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Testing of geogrid-stabilized noncohesive soil in triaxial apparatus under cyclic loading

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Subject review

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In road base layers, geogrids assume the reinforcement or stabilization function where good interaction between geogrid and unbound base material is important. The cyclic triaxial test can be used for analysing interaction between geogrid and unbound base material. The paper includes an overview of research where cyclic triaxial test is primarily used for assessing the influence of parameters such as geogrid stiffness, geometry and aperture size, position and number of geogrid layers, on the interaction with the base layer material. The cyclic triaxial test can be used to determine contribution the geogrid application in non-cohesive materials has on the reduction of permanent deformations.

Key words:
geogrid, cyclic triaxial test, stiffness, aperture geometry, aperture size

Pregledni rad

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Ispitivanje nekoherentnog tla armiranog geomrežom u uređaju za troosni posmik pri cikličkom opterećenju

U nosivim slojevima kolničke konstrukcije geomreže imaju funkcije ojačanja ili stabilizacije, pri čemu je važna dobra interakcija geomreže i nekoherentnog materijala nosivog sloja. Za ispitivanje interakcije geomreže i materijala nosivih slojeva kolničkih konstrukcija može se primijeniti pokus cikličkim troosnim posmikom. Rad obuhvaća pregled istraživanja primjene cikličkog troosnog posmika posebice tijekom ocjenjivanja utjecaja parametara kao što su krutost, geometrija i veličina otvora, položaj i broj slojeva geomreže na interakciju s materijalom nosivog sloja. Ocjenjuje se da se cikličkim troosnim posmikom može utvrditi doprinos primjene geomreža u nekoherentnim materijalima u vidu smanjenja trajnih deformacija.

Ključne riječi:
geomreža, ciklički troosni posmik, krutost, oblik otvora, veličina otvora

Übersichtsarbeit

Jelena Kaluđer, Mensur Mulabdić, Krunoslav Minažek

Prüfung von inkohärentem geogitterverstärktem Boden in einer Vorrichtung zur dreiachsigen Scherung unter zyklischer Belastung

In den tragenden Schichten haben die Fahrbahnstrukturen des Geogitters die Funktion der Bewehrung oder Stabilisierung, wobei ein gutes Zusammenspiel des Geogitters und des inkohärenten Materials der tragenden Schicht wichtig ist. Um die Wechselwirkung des Geogitters und des Materials der tragenden Schichten von Fahrbahnstrukturen zu testen, kann ein zyklisches Dreiachsen-Scherexperiment angewendet werden. Diese Arbeit enthält einen Überblick über die Forschung zur Anwendung der zyklischen dreiachsige Scherung, insbesondere während der Bewertung des Einflusses von Parametern wie Steifheit, Geometrie und Größe der Öffnungen, Position und Anzahl der Geogitterschichten auf die Wechselwirkung mit dem Lagerschichtmaterial. Es wird geschätzt, dass der Beitrag der Anwendung von Geogittern in inkohärenten Materialien in Form einer Verringerung dauerhafter Verformungen durch zyklische dreiachsige Scherung bestimmt werden kann.

Schlüsselwörter:
Geogitter, zyklische dreiachsige Scherung, Steifheit, Lochform, Lochgröße

1. Introduction

Reinforced soil, as a composite formed of geosynthetics (mostly geogrids) and soil, is extensively used in many civil engineering applications – from improvement of foundation soil, to embankments and retaining walls, load bearing platforms, and base course layers of pavements. For instance, while geosynthetics in retaining structures function as reinforcement in base courses of pavements they can be used for either reinforcement or stabilization. When they function as reinforcement, where the tensioned membrane mechanism is dominant (Figure 1, left), large deformations are needed which also require large deformation to the top pavement zone, while the lateral restraint mechanism (Figure 1, right) or stabilization is dominant at smaller deformations [1]. Reinforcement is defined in HRN EN ISO 10318-1:2015 [3] as "use of the stress-strain behaviour of a geosynthetic material to improve the mechanical properties of soil or other construction materials", while in HRN EN ISO 10318-1:2015/A1 [4] stabilization is defined as "improvement of the mechanical behaviour of an unbound granular material by including one or more geosynthetic layers such that deformation under applied loads is reduced by minimizing movements of the unbound granular material". In stabilization, geogrids are mostly used. They are in most cases biaxial (prominent strength in two directions), with the square or rectangular aperture shape, and triaxial (prominent radial stiffness in several directions), with triangular aperture shape. Geogrids interact with soil primarily through interlocking of particles in geogrid apertures, and less by friction along the surface of the ribs or by friction of particles interlocked in geogrid apertures [5]. The interlocking of particles in geogrid apertures creates a zone of improved soil properties where the best properties are registered immediately next to the geogrid, while the influence of interlocking reduces with an increase of the distance from the geogrid. According to [6] the height of the zone of improved properties is 150 mm (below and above the geogrid), as determined via a cyclic triaxial test on a sample of geogrid-stabilized granular material with 600 mm in height and 300 mm in diameter. According to McDowell et al. [7], this zone is situated 100 mm below and above the geogrid, which is based on simulation of cyclic triaxial test conducted by numerical modelling using the discrete element method (DEM). Minažek [8] defines the height of the zone of influence as being approximately 30xD_{50} for river gravel samples (D_{50} = 6 and 12 mm). Cook and Horvat [9] report that the reinforced ballast interlocking zone (defined by direct shear test) lies 200 mm above the geogrid, and they assume that the zone without the influence of interlocking is situated 400 mm from the geogrid.

The use of geogrids in roads started somewhat later compared to the use of geotextiles. The first use of woven geogrids in paved roads was registered in 1985 in Malaysia [10], while the first laboratory testing of the use of geogrids in base course layers of pavements started in the late 1980s [11, 12]. Research [11-15] have revealed good effects of the use of geogrids in the stabilization of base courses with several observed advantages, including reduction of permanent deformation of pavement surface, reduction of maintenance costs and extension of road life span, and/or increase in bearing capacity, and/or reduction in the base course thickness (savings in material).

When testing geogrid and soil interaction, it is necessary to consider loading conditions to which these materials will be exposed in a particular type of structure. In testing suitability of geogrids use in roads, and due to nature of traffic load that can be characterized as cyclic, it is necessary to conduct testing under cyclic loading. First tests with repeated load were conducted using a plate load test with approximately ten load cycles. However, very soon - in the mid 1950s – triaxial shear devices started to be used for repeated load testing purposes [16]. In addition to the cyclic load triaxial test, some other cyclic load tests have subsequently been developed, such as cyclic direct shear test, and overview of these tests can be found in [17]. Christopher at al. [18] point to advantages of the use of triaxial test, such as the possibility of applying different combinations of stress onto sample (simulation of traffic load), simplicity of strain measurements (local and outside of the cell), availability of testing equipment, and existence of regulations and standards. Brecciaroli and Kolisojaa [19] additionally point to the cost and time savings as compared to in-situ testing, while also reporting some deficiencies such as the impossibility of simulating movement of wheels (only the state of stress below the wheel axle is observed in the test) and definition of principal stress values, where two of the principal stress values are always the same. Today, cyclic load triaxial tests are widely used for testing behaviour of base course materials, as test results can provide information about the increase in permanent deformation with an increase in the number of load cycles, which in turn enables ranking of the material under study (shakedown theory, acceptability of the use of this material in loose base courses) and definition of modules that can be used in the design of pavement structures.

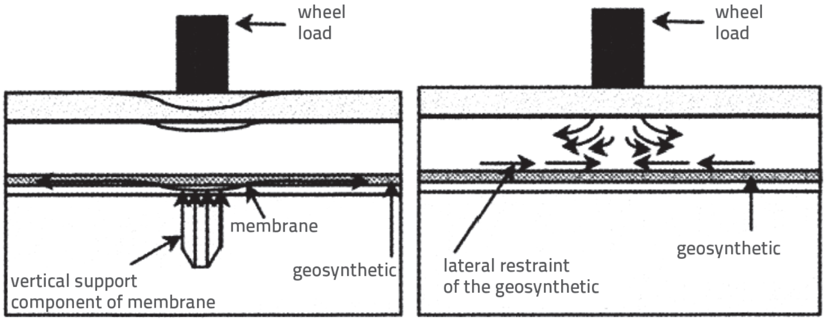

Figure 1.Tensioned membrane mechanism (left), lateral restraint mechanism (right) [2]

2. Cyclic load triaxial test

2.1. Description of testing procedure

The cyclic load triaxial test can be used to simulate traffic load and to determine resilient and plastic (permanent) deformations of the used sample. The test is most often conducted on unstabilized samples, although samples stabilized with geosynthetics can also be tested. The test itself is conducted in a cell (Figure 2) in which the sample is placed and exposed to the planned triaxial stress. The test is conducted in stages, the first one being the conditioning of the sample, while the value of resilient moduli (the ratio of resilient axial stress to resilient axial strain) is determined in the second stage. In addition to the above mentioned, the cyclic load triaxial test can also be used to monitor development of permanent deformations after a greater number of load cycles. The development of elastic and permanent deformations is shown in Figure 2 (bottom) where the accumulation of permanent deformations, and reduction in their increase with an increase of the number of load cycles, can be seen.

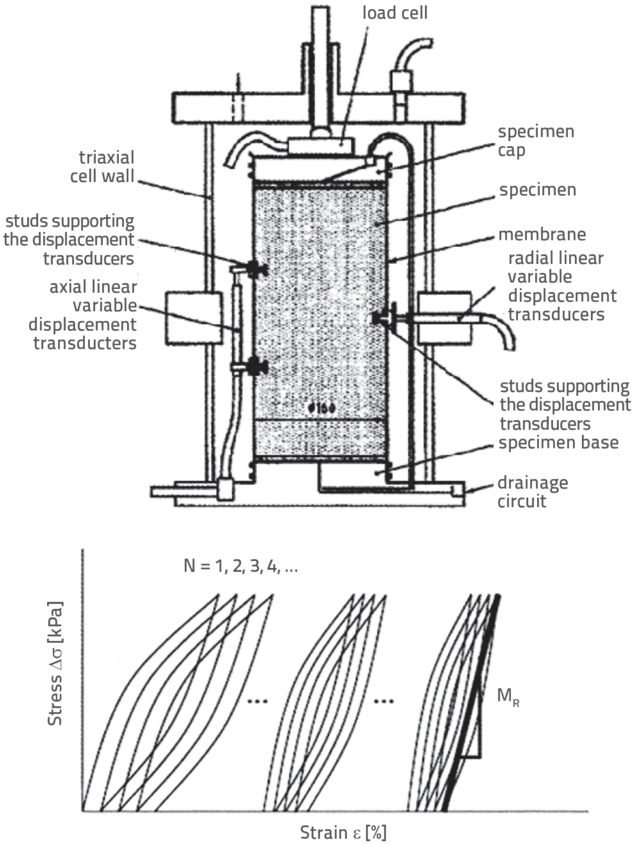

Figure 2. Shematic view of the triaxial cell used for cyclic load triaxial test [20], top; Deformations during cyclic loading of sample [18], bottom

First repeated load triaxial tests were conducted in the mid-20th century [21-24], and the first procedure for the resilient modulus tests AASHTO T274 was published in 1982, according to [18]. Currently, there are several standards and procedures such as AASHTO T307-99 [25], NCHRP 1-28A [26], EN 13286-7 [20], AG:PT-T053-07 [27], and they differ from each other by the definition of sample size and maximum grain size of material in the sample, by sample preparation and by testing procedure and response measurements.

The first test stage is conditioning where permanent deformation stabilization and stable resilient behaviour of the sample is achieved [20]. According to Hicks and Monismith [28] and Allen [29], 1,000 load cycles are sufficient for completion of the conditioning stage. It is indicated in AASHTO T307 [25] that 500 to 1,000 load cycles are needed for the conditioning stage, while 1,000 load cycles are specified in NCHRP 1-28A [26] and AG:PT/T053 [27]. The European standard [20] offers the possibility of adjusting the number of cycles to the behaviour of the sample, i.e. it permits earlier stop of the conditioning stage (the standard defines 20,000 load cycles) if resilient behaviour of the sample is achieved. In the second test stage, various combinations of confining pressures and axial loads (differing from the stresses from the conditioning stage) are used at small number of cycles, usually 100 cycles [20, 25, 26] to 200 [27] for determination of resilient modulus values. Figure 2 (bottom) shows the change of resilient modulus with an increase in the number of load cycles for the same value of deviator stress (marked in the figure as inclination of the straight line M_R); therefore, only the last several load cycles (ten last cycles according to [20], or five last cycles according to [25, 26]) are usually observed in the calculation of the modulus. For the study of permanent deformations, a greater number of load cycles is necessary to ensure that an increase in permanent deformations becomes negligible. According to research conducted by Morgan [24] an increase of permanent strains was registered even after two million load cycles, but this increase was negligible. Boyce [30] reports stabilization of permanent deformations increase for well graded crushed stone sample up to 100,000 load cycles (Figure 3). The European standard [20] requires 80,000 load cycles for a single-stage testing (one stress combination), while 10,000 cycles are required for each combination in the case of multi-stage testing (involving several different stress combinations). Requirements for the duration of one load cycle are differently defined in various standards and regulations. Thus it is specified in AASHTO T307 [25] that one cycle may vary from 1 to 3.1 seconds, in NCHRP 1-28A [26] this period is one second, in AG:PT/T053 [27] three seconds, while a wider range of load frequencies, from 0.2 to 10 Hz is specified in EN 13286-7 [20]. According to [24, 28, 29, 31], the duration and frequency of load have small to no influence on the resilient behaviour of granular materials.

Sample deformation can be measured using external and/or local displacement transducers. The use of local displacement transducers enables accurate measurement at smaller strains that can not be successfully registered at the total (external) strain measurement, and the bedding error is thus also avoided. The European standard [20] specifies the use of local displacement transducers for the measurement of radial and axial strains only. According to [26] two local displacement transducers are to be used for the measurement of axial strains, while it is specified in [25] that two external displacement transducers are to be used for the measurement of axial strains. Local displacement transducers are usually installed in the middle third of the sample height (Figure 2, top) which, in the case of samples stabilized with geosynthetics respectively geogrids (with installation of geogrids at the middle height of the sample), enables measurement of displacement within the zone of improved properties.

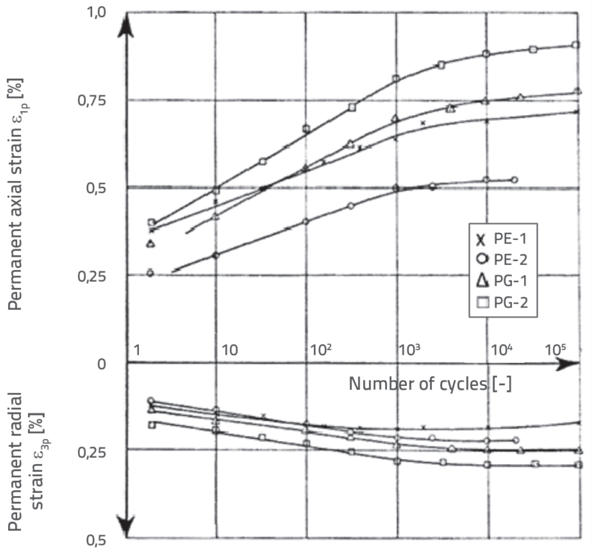

Figure 3. Increase of permanent strains with the number of load cycles [30]

2.2. Overview of the use of cyclic load triaxial test in the study of reinforced soil

Cyclic load triaxial test has been in use more than sixty years now, and tests have so far been conducted on various types of natural soil (cohesive and non-cohesive). An increase has been registered in recent years in the number of cyclic triaxial tests on samples made of industrial and recycled materials. Thus, tests were inter alia conducted on samples made of crushed/recycled concrete aggregate [32-34], recycled clay masonry, mixtures of recycled clay masonry with recycled concrete aggregate [35], iron and steel slag [36], mixture of crushed stone, and waste glass and/or rubber [37, 38].

Cyclic load triaxial test on samples stabilized with geosynthetics has been conducted over the past two decades. These tests mostly involve the use of geogrids [6, 34, 39-50], but the use of geotextiles and geocomposites has also been registered [6].

Moghaddas-Nejad and Small [39], Kamel et al. [40] and Perkins et al. [6] were among the first ones to test geogrid-stabilized samples using the cyclic load triaxial test. Nazzal [41] investigated how test results were influenced by the position of geogrid in the sample, by the number of geogrid layers in the sample, and by stiffness of geogrids, using five different types of biaxial geogrids. In the study conducted by Wayne et al. [42] the focus was on the difference in density, i.e. on the level of compaction of a reinforced sample, which was done in such a way that the lower half of the sample had lower level of compaction compared to the upper half of the sample. Abu-Farsakh et al. [43] conducted a comprehensive research, the aim being to determine in which way test results are influenced by the shape of geogrid apertures, number of geogrid layers in the sample, position of geogrid in the sample, and stiffness of geogrid. In order to determine interlocking of particles of uniformly graded ballast material in the apertures of the biaxial and triaxial geogrid, Qian et al. [44] conducted a cyclic load triaxial tests and additionally performed numerical modelling using the discrete element method. In their study, Nair and Latha [45] considered the influence of the number of geogrid layers on test results. Rahman et al. [34] conducted a cyclic load triaxial test using crushed brick and recycled concrete aggregate stabilized with biaxial and triaxial geogrid, respectively. In his study, Gu [46] analyzed the influence of the position of geogrid (biaxial or triaxial) placed at the bottom of the sample, at one fourth of the sample height, or at mid-height of the sample. Guthrie and Knighton [47] also studied the influence of various geogrid aperture shapes and the influence of geogrid position in the sample. Byun et al. [48] and Kim et al. [49] conducted cyclic load triaxial test and also measured shear wave velocity using three sets of bender elements. In addition to the above mentioned, Kim et al. 49], analyzed the suitability of grain size composition for triaxial geogrids with various aperture sizes. An overview of the mentioned studies involving cyclic load triaxial test on geogrid-stabilized samples is presented in Table 1.

3. Granular material and geogrid interaction

Results of cyclic load triaxial test on samples of granular soils/materials stabilized with geogrids depend on the properties of soil/material, test conditions, on the position and number of installed geogrids in the sample, and on geogrid properties. According to [51], good interaction between the geogrid and granular material – achieved by particle interlocking at geogrid apertures – is influenced by the geogrid aperture size as related to the material grading, aperture shape, stiffness and shape of ribs and stiffness of geogrid junctions. Mulabdić et al. [5] provide an illustration (Figure 4) of the geogrid - soil interaction intensity influence related to the aperture size, geogrid stiffness and type of geogrid. The mentioned illustration shows that the highest intensity of interaction is achieved for a particular range of geogrid aperture sizes (A) and average particle sizes (D_{50}), where the interlocking of particles in apertures is more dominant than the friction at contact.

Table 1. Overview of studies with cyclic load triaxial test on geogrid-stabilized samples

Research	Sample dimensions	Material / soil*	Geosynthetic	Position and number of installed geosynthetics
Moghaddas-Nejad and Small, 2003, [39]	D = 200 mm H = 400 mm	GU SW	1 BX GGR	1 GGR (½ H)
Kamel et al, 2004, [40]	D = 100 mm H = 200 mm	SP CL ML	2 BX GGR	1 GGR (24-28% H)
Perkins et al, 2004, [6]	D = 300 mm H = 600 mm	GW-GM SM	2 BX GGR 1 GTX-W 1 GCO	1 GGR (½ H)
Nazzal, 2007, [41]	D = 150 mm H = 300 mm	GW-GM	5 BX GGR	1 GGR (½ H, ⅔ H) 2 GGR (⅓ H and ⅔ H)
Wayne et al, 2011, [42]	D = 150 mm H = 300 mm	G	1 TX GGR	1 GGR (½ H)
Abu-Farsakh et al, 2012, [43]	D = 150 mm H = 300 mm	GW	3 BX GGR 2 TX GGR	1 GGR (½ H, ⅔ H) 2 GGR (⅓ H and ⅔ H)
Kwon et al, 2012, [50]	D = 150 mm H = 300 mm	GP-GM	1 TX GGR	1 GGR (½ H)
Qian et al, 2013, [44]	D = 305 mm H = 610 mm	GU	1 BX GGR 1 TX GGR	1 GGR (½ H)
Nair and Latha, 2014, [45]	D = 300 mm H = 600 mm	GW	1 BX GGR 1 GCE	2 GGR (⅓ H and ⅔ H) 3 GGR (¼ H, ½ H and ¾ H) 4 GGR (⅕ H, ⅖ H, ⅗ H and ⅘ H) 5 GGR (⅙ H,⅓ H, ½ H, ⅔ H and ⅚ H)
Rahman et al, 2014, [34]	D = 100 mm H = 200 mm	RCA (W) CB (W)	1 BX GGR 1 TX GGR	1 GGR (½ H)
Gu, 2015, [46]	D = 150 mm H = 150 mm	GW	1 BX GGR 2 TX GGR	1 GGR (½ H, ¼ H, 0 H)
Guthrie and Knighton, 2015, [47]	D = 150 mm H = 300 mm	SW-SM GW	1 BX GGR 1 TX GGR	1 GGR (½ H, ¾ H)
Byun et al, 2019, [48]	D = 150 mm H = 300 mm	GW	1 BX GGR 1 TX GGR	1 GGR (½ H)
Kim et al, 2020, [49]	D = 150 mm H = 300 mm	2 GW GP	2 TX GGR	1 GGR (½ H)

Legend:
* USCS classification conducted according to published grading curves and/or soil/material descriptions, H – sample height, D – sample diameter, GGR – geogrid, GTX – geotextile, GTX-W – woven geotextile, GTX-NW – nonwoven geotextile, BX – biaxial (geogrid), TX – triaxial (geogrid), GCO – geocomposite (in table GGR+GTX-NW), GCE – geocell (in table made by sewing GTX, 298 mm in diameter), 1/2 H (1/3H, 2/3H, 1/4H, 3/4H, 5/6H) – geogrid position viewed from bottom of the sample, at 1/2 (1/3H, 2/3H, 1/4H, 3/4H, 5/6H) of height of the sample, 0H – geogrid positioned at the bottom of the sample, RCA – recycled concrete aggregate, CB – crushed brick

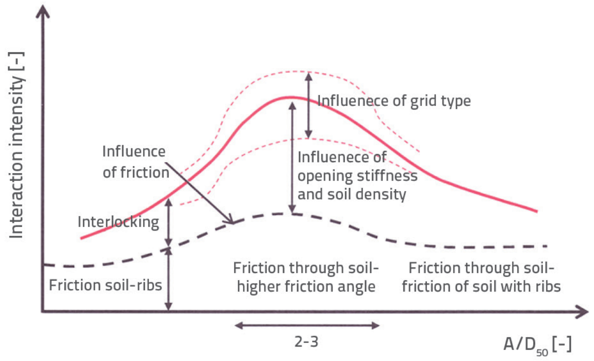

Figure 4. Qualitative representation of geogrid-soil interaction [5]

3.1. Parameters influencing interaction of granular material and geogrid

3.1.1. Properties of material and test method

The way in which shear strength of granular materials is influenced by mineralogical composition, grain size and grading of material, shape and texture of grains, density of material, and cell pressure, has been studied by many researchers from the introduction of the triaxial apparatus (e.g. see [52]). Lekarp et al. [53] also mention the influence of the number of load cycles, frequency, and load duration. An overview of individual soil properties influence on the resilient response of granular soil and permanent deformations is presented by Lekarp et al. [53, 54].

3.1.2. Position and number of geogrid layers

The deformation of samples is influenced by the position and number of geogrids in the sample, as has been confirmed by cyclic load triaxial test. By comparing test results obtained with the geogrid installed at mid-height of the sample and with the geogrid in the top third of the sample height, Nazzal [41] determined that both geogrids contributed to the reduction of permanent deformations, but that better results were achieved for geogrids situated in the top third of the sample height (Figure 5). By comparing various test results in which stiffness and positon (distribution) of geogrids and the number of load cycles were varied, Nazzal [41] demonstrated that the reduction of permanent deformations is dominantly influenced by the position (distribution) of geogrids. Abu-Farsakh et al. [43] reached the same conclusion as to the most favourable position of geogrid, but they also determined the dominant influence of the position of geogrid as related to other parameters (distribution/position of geogrid, stiffness and geometry of geogrid apertures). Gu [46] analysed the influence of geogrid position at the bottom of the sample, at the bottom fourth of the height, and at the mid-height of the sample. Gu [46] states that geogrid placing at the bottom of the sample has no effect on reduction of permanent deformations and reports that, out of three geogrid placing positions, the best results were obtained by geogrid placed at mid-height of the sample. Guthrie and Knighton [47] analysed geogrid position at mid-height of the sample and at top fourth of the sample height and established that the latter position was more favourable. However, triaxial shear tests give advantage to geogrid placing at mid-height of the sample [55] because the failure surface passes through the middle part of the sample. As in on-site conditions geogrids are installed at the bottom and/or at mid height of base course, which depends on the base course thickness, expected traffic load levels [2], and subsoil strength [11]. It can be concluded that, for geogrid efficiency testing purposes, a favourable geogrid position is at the mid-height of the sample.

Comparison of test results obtained when one geogrid or several geogrids were used showed that permanent deformations are more reduced if two or three geogrid layers are used. The benefit of two geogrid layers, compared to one layer, is confirmed by Nazzal [41] and Abu-Farsakh et al. [43] (Figure 5). Nair and Latha [45] tested samples where two, three, four, and five geogrids were installed. Their results show that the use of up to three geogrids is advantageous, while further increase in the number of geogrid layers does not add much to the efficiency and they conclude that in the selection of optimal number of geogrid layers, the improvement effects as well as economic considerations have to be taken into account. Although reference [45] points to advantages that are gained if three geogrid layers are used, it is nevertheless important to consider conditions and possibilities for installing this number of geogrids in base course in on-site conditions, where up to two geogrid layers, and most frequently only one geogrid layer, are normally installed. It is also necessary to bear in mind the fact that in samples tested by cyclic load triaxial test, geogrids are spaced at very small distance (because of small sample dimensions) as compared to on-site situations where the distance between individual geogrid layers is about 25-50 cm, depending on layer thickness and type of structure.

3.1.3. Geogrid aperture size

The interlocking efficiency greatly depends on the ratio of geogrid aperture size to soil grading in which the geogrid is installed. In many instances, the focus is on the relationship between rib length and average grain size (D_{50}, meaning that 50 % of grains in the sample have smaller diameter), the aim being to establish an optimum relationship between the geogrid aperture size and the soil grading. If the observed ratios are too large or too small, compared to an optimum ratio, there is a possibility that an optimum interlocking will not be achieved, with a consequent weaker reinforcement or stabilization of soil (Figure 4). Optimum ratios of geogrid aperture size and average grain size differ in studies presented in [7, 8, 56-60], where these values range from approximately $1.2xD_{50}$ [58] to more than $3.5xD_{50}$ [61, 62]. However, these ratios are the results of studies conducted using other tests and/or numerical analyses, either in static or cyclic load conditions. In the research conducted by Kim et al. [49] with cyclic load triaxial test on crushed stone samples (crushed aggregate with three different gradations, with D_{50} = 2.82 mm,

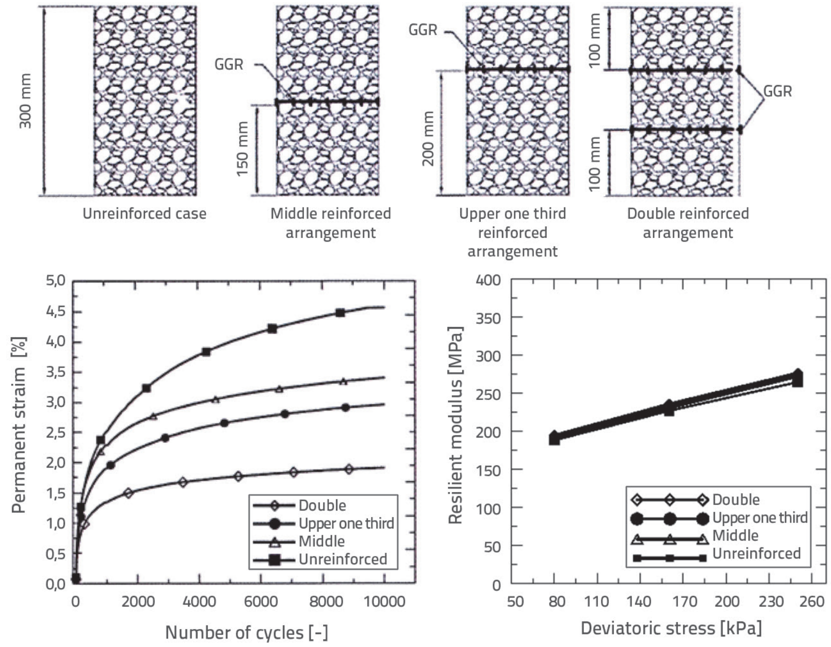

Figure 5. Cyclic load triaxial test results for various positions and numbers of installed geogrids in the sample, top: geogrid positions in the sample, bottom left: accumulated permanent deformations; bottom right: resilient modulus [41]

5.88 mm and 9.27 mm) stabilized by geogrid at mid-height of the sample (two different triaxial geogrids, with 33 and 40 mm in rib length), the smallest accumulation of permanent deformations was achieved after 2,500 load cycles for the sample with D_{50} = 5.88 mm and for 33 mm geogrid rib length. For the said result, the A/D_{50} ratio amounts to approximately 3.2 (A is defined as an equivalent aperture size equal to the inscribed circle diameter, according to the criterion from [58]). The highest shear wave velocity was registered for the same sample. According to Kim et al. [49], this velocity is attributed to possible optimum gravel to sand ratio (G/S) in the sample which enabled better particle interlocking in geogrid apertures (G/S = 1.63). Correlations of grading and geogrid aperture size are not given in the remaining studies with cyclic load triaxial test that are given in Table 1. The lack of research on the relationship between sample grading and geogrid aperture size by cyclic load triaxial test can be explained by the fact that there are certain limitations with regard to maximum sizes of samples that are being tested (standard sample dimensions are 150 mm in diameter and 300 mm in height) and limitations regarding the maximum grain size, i.e. grading of the material (according to [20, 25] maximum grain should be smaller than 1/5 of the sample diameter). Due to this limitation, commercially available geogrids installed in such samples can have apertures that are greater than optimum as related to average grain size (D_{50}). To overcome limitations related to the testing of interaction between geogrid and granular soil or other materials, some adjustments have to be made as to change in geogrid dimensions (aperture size), which is achieved by special fabrication of geogrids that are used in these tests. Fabrication of specially adapted woven geogrids [63] and welded geogrids [64] has been reported, although the testing has not been conducted by cyclic load triaxial test in these studies [63, 64].

3.1.4. Geogrid aperture shape

As biaxial and triaxial geogrids are also installed in base courses of pavement structures, some studies involving cyclic load triaxial test have been conducted in order to determine the most favourable geogrid aperture shape. Abu-Farsakh et al. [43] tested five different geogrids (three biaxial and two triaxial geogrids) and determined lower values of permanent deformation on samples stabilized with triaxial geogrids (Figure 6). Studies conducted in [34, 44, 46] also reveal smaller permanent deformations of samples stabilized with triaxial geogrids as compared to samples stabilized with biaxial geogrids (Table 1 shows the position and number of analysed geogrids and the classification symbol of material in which geogrids are installed). Byun et al. [48] report greater shear moduli in the sample with installed triaxial geogrid compared to the sample with installed biaxial geogrid. However, when comparing commercially available geogrids, ti should be noted that it is difficult to single out and define the influence of only one parameter on the interaction with soil, such as for instance the aperture shape, as the interaction is also influenced by the geogrid stiffness and the shape and dimensions of ribs.

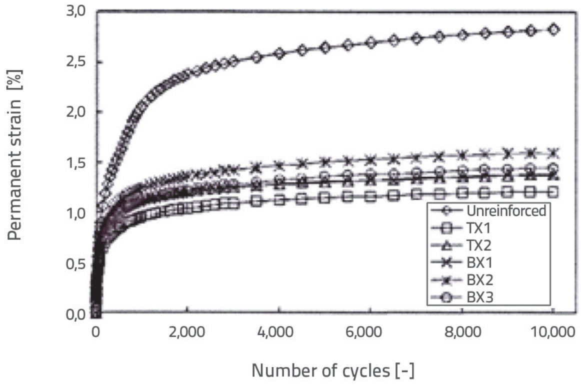

Figure 6. Development of permanent deformations with the number of load cycles for unstabilized sample and samples stabilized with biaxial (BX) and triaxial (TX) geogrids [43])

3.1.5. Geogrid stiffness

Results obtained by cyclic load triaxial testing have revealed that better results are achieved by samples stabilized with geogrids characterized by greater tensile stiffness [40, 41, 43, 46]. After having compared results with two different geogrids and three different types of soil, Kamel et al. [40] noted 18-44 % reduction of permanent deformation in the samples stabilized with geogrids having greater tensile stiffness. Nazzal [41] conducted an extensive research involving five geogrids with different tensile stiffness and with different geogrid positions within the sample, and with one or two geogrid layers. His results give the advantage to geogrids with greater stiffness at certain positions within the sample. Abu-Farsakh et al. [43] analysed two triaxial geogrids of equal aperture size but with different stiffness, and three biaxial geogrids with different stiffness values. The results obtained by Abu-Farsakh et al. [43] are shown in Figure 6 where it can be seen that the smallest accumulation of permanent deformations was registered in the case of the triaxial geogrid (marked with TX1 in Figure 6), which also had greater tensile stiffness. On the other hand, the greatest accumulation of permanent deformations in geogrid-stabilized samples was registered for the sample stabilized with biaxial geogrid with lower tensile stiffness (marked as BX2 in Figure 6; geogrids BX1 and BX2 have the same aperture size, but different stiffness). The results of cyclic load triaxial tests are in accordance with the results obtained on model tests [13, 65, 66], where advantages of stiffer geogrids use were detected.

3.2. Significant findings based on published cyclic load triaxial test results

The results of investigations conducted in [6, 41, 43] show that the installation of geogrids in samples reduces permanent vertical deformation of samples, which can not be observed for the increase in resilient modulus, that was either not registered at all or was negligible. Insignificant increase in the value of resilient moduli with the application of geogrids can be seen in Figure 5 (bottom, right), while in the case of accumulated permanent deformations (Figure 5, bottom left) the contribution of geogrids is more pronounced. Kamel et al. [40] and Rahman et al. [34] report reduction of vertical permanent and elastic deformations on geogrid-stabilized samples when compared to unstabilized samples. Gu [46] shows that the influence of geogrids on resilient modulus is greater at relatively low stress levels. Byun et al. [48] report lower values of resilient moduli when determined by cyclic load triaxial test for stabilized samples, compared to an unstabilized sample and conclude, just like in [67], that resilient moduli determined in this way can not be used for determining the effect of geogrids on the stabilization of granular materials. Although the cyclic load triaxial test according to current standards have revealed to be favourable for determining resilient moduli and permanent deformation of (unreinforced) materials that are incorporated in base course, in the case of samples stabilized by geogrids, the tests are currently favourable for determining permanent deformations only. Therefore, other tests can be used for determining stiffness of composites, such as for instance the cyclic (direct) shear test, which is reported by Han et al. [67] to be suitable for reinforced soil.

Most studies mentioned in this paper were conducted using samples 300 mm in height and 150 mm in diameter, where possibly, the interaction between geogrid and granular material did not develop as it would have been on-site. After comparison of cyclic load triaxial test results of an unstabilized smaller-size sample (204 mm in height and 102 mm in diameter) with test results for a bigger-size unstabilized sample (600 mm in height and 300 mm in diameter), Perkins et al. [6] point to the consistency in resilient modulus values and mention the possibility that the sample size has no influence on resilient modulus values. However, this conclusion is related to unstabilized samples. In addition, conventional sample sizes also dictate the values of maximum grain in the sample, which are lower than the grain size that will be incorporated in the structure, which also influences stability of interaction between granular soil and geogrids.

4. Comment on studies of geogrid-stabilized soil in triaxial apparatus under cyclic loading

The overview of the studies presented above focused on behaviour of granular soil stabilized with geogrids, based on cyclic load triaxial testing, comprises the studies that are mainly related to base courses of pavements. Considering the character of load that is transferred from vehicle wheels to base courses, the triaxial test is more favourable for laboratory testing of granular soil stabilized with geogrids when compared to direct shear or pullout test. The resilient modulus and deformation of base courses are both important for the durability and proper functionality of roadways. This is the reason why it is necessary to apply cyclic load in triaxial test, the aim of which is not to bring the sample to failure but to determine deformations and moduli after a sufficient number of load cycles. A part of published studies so far shows that resilient modulus does not increase with the application of geogrids, but that permanent deformations decrease. As mentioned previously, laboratory tests can not fully imitate real-life structures especially when the number of geogrids in the sample is increased, as such situation does not exist in the real-life structures, where the distance between individual geogrids is much greater compared to those in samples in the triaxial apparatus. Model tests and on-site road tests point to great efficiency of base course stabilization, resulting in better behaviour of pavements, both meaning the smaller incidence of rutting and lower maintenance costs. This means that mechanical properties of base courses are improved by stabilization, which can not clearly be determined in laboratory on most frequent sample sizes (150 mm in height and 300 mm in diameter) tested by cyclic triaxial test. It can be expected that with the advent of larger devices (presently such devices are commercially available for samples measuring 300 x 600 mm, while greater dimensions are also available for research purposes), it will be possible to better reproduce on-site conditions corresponding to actual realisation and use of reinforced soil structures. It is expected that with the use of cyclic triaxial apparatus for larger samples, and with the application of new measurement methods (such as those for measuring wave velocity passing through the sample), it will be possible to gain better insight into the behaviour of geogrid-stabilized granular soil for base course.

5. Conclusion

The cyclic load triaxial test is standardly used for determining resilient modulus and permanent deformation of base course materials, the aim being to determine acceptability of such materials and enable proper design of pavement structures. Due to an increasing frequency of the geogrid usage in base course of pavements, the cyclic load triaxial test has been applied over the past two decades to examine contribution of geogrids to an increase in base course bearing capacity, by varying the geogrid structure, number, and position of geogrid layers in the sample. Conducted research have revealed no or insignificant influence of geogrids on the improvement of resilient modulus, but a contribution has been noted in the reduction of accumulated permanent deformations. It has been shown that the position of geogrids greatly influences its efficiency. Samples with greater number of installed geogrid layers exhibit a greater reduction in permanent deformations; but it has also been established that more than three geogrid layers in a sample are redundant. Analyzed studies have shown a better efficiency of geogrids with greater tensile stiffness and with triangular aperture shape. However, geogrids subjected to testing were characterized by different structure (dimensions and roundness or ribs, stiffness, aperture shapes), and the impacts of individual elements were not analyzed. Future research should be focused on larger-size samples, using advanced measurement methods (wave velocities) and to distinguish the influence of elements of structure and stiffness of geogrid on its efficiency.

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