THE RESILIENT MODULUS OF HYBRID CONSTRUCTION AND DEMOLITION WASTES REINFORCED BY A GEOGRID

MODUL PROŽNOSTI HIBRIDNIH GRADBENIH ODPADKOV IN ODPADKOV PRI RUŠENJU, OJAČAN Z GEOMREŽO

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Keywords

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Ključne besede

gradbeni odpadki in odpadki pri rušenju objektov, geomreže, geotehnični inženiring, trajnost, modul prožnosti, ravnanje z odpadki

Abstract

The use of construction and demolition wastes (C&D) in engineering applications is an important development for better sustainability. The main objective of this study, therefore, was to increase the use of C&D by improving their engineering behaviour. For this purpose, two methods were employed in this study: first, adding the virgin aggregates (VA) to the C&D, called hybrid C&D (C&D-VA), and second, reinforcing the C&D with a geogrid material. Test samples were prepared in six groups. The first three test groups were prepared with C&D, VA and C&D-VA. The other three test groups were formed with geogrid-reinforced C&D, VA and C&D-VA. Firstly, for the strength characteristics of the samples, the unconfined compressive strength and the California bearing ratio values were obtained with large-scale experiments. Subsequently, for the resilient behaviour of the samples, the resilient modulus values were determined using a large-scale triaxial test device. Consequently, some significant improvements

Izvleček

Uporaba gradbenih odpadkov in odpadkov pri rušenju (C&D) v inženirskih objektih je pomemben pri razvoju za večjo trajnost. Glavni cilj pričujoče študije je torej povečati uporabo C&D z izboljšanjem njihovega inženirskega obnašanja. V ta namen sta bili v tej študiji uporabljeni dve metodi, in sicer prva dodajanje neobdelanih agregatov (VA) v C&D, imenovano hibridni C&D (C&D-VA), in druga, ojačitev z geomrežami C&D. Preizkušanci so bili pripravljeni v šestih skupinah. Prve tri preizkusne skupine so bile pripravljene s C&D, VA in C&D-VA. Druge tri preizkusne skupine so bile pripravljene tako, da so zgornjim trem skupinam bile dodane geomreže, torej ojačane C&D, VA in C&D-VA. Najprej so bile z izvajanjem obsežnih preizkusov enoosne tlačne trdnosti in kalifornijskega faktorja nosilnosti pridobljene vrednosti trdnostnih karakteristik preizkušancev. Nato so bile za deformacijsko obnašanje vzorcev določene vrednosti modula prožnosti z uporabo velike triosne preskusne naprave. Posledično *were achieved via the methods employed in this study. In addition, it was observed that the best reinforcement effect for the C&D occurred when the geogrid was used and the VA was added to the C&D.*

je bilo z metodami, uporabljenimi v tej študiji, doseženih nekaj pomembnih izboljšav. Poleg tega je bilo ugotovljeno, da je najboljši učinek ojačitve za C&D dosežen, ko je bila nameščena geomreža in dodana VA v C&D.

1 INTRODUCTION

Construction and demolition wastes (C&D) occur in construction, repair, maintenance, environmental disasters and demolition activities [1]. The C&D can consist of different types of materials, depending on the construction or demolition activities. These materials can be concrete, brick, tile, ceramic, wood, glass, plastic, bituminous mixtures, coal, petroleum products, metals, soil pieces, insulating materials, building materials containing asbestos, gypsum-based construction materials, etc. [2]. On the other hand, C&D is some of the heaviest and most voluminous waste and constitutes between 30 % and 40 % of the total solid waste [3]. Therefore, this solid waste can cause negative impacts on the environment when it is stored in a landfill. In addition, this storage is not economic. However, if the C&D is reused in some construction applications by recycling, the storage costs of the solid waste produced by the construction industry can be reduced, the need for the area of the landfill can be diminished, the use of natural resources for construction can be decreased, energy waste and greenhouse-gas emissions can be reduced, and sustainability can be increased [4-6].

Many undeveloped and developing countries store C&D without recycling in landfills. Although some developed countries recycle a part of the C&D, the level of recycling is insufficient [3]. Overall, the recycling of C&D in developed or developing countries should be increased, since recycling, recovery and sustainability are indispensable for our world at this time. Therefore, many researchers have recommended increased studies on the subject to expand the areas of use for C&D [5-11].

Generally, it is predicted that the C&D in some geotechnical applications such as fillings for various aims and base/subbase layer in an unbound pavement can be reused instead of virgin aggregate. Accordingly, several studies were conducted involving conventional laboratory tests such as proctor, unconfined compressive strength, and California bearing ratio tests. In these studies, it was mentioned that the C&D could be a good alternative to virgin aggregates in fillings. However, in many studies, it is stated that the quality of the C&D in terms of several geotechnical and physical parameters is less than that of virgin aggregates [2, 8]. In these studies, it is suggested that the engineering behaviours of the C&D should be improved. Therefore, some studies have used geosynthetics [12, 13] or additives [9, 14, 15] to improve the engineering properties of the C&D. Moreover, for the same purpose, the C&D was mixed with virgin aggregates in a few studies, and subsequently some tests were carried out with mixture aggregates [16-18]. However, because the studies usually involve small-scale conventional laboratory tests, more comprehensive research is needed to increase the reuse of C&D.

In some geotechnical applications, such as fillings and unbound pavement layers, granular soils are generally used as the filling material. Geogrids, which are a type of geosynthetics and used for reinforcement purposes, can be more suitable for an improvement of the C&D since they have an interlocking mechanism with particles if the C&D is to be transformed into a granular material and reused. Although in the literature there are many studies on the advantages of the interaction mechanism between geogrids and virgin granular soils [19-28], there are only a few studies related to C&D reinforced by geogrids [12, 13]. In addition, in studies on C&D reinforced by a geogrid, it was emphasized that the subject should be examined in more detail. On the other hand, the granular fill layers should be capable of resisting static and repeated stresses [29, 30]. Generally, the C&D consists of a wide variety of waste materials that would further complicate the behaviour under repeated stresses. When the use of C&D instead of virgin aggregates is investigated, the complex behaviour under repeated stresses of the C&D needs to be determined. The resilient modulus tests, which are performed by applying the cycling stresses in different stress combinations in a repeated load triaxial test device, can us help to understand this complex behaviour. For this reason, a few researchers have conducted resilient modulus tests on C&D. In those studies, it was stated that the C&D needs reinforcement in terms of resilient behaviour [31-34]. Recently, Chen et al. [29] in their study stated that the resilient behaviour of low-quality virgin aggregate can be improved with a geogrid. Accordingly, the resilient behaviour of the C&D can be improved with a geogrid, for example, low-quality aggregates. In this regard, Rahman et al. [35] in their study reported that the inclusion of a geogrid had effects on the resilient modulus and permanent deformation behaviour of the C&D. However, in this study, it was mentioned that studies that are related to C&D reinforced with geogrids are limited and the reinforcement effects of the geogrids under repeated stresses are still unknown.

In summary, it is necessary to improve some properties such as the resilient behaviour and the compressive strength of the C&D to increase the reuse of C&D in fillings. However, according to the literature, further investigations need to be conducted for that. In this study, two different improvement methods were investigated to improve the C&D. The first was to mix the C&D with virgin aggregates (VA). In other words, to produce a type of hybrid C&D (C&D-VA), which is an easy improvement method. The second was reinforcing the C&D with a geogrid, which is a widely used method to improve granular soils. In addition, in the case of using both methods together, the improvement of the C&D was investigated as well. The effects of improvements were evaluated for both monotonically increased stresses and cycling stresses. Accordingly, tests were carried out on large-scale test samples. It is believed that this study will make a great contribution to the literature as it investigates the effects of different improvement types and evaluates these effects in terms of monotonically increased stresses and cycling stresses. It is also estimated that the suggestions to be presented to the designer at the end of the study will increase the reuse rate of the C&D. Besides, this study offers alternatives related to reusing even low-strength C&Ds by means of some improvements. The focus of this study is to investigate the reusability by improving the C&D obtained from low-strength, classically reinforced concrete structures, of which the mean compressive strength of the concrete core samples was 14.5 MPa. The C&D was obtained by carrying out several recycling processes. For the improvement of the C&D, two methods were used for the mixing with the VA of the C&D, (C&D-VA), and the reinforcing with the geogrid. In addition, those methods were also used together . Reinforced and unreinforced C&D and the VA test samples were prepared. The resilient modulus for the resilient behaviour and the unconfined compressive strength for the compressive strength of the samples were determined using large-scale samples. The results are presented in the form of a comparison.

2. MATERIALS

2.1. Recycled, virgin and hybrid aggregates

Three different types of filling materials (granular materials) such as recycled aggregates, virgin aggregates and hybrid aggregates were used. These materials are construction and demolition waste aggregates (C&D) obtained from debris as recycled aggregates, virgin aggregates (VA) taken from a quarry and hybrid aggregates (C&D-VA) derived by mixing the C&D with the VA in equal amounts (Figure 1).

Figure 1. C&D, VA and C&D-VA.

The debris was taken from the group of low-strength RC structures, where the concrete compressive strengths of the core samples were varied between 7.5 MPa and 20 MPa, and the C&D was obtained by carrying out several recycling processes on this debris. Firstly, the debris was transferred to a crushing machine to produce proper-sized granular materials. Subsequently, steel bars and iron pieces in the debris were removed by passing them through a magnet system. After this process, the debris was crushed and the C&D materials, which have three different grain-size ranges, i.e., 0–5, 5–12, and 12–25 mm [36], were obtained. Subsequently, based on the particle size of those C&D materials, a mixture calculation was made to obtain a gradation that is suitable for use in highway base and sub-base courses [37]. Finally, the C&D materials obtained in different gradations were mixed and the C&D used as a test sample was obtained. On the other hand, for a comparison with the C&D, the VA with limestone particles was obtained from a quarry in Turkey. The gradation of the VA was made suitable to

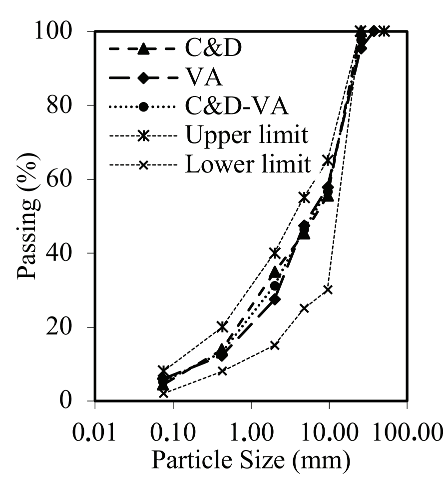

Figure 2. Gradations of the C&D, VA and C&D-VA with limit values recommended by ASTM [37].

use in highway base and sub-base courses [37], similar to the C&D [38]. Furthermore, the C&D with the VA, which has similar gradations, was mixed in equal amounts and the C&D-VA mixtures were obtained. The gradations of the C&D, the VA and the C&D-VA are shown in Figure 2.

When the C&D was examined in detail, it was clear that the C&D includes different recycled wastes, such as concrete, aggregate, brick, glass and some other materials. According to the tests carried out considering BS EN 933-11 [39], the C&D in this study consists of 36.33 % concrete (R_c), 52.65 % aggregate (R_u), 10.53 % brick (R_b), 0.11 % glass (R_g) and 0.38 % other materials (metals, non-floating wood plastic, rubber, plaster) (X). It also contains 0.7 kN/m^3 of floating particles (FL) [8].

Some physical and geotechnical properties of the C&D, the VA and the C&D-VA were obtained with laboratory tests, such as a sieve analysis, flatness index, Los Angeles abrasion, water absorption, pycnometer tests and modified compaction tests [36, 40-44]. The results obtained from these tests are shown in Table 1. In addition, compaction curves obtained from modified compaction

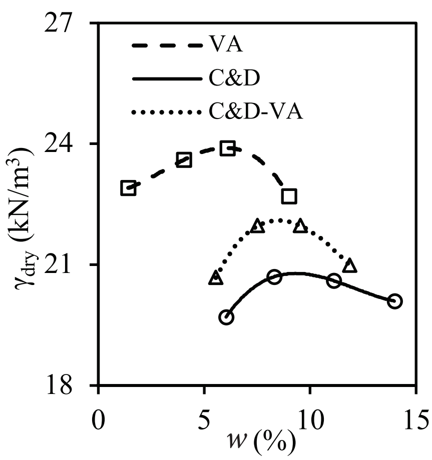

Figure 3. Compaction curves of the granular materials.

tests are shown in Figure 3. Detailed characteristics of the C&D and the VA were reported by Ok et al. [8].

2.2 Geogrid

In this research, a triaxial geogrid, which is obtained from a manufacturer, was used to improve the resilient modulus and the unconfined compressive strength of the C&D and the C&D-VA. This triaxial geogrid was manufactured from punched polypropylene sheets and has an equilateral direction to form its triangular apertures. The texture of the geogrid is shown in Figure 4, and the physical and mechanical properties of the geogrid, as provided by the manufacturer, are presented in Table 2.

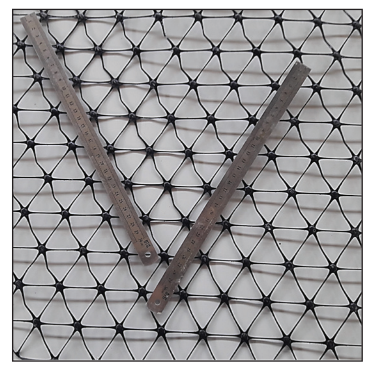

Figure 4. Geogrid.

Table 2. Properties of geogrid.

Properties	Unit	Description or value
Raw Material	-	Polypropylene
Aperture Type	-	Triangle
Aperture Dimensions	mm	40×40×40
Thickness	mm	1.1
Tensile Strength at 5 % strain, md/cmd*	kN/m	300

*: machine direction/cross machine direction

Table 1. Physical and geotechnical properties of C&D, VA and C&D-VA mixture.

Properties	Unit	C&D	VA	C&D-VA
Coefficient of uniformity (C_u)	-	41.87	35.88	39.97
Coefficient of curvature (C_c)	-	1.06	1.89	1.35
Flakiness index	%	11.68	12.66	12.11
Los Angeles abrasion loss	%	33.58	23.40	29.89
Particle Density (γ_s)	kN/m^3	26.30^f, 26.10^c	26.90^f, 27.10^c	26.55^f, 26.50^c
Water absorption	%	6.82^f, 4.06^c	0.40^f, 0.36^c	3.88^f 2.51^c
Maximum dry unit weight (γ_{drymax})	kN/m^3	20.77	23.90	21.10
Optimum water content, (w_{opt})	%	9.7	6.0	8.5

^{f}: Fine particle, ^{c}: Coarse particle

3 TESTING METHODS

3.1 California bearing ratio (CBR)

The CBR test is commonly used to compare the strength of filling materials. The test is performed by penetrating a cylindrical steel piston of 50 mm diameter into the sample, which is placed in a mold (152.4 mm diameter), at a rate of 1.27 mm/min [45]. The result of the test can be presented both in terms of load–displacement curves and percent relative (CBR value) to the reference value in the ASTM D1883–99 [45]. For the CBR tests, the filling materials with optimum water content were placed in a mold, which is used in modified compaction tests, by compacting to provide their maximum dry unit weight. Then, the prepared samples were tested according to ASTM D1883–99 [45] and their CBR values were obtained.

3.2 Large-scale unconfined compressive strength (UCS)

The UCS test is one of the most popular tests used as a key design index parameter for estimating the stiffness of soils. The UCS test includes the application of an axial vertical load through loading platens, using strain-control conditions, to a cylindrical soil sample that is unconfined. The maximum unit stress obtained from the result of the UCS test is defined as the UCS [46]. Large-scale UCS tests on geogrid-reinforced and unreinforced C&D, VA and C&D-VA were performed in this study. In the preparation of test samples, since the maximum aggregate size of the filling materials is 20 mm, a large-scale split mold, in which the effective internal height is 300 mm and the effective internal diameter is 150 mm, was used. For large-scale UCS tests, the filling materials with optimum water content were placed in a large-scale split mold and compacted to achieve the maximum dry unit weight. According to ASTM D2166 [46], the UCS tests were conducted by applying an axial strain rate of 0.5 % per minute to the samples.

3.3 Resilient modulus (M_R)

The fillings beneath oil storage tanks, silos or machine foundations and embankments such as road base/sub-base are subjected to repeated loads. In these cases, and many similar situations, the resilient behaviour of the fillings is significant in addition to the unconfined compressive strength. However, the resilient behaviour of granular materials depends on some agents. For example, granular materials can have different resilient deformation values according to the stress levels applied to them. Hence, the resilient behaviour can usually be characterized by the resilient modulus (M_R), which has different values for different stress levels. Accordingly, M_R was used by several researchers to characterize the resilient behaviour of the base/sub-base course material and the subgrade soil [47]. M_R is defined as the ratio of the deviator stress to the vertical elastic deformation [48]. In this study, M_R tests were performed using a large-scale cyclic triaxial test device to determine the resilient behaviour of the geogrid-reinforced and unreinforced C&D, VA and C&D-VA [49]. The M_R test samples with optimum water content were placed in the split mold with a diameter of 150 mm and a height of 300 mm, by providing the maximum dry unit weight. M_R tests were performed with 1000 cycles in the initial stage and then 100 cycles in each stage, for a total of 2500 load cycles. Since permanent deformation values are almost constant in the last cycles of the stress stages, the resilient modulus value of any stress stage is determined by considering the last five cycles. The stress stages for aggregate materials are shown in Table 3. According to AASHTO T-307 [49], the load pulses applied in M_R tests had a haversine-shaped loading of 0.1 seconds and rest periods of 0.9 seconds.

Table 3. Stress stages and values according to AASHTO [49].

Stress stages	Confining stress (kPa)	Deviator stress (kPa)	Bulk stress (kPa)	Stress stages	Confining stress (kPa)	Deviator stress (kPa)	Bulk stress (kPa)
0	103.4	103.4	413.7	8	68.9	137.9	344.7
1	20.7	20.7	82.7	9	68.9	206.8	413.7
2	20.7	41.4	103.4	10	103.4	68.9	379.2
3	20.7	62.1	124.1	11	103.4	103.4	413.7
4	34.5	34.5	137.9	12	103.4	206.8	517.1
5	34.5	68.9	172.4	13	137.9	103.4	517.1
6	34.5	103.4	206.8	14	137.9	137.9	551.6
7	68.9	68.9	275.8	15	137.9	275.8	*689.5*

3.4 Geogrid reinforcement

Geogrid reinforcement (RF) has been used to improve the resilient behaviour and compressive strength of filling materials (C&D and C&D-VA) obtained from recycled aggregates in this study. Furthermore, to compare the effect of geogrid reinforcement, samples of the geogrid-reinforced VA were also prepared and tested. For this purpose, the M_R and the UCS tests were carried out on geogrid-reinforced and unreinforced C&D, VA and C&D-VA. Abu-Farsakh et al. [25] conducted resilient modulus tests on virgin aggregates by placing the geogrid at different locations on the test specimen. Consequently, they stated that when the geogrid is placed in the upper or middle of the test specimen, more improvement than other locations was obtained. In this study, considering some studies in the literature [25, 35, 50], the geogrid reinforcement was placed at the mid-height of the test samples. The placement and layout of the geogrid reinforcement are shown in Figure 5.

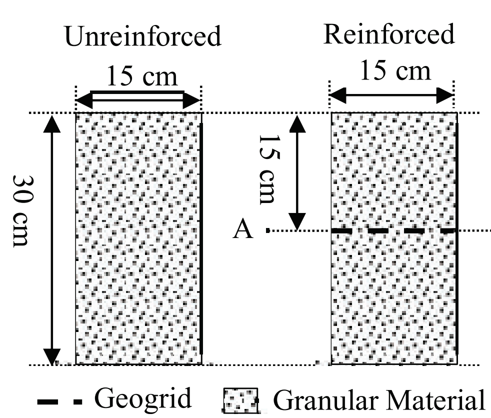

Figure 5. Placement and layout of the geogrid reinforcement.

4 DISCUSSION OF RESULTS

4.1 Evaluation of the CBR values of filling aggregates

The CBR tests were carried out on the C&D, the VA and the C&D-VA samples. The CBR values and load-displacement curves of the samples were determined according to the results of those tests. The CBR values of the C&D, the VA and the C&D-VA samples were 98.99 %, 125.16 % and 105.51 %, respectively. The load–displacement (N-s) curves of those aggregates are shown in Figure 6.

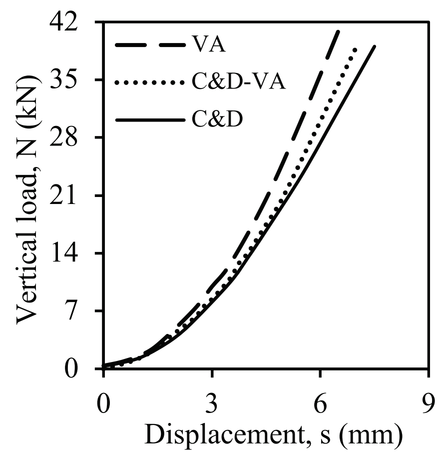

Figure 6. Load–displacement curves of the filling aggregates in CBR tests.

Considering the CBR test results, the behaviour of the load-displacement curves for all the samples were similar for displacements of less than 2 cm. However, as with the displacement increases, the situation changed in favour of the VA. This result is attributed to the fact that the VA particles are stronger than the C&D particles, as seen in the Los Angeles abrasion tests [8]. However, the CBR values indicate that the C&D and the C&D-VA samples are appropriate for use as a filling material according to some technical specifications [51, 52].

4.2 Comparison C&D with VA

Firstly, the M_R and the UCS tests were performed to determine the resilient behaviour and compressive strength of the C&D. Subsequently, for comparison, those tests were conducted on the VA. The results of those tests are shown by comparing each in Figure 7.

Figure 7 shows that the C&D is less than that of the VA in terms of both M_R and UCS. The UCS value of the VA is 30.7 % higher than that of the C&D. Moreover,

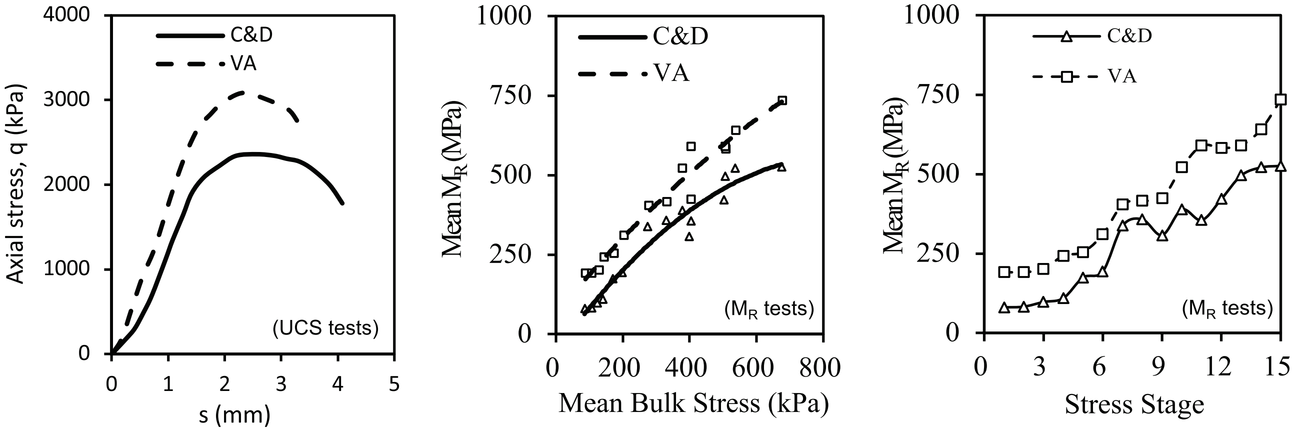

Figure 7. Stress-displacement curves and the M_R values of the C&D and the VA.

for all the stress stages, the M_R values of the C&D are lower than those of the VA. Although it has been stated in various studies that C&D can be used in some fillings, even with this performance, it has been mentioned in those studies that various improvements are needed to increase the performance of the C&D [6, 8, 16, 35, 53, 54]. Therefore, in this study, the performance of the C&D was increased by mixing the C&D with VA or using the geogrid reinforcement.

4.3 Evaluation of the C&D-VA mixture

A new aggregate mixture, namely the hybrid C&D (C&D-VA), was obtained by mixing the C&D with VA in the same proportions to increase the M_R and the UCS of the C&D. The results of the UCS and the M_R tests of the C&D-VA are shown by comparing with that of the C&D and the VA in Figure 8.

Mixing the C&D with the VA increased the UCS by approximately 11 %. Also, in all stress stages, the M_R values of the C&D-VA are more than those of the C&D. However, the improvement of both the M_R and the UCS are very limited, and the M_R and the UCS values of the VA are greater than the C&D-VA. Even if according to those results, also the C&D-VA like the C&D may be an alternative to the VA to use as a filling material, it is thought that it might need an improvement such as geogrid reinforcement [6, 8, 35].

4.4 Effects of geogrid reinforcement

Geogrid reinforcement (RF) was used to increase the M_R and the UCS of the C&D and C&D-VA. Furthermore, to compare the effect of geogrid reinforcement, the M_R and the UCS tests were also carried out on the VA reinforced by the geogrid. Accordingly, the effects of geogrid on

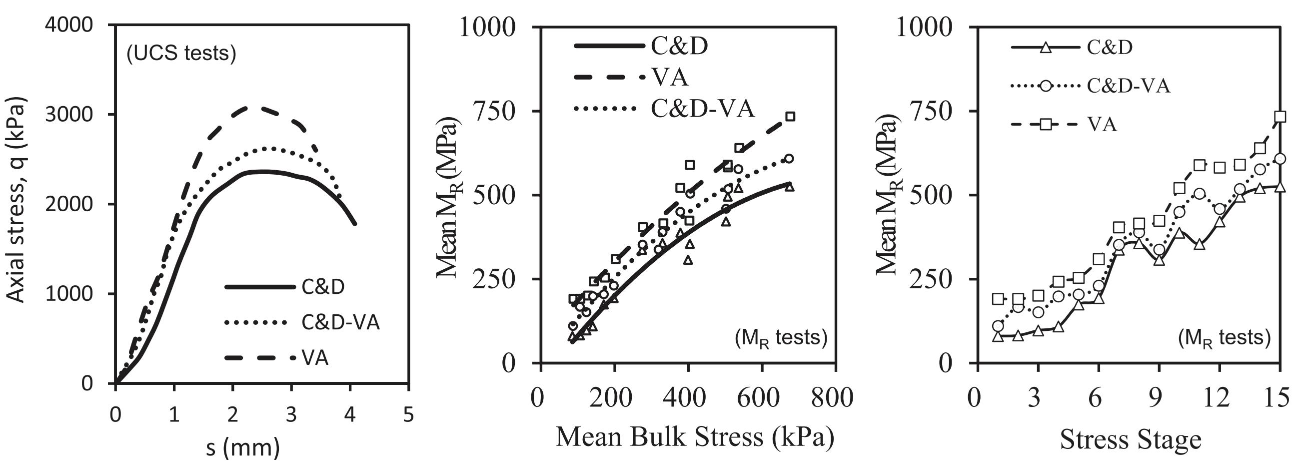

Figure 8. Stress-displacement curve and M_R values of the C&D-VA in comparison to C&D and VA.

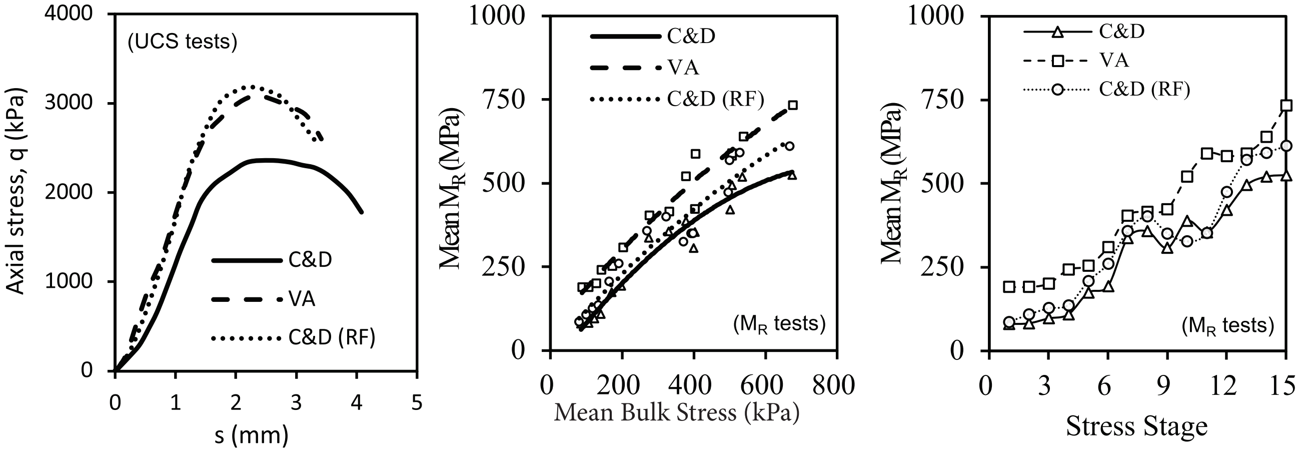

Figure 9. Stress-displacement curve and the M_R values of the C&D (RF) in comparison with the C&D and the VA.

those parameters were discussed in terms of the C&D and the VA according to the results of the tests on both reinforced C&D and reinforced VA. The results of the UCS and the M_R tests of the geogrid reinforced C&D, namely, C&D (RF), are shown by comparing with that of the C&D and the VA in Figure 9.

According to the results of tests performed on the C&D (RF), the UCS value of the C&D (RF) was approximately 35 % higher than that of the C&D. In other words when the C&D is reinforced by a geogrid, the UCS value exceeded that of the VA. However, in all the stress stages, although the M_R values of the C&D (RF) are more than those of the C&D, they are less than those of the VA. Therefore, there is a significant improvement in monotonic stress for the geogrid-reinforced C&D, while the improvement is limited in cycling stress. Consequently, for fillings exposed to static loads, the geogrid-reinforced C&D can achieve the performance of natural aggregates, but it may be necessary to develop different solutions to obtain the performance of natural aggregates in fillings exposed to repeated stress such as cycling stress. For this, reinforcement of the C&D-VA sample with a geogrid was considered. Accordingly, the UCS and the M_R tests on the C&D-VA reinforced by the geogrid, namely C&D-VA (RF), were performed. The results of those tests are shown by comparing with that of the C&D and the VA in Figure 10.

According to the results of the tests performed on the C&D-VA (RF), the UCS value of the C&D-VA (RF) was obtained as approximately 44 % and 10 % higher than that of the C&D and that of the VA, respectively. On the other hand, for all the stress stages, the M_R values of the C&D-VA (RF) are more than those of the C&D. Moreover, in the low-stress stages, although the M_R values of the C&D-VA (RF) are slightly less than those of the VA, in high-stress stages, the M_R values of the C&D-VA (RF)

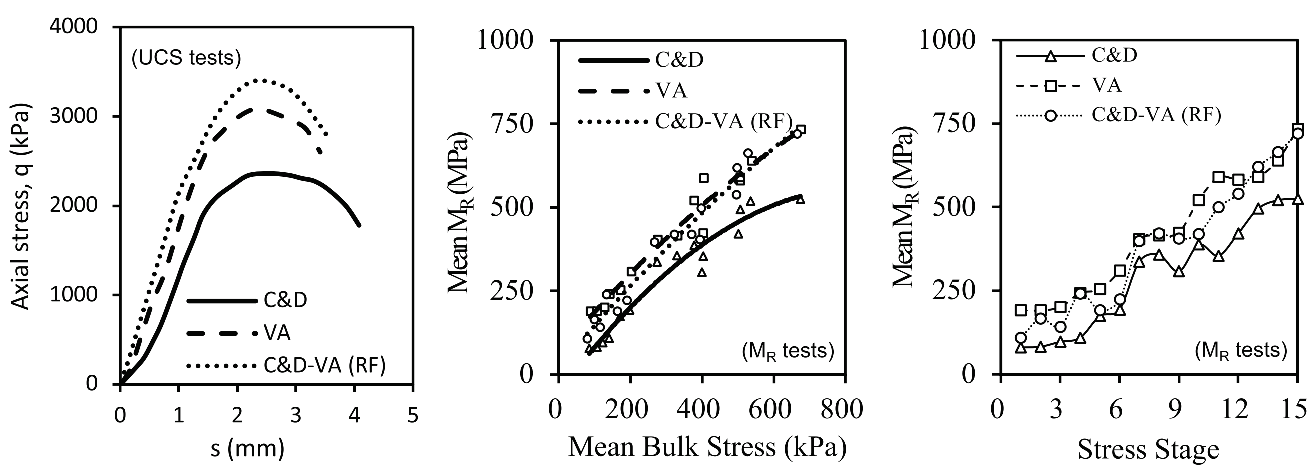

Figure 10. Stress-displacement curve and the M_R values of the C&D-VA (RF) in comparison with the C&D and the VA.

are close to those of the VA. This result is thought to be obtained due to the geogrid's reinforcement mechanisms. Geogrids have main reinforcement functions, such as lateral confinement and a membrane effect. [55]. The lateral confinement function, one of the geogrid reinforcement mechanisms, is due to the soil particles interlocking within the geogrid aperture. While soil particles cannot resist the tensile stress, the geogrid material can resist a higher tensile stress than soil particles. As the soil particles begin to deform laterally, they fall into the geogrid apertures. This situation caused the interlocking mechanism. Thus, the tensile stresses occuring in the soil particles transmit to the geogrid. Since the geogrid can resist much more tensile stress, the strength of the soil layer increases [48]. The membrane effect, another of the geogrid-reinforcement mechanisms, occurs as a result of the deformation of the soil. When any stress is applied to the soil layers, the soil layers can move down from its current position. As a result of this situation, the geogrid is deformed and tensioned. The vertical deformation creates a concave shape in the geogrid. Due to tensile stiffness of the geogrid, the concave shape performs an upward force to support the applied load and reduce the vertical stress on the soil layers. However, to achieve this effect, there must be a significant deformation [56]. When Figure 10 is examined, the deformation and stress increase, the improvement of the sample increases due to the reinforcement mechanisms, such as the membrane effect and the lateral confinement of the geogrid. Similarly, the same reinforcement mechanism was observed in geogrid-reinforced (i.e., the VA (RF)) and unreinforced VA.

The results of the M_R and the UCS tests of the VA (RF) and VA are shown Figure 11. As the deformation and stress increase, the improvement of the sample increases. For virgin aggregates, this event is in line with previous studies in the literature. In this study, in the geogrid-reinforced C&D, a reinforcement mechanism similar to the geogrid-reinforced VA was observed. Therefore, it was considered that C&D is a convenient material to reinforce with a geogrid. However, it should be considered that the reinforcement with a geogrid is more effective in high deformation and stress.

4.5 UCSR and M_RR

Two coefficients, the UCSR and the M_RR, have been defined as dimensionless parameters obtained from the results of tests. The UCSR was defined as the ratio of the UCS value obtained in the result of a test, which will be compared to the UCS value of the C&D. Similarly, M_RR was defined as the ratio of the M_R value obtained in the result of a test, which will be compared to the M_R value of the C&D, which has the same stress stages. A calculation of those coefficients is shown in Equation 1 and 2. The UCSR and M_RR values calculated from the test results are shown in Figure 12 and Figure 13, respectively.

$$UCSR = \frac{UCS}{UCS_{C\&D}} \qquad (1)$$

$$M_RR = \frac{Mean\ M_R}{Mean\ M_{R(C\&D)}} \qquad (2)$$

As seen in the UCSR values obtained from the results of the tests, for monotonically increased stresses, the performance of the C&D can increase sufficiently to obtain that of the VA when it is reinforced by a geogrid only. However, as seen in the MRR values, in repeated stresses, the reinforcing with the geogrid of the C&D might not be enough to obtain the performance of the VA. In this case, i.e., under repeated stresses, if the C&D is mixed with the VA and then the mixture is reinforced

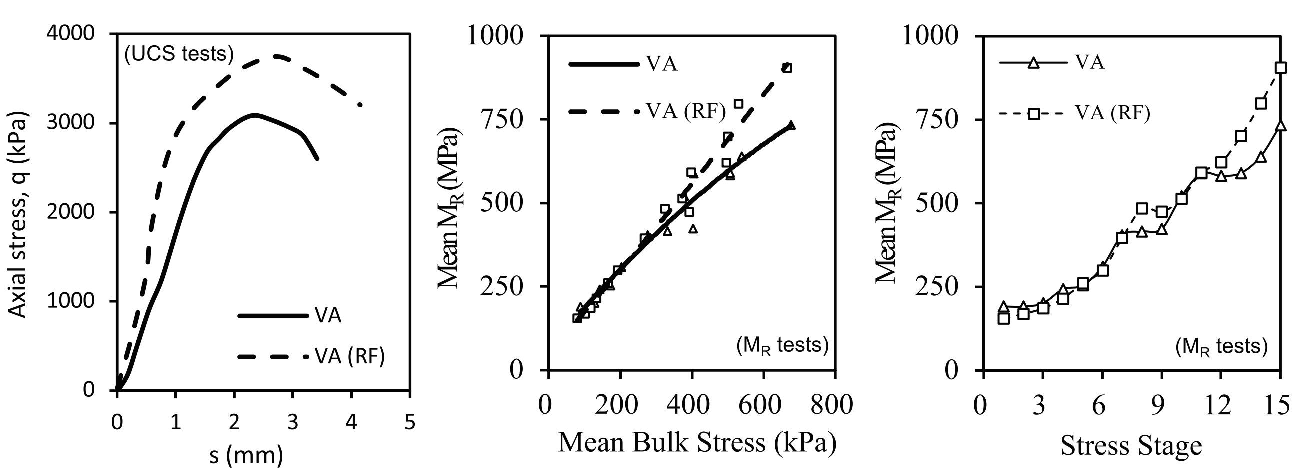

Figure 11. Stress-displacement curves and the M_R values of the reinforced and unreinforced VA.

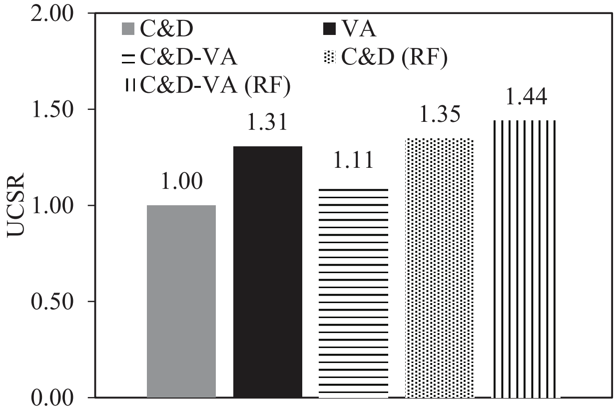

Figure 12. UCSR values.

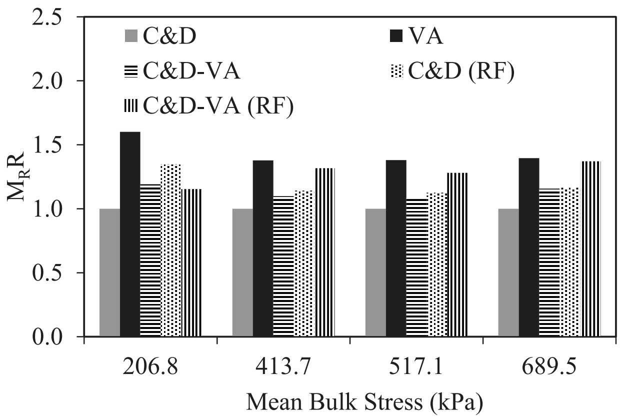

Figure 13. M_RR values according to mean bulk stress.

by the geogrid, it is clear that the performance of the VA can be achieved. It was considered that the reason for this was that the effect of cyclic loads on brittle soil grains could be greater.

5 CONCLUSIONS

In this study, laboratory tests such as resilient modulus tests and unconfined compressive tests, including large-scale tests, to improve the resilient behaviour and compressive strength of the C&D were performed. For this purpose, the effectiveness of some improvement methods, such as both the mixing with the VA of the C&D (in other words producing a type of hybrid C&D) and reinforcing the C&D with geogrid was evaluated. On the basis of the results of these tests, the following conclusions can be drawn:

- The UCS value of the C&D was obtained as 30.7 % less than that of the VA. Moreover, it was seen that the M_R values in all the stress stages of the C&D are less than those of the VA. These results, similar to those from Los Angeles abrasion tests, are assumed to be due to the VA particles being stronger than the C&D particles. The CBR test results confirm this result. So, the test results show that there is a quality difference between the C&D and the VA in terms of both monotonically increasing and repeated stresses.
- According to the results of tests on the hybrid aggregate (C&D-VA), the M_R values in all the stresses stages and the UCS value of the C&D-VA were more than those of the C&D. In the case of adding the VA to the C&D, the UCS value was increased by 11 %. However, the improvement is limited and the values of C&D-VA do not reach those of the VA.
- C&D (RF)'s UCS was approximately 35 % higher than that of C&D, thus exceeding that of the VA. However, it was found that although the M_R values of the C&D (RF) are more than those of the C&D, they are less than those of the VA for all stress stages. Therefore, it was a significant improvement in monotonically increased stresses, while the improvement was limited in the cycling stresses because the C&D is reinforced by a geogrid. If C&D is to be used in the construction of a fill, these consequences should be considered for a filling material that could be subjected to repeated stresses.
- According to the results of tests on the hybrid aggregate reinforced by a geogrid, the UCS value of the C&D-VA (RF) is approximately 44 % higher than that of the C&D, and the M_R values of the C&D-VA (RF) are more than those of the C&D.
- The UCS value of the C&D-VA (RF) was approximately 10 % higher than that of the VA. Also, the M_R values of the C&D-VA (RF) are close to those of the VA in high-stress stages, although in the low-stress stages they are slightly less. This result is thought to be due to reinforcement mechanisms, such as lateral confinement and the membrane effect of the geogrid.
- The reinforcement mechanisms of all the test samples reinforced with the geogrid were similar. Therefore, the C&D could be a suitable material to reinforce with a geogrid.
- In the case of both mixing with the VA and reinforcing with the geogrid, for the C&D it can be considered that the best improvement was achieved on both the monotonically increased and the repeated stresses. With these improvements it can be possible to have durable fillings even when using low-strength C&D, and this can increase the reuse of the C&D. Nevertheless, it should be considered that reinforcement with a geogrid is more effective for high deformation and stress in designs.
- Due to the energy-absorption feature of the geogrid, there are important advantages in dynamic cases. So,

it is recommended to conducted studies that include earthquake analysis such as Edinçliler and Yildiz [57] and Yildiz [58] for a better understanding of the behaviour of geogrid-reinforced C&D and C&D-VA.

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