

- The structural response observed during repeated load triaxial testing proved to be affected significantly by the grading scale, or the maximum particle size of the aggregate used in the specimens. Both the resilient and permanent strain responses were influenced.
- The material stiffness was shown to decrease as the grading scale was reduced. The extent of the impact, however, was different in different materials. In CONC, the resilient modulus dropped by no more than 10%, whereas the reduction in LS and S&G was about 20% and 35%, respectively.
- The reduction of the grading scale had an increasing effect on the resilient Poisson's ratio. In LS and S&G, Poisson's ratio changed by up to 60%, but the mode of variation was not consistent with the change in the grading scale. In CONC, however, the impact was negligible.
- In all three materials tested, the resistance to permanent strain development varied with the grading scale. However, the nature of the response was highly inconsistent and no distinguishable patterns could be extracted from the results.
- The experimental outcome of this investigation is in general agreement with the results of previous studies, outlined in the initial part of this paper. The analyses of the test results confirm the complexity of the nature and the extent of the impact of grading scale reduction on triaxial test results. It is, therefore, recommended that triaxial specimens be made large enough to allow testing of granular materials at their natural gradings.

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