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Compaction Quality Monitoring of Open-Graded Aggregates by Light Weight Deflectometer and Soil Stiffness Gauge

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Abstract: Open-graded aggregates (OGAs) are free-draining materials often used as the base layer of permeable pavements to allow the infiltration or drainage of stormwater. Despite their widespread use, the compaction quality of OGA base layers has not been specified properly. The currently used density-based compaction quality control (QC) has limitations; obtaining the field density and maximum dry density of OGAs by typical methods is challenging, due to their unique properties. To overcome these limitations, modulus-based compaction QC can be used as an alternative. In this study, five different OGAs were chosen and compacted into a specially built soil chamber to measure their densities. The light weight deflectometer (LWD) and the soil stiffness gauge (SSG) were used to evaluate the modulus of the compacted OGAs. The vibratory hammer compaction test was conducted to obtain the maximum dry density of the aggregates. Through these tests, the relationship between the modulus of the compacted aggregates and the relative density was obtained, and efforts to find a modulus range that ensures proper compaction were made. It was found that the LWD and SSG are valid and reliable devices for monitoring the modulus change of OGAs due to compaction.

Keywords: permeable pavement; open-graded aggregate; compaction quality control; light weight deflectometer (LWD); soil stiffness gauge (SSG); vibratory hammer compaction test

1. Introduction

Permeable pavement is a widely acknowledged low impact development (LID) technology that is used to mitigate water circulation problems related to recent urbanization. By allowing stormwater to infiltrate or drain under the surface of the pavement, unlike conventional impervious pavements, permeable pavements have the function of reducing surface runoff [1,2]. They are also effective in reducing pollutants included in stormwater, especially when the filter layers are installed under the surface layers, by capturing heavy metals, motor oils, and sediment [3–5]. To encourage these hydrologic functions of permeable pavements, their structure should contain connected pores. For example, in the surface layer, porous asphalt and pervious concrete are typically used; in the base layer, the layer placed directly below the surface layer, open-graded aggregates (OGAs) are generally used. OGAs are free-draining materials whose particle size distribution is very uniform and contain little fines [5,6]. When OGAs are used to construct base layers, the layers will contain large voids between particles, unlike dense-graded aggregates that are used to construct conventional base layers (Figure 1).

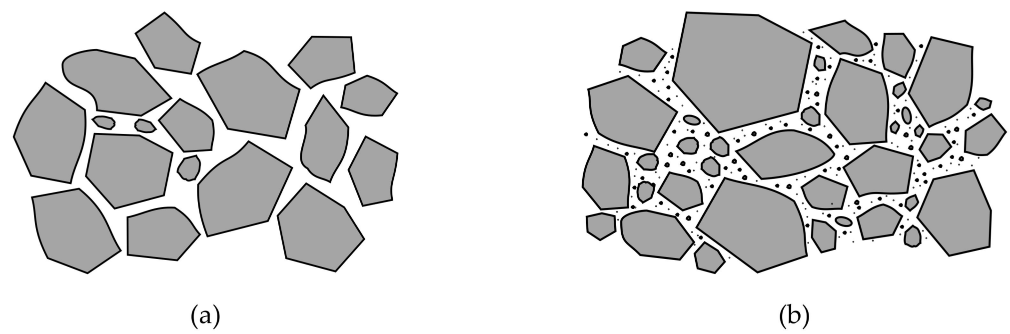

Figure 1. Conceptual illustration of pavement base materials [6]: (**a**) open-graded aggregates (OGAs); (**b**) dense-graded aggregates.

During the construction of the road pavement, the compaction of the base layer is an essential process that affects the stability and durability of the pavement, which are key engineering performance [7,8]. To properly achieve these performances, compaction quality control (QC) of the base layer should be conducted adequately during construction. However, compaction QC specifications of OGA materials have not been well established, despite the widespread use of permeable pavements.

The most common way to assess the compaction quality of compacted soil is a density-based compaction QC method. It uses the relative compaction (RC)—the ratio of field dry density (γ_d) of compacted soil and the maximum dry density ($\gamma_{d\ max}$) obtained in the laboratory—as a quality measure of compaction. However, for OGA materials, it is challenging to measure field γ_d using conventional methods such as the sand cone [9] or the rubber balloon tests [10] because OGAs cannot stand alone and maintain the shape of the test hole. Evaluating $\gamma_{d\ max}$ with the Proctor test also has limitations because the particle size of OGA is too large to meet the specifications of this test [6]. Moreover, the impact energy that this test applies to samples is not appropriate for granular soils, such as OGAs, because it causes degradation (particle breakdown) of the large aggregates and severely changes the samples. In addition, the impact energy is not an efficient compaction mechanism for granular soils, nor does it reflect the field compaction effort applied to these materials [11–13].

Besides the prevalent density-based QC method, there exists a method that assesses the quality of compaction by measuring the stiffness or modulus of on-site compacted fill using modulus evaluating devices or tests. This method, which is called modulus-based QC, is gaining popularity with the adoption of the mechanistic-empirical pavement design (MEPDG) method, and its advantage is that the measured modulus is directly related to the structural performance of the pavement and its design parameters [14]. Correspondingly, many studies have been conducted, and related specifications have been established [8,15–20]. In particular, Nazarian et al. [21] conducted extensive laboratory, small-scale, and field tests with various unbound road base materials and proposed modulus-based compaction specifications for estimating target modulus and for field quality control; Walubita et al. [22] established a comprehensive data storage system for better calibration of the mechanical-empirical design and rehabilitation of flexible pavements.

Modulus-based QC can be an effective alternative for compaction QC of OGAs because the onerous density measuring process mentioned above is not necessary. According to the trend, various permeable pavement construction guides [2,5] recommend using modulus evaluating devices such as the light weight deflectometer (LWD) or the soil stiffness gauge (SSG) to access compaction quality of OGA layers, and suggest to achieve the RC value at least 90–95% based on the standard Proctor compaction test. However, these guides [2,5] are difficult to be applied in practice because not only determining the RC of OGAs is challenging, but they do not provide target modulus values to be accomplished in the field for ensuring proper compaction, although they mention that LWD and SSG can be used to access compaction quality. Moreover, there has been a lack of research into investigating the compaction characteristics of OGAs using these devices, compared to research into commonly used dense-graded materials. Therefore, it is not yet clear whether the LWD and SSG are valid modulus-based compaction QC tools for OGA materials. Accordingly, it is difficult to implement modulus-based QC in practice based on the LWD and SSG.

For investigating the validity of the LWD and SSG as modulus evaluation and compaction QC devices and for finding possible target modulus that ensures proper compaction for OGA materials, in this study, the modulus changes of compacted OGAs corresponding to RC were investigated by the LWD and SSG. Considering the limitations existing in obtaining the $\gamma_{d\ max}$ and field γ_d of compacted OGA lift, the vibratory hammer compaction method was used to obtain the $\gamma_{d\ max}$, and five different kinds of OGA were compacted into a soil chamber specially built to measure the γ_d of the compacted OGA samples. The modulus of the compacted OGA samples was evaluated by the LWD and SSG, and the relationship between the modulus and RC was investigated.

2. Light Weight Deflectometer and Soil Stiffness Gauge

Two kinds of modulus evaluating device (LWD and SSG) were used in this study (Figure 2). The LWD is a portable device that evaluates the modulus of compacted soil by applying an impact load to the soil through the plate, and measuring the corresponding displacement. The load is applied by a falling weight dropping from a specified height, and the displacement is measured by an embedded sensor integrated into the center of the plate. From the measured deflection, the modulus is calculated based on the Boussinesq solution (Equation (1)) [23].

$$E_{LWD} = \frac{k\left(1-\nu^2\right)\sigma R}{s} \tag{1}$$

where E_{LWD} = modulus evaluated by LWD; k = 2 for flexible plate; ν = Poisson's ratio; σ = peak stress applied on the plate; R = radius of the plate; and s = peak displacement at the center of the plate. Compared to traditional plate-based modulus evaluating tests, such as the plate load test, LWD has the merits that the test is simple, the device is portable, and it disturbs the soil little. The LWD used in this study was the ZFG 3000 GPS model made by Zorn Instruments (Stendal, Germany) [24]. The radius of the plate (R) was 150 mm. A falling weight of 15 kg was used for the test. It was dropped from a height of 1150 mm, and induces 0.15 MPa peak stress (σ) to the plate. In modulus calculation, ν was assumed as 0.35, which is a typical ν of granular material [23].

The SSG, which is also referred to as a Geogauge, is a portable device that evaluates the stiffness of compacted soil by applying a very small dynamic force of about 9 N to the soil via the ring-shaped foot of the device, and measuring the corresponding displacement. The dynamic force composed of 25 steady state frequencies between 100 and 196 Hz is generated by the shaker in the device, and the displacement is measured by the embedded velocity sensor in the device. By dividing the applied load by the displacement, the SSG determines the stiffness of the soil, and displays the average stiffness (K_{SSG}) determined over the frequencies as a result. The measured stiffness can be converted to the modulus using the following equation (Equation (2)) [18].

$$E_{SSG} = K_{SSG}\frac{\left(1-\nu^2\right)}{1.77R} \tag{2}$$

where E_{SSG} = modulus evaluated by SSG; ν = Poisson's ratio; R = outside radius of SSG foot (114 mm). This non-destructive test device developed by Humboldt (Elgin, IL, USA) [25] has the advantages that the test is simple and fast, and the device is very portable. In this study, ν was assumed as 0.35, which was the same value as with the case of the LWD.

(a)

(b)

Figure 2. Devices for modulus evaluation: (**a**) light weight deflectometer (LWD) [24]; (**b**) soil stiffness gauge (SSG) [25].

Many studies have been conducted to verify the effectiveness of the LWD and SSG for modulus evaluating and as QC devices for typical road bases and subgrades that use dense-graded soils. Abu-Farsakh et al. [15] conducted a comprehensive laboratory and field experimental program on various types of subgrade and base materials using modulus evaluating devices, including the LWD and SSG, and assessed their potential use as QC devices for compacted soils. The German Federal Ministry of Transport [17] suggested target LWD modulus (E_{LWD}) values for compacted soil that ensure a certain RC. Examples of the target values are shown in Table 1.

Table 1. German modulus-based compaction specification based on LWD [17].

Soil Group (DIN 18196 [1])	RC [3] (%)	E_{LWD} [4](MPa)
GW, GI [2]	≥ 103	≥ 60
	≥ 100	≥ 50
	≥ 98	≥ 40
	≥ 97	≥ 35
GE, SE, SW, SI [2]	≥ 100	≥ 40
	≥ 98	≥ 35
	≥ 97	≥ 32

[1] German soil classification; [2] Abbreviations G, S, W, I, E corresponds to gravel, sand, well-graded, gab-graded, poorly graded, respectively; [3] Relative Compaction; [4] LWD modulus.

Elhakim et al. [16] built a 1 m^3 soil chamber and obtained relationships between the RC and E_{LWD} of two poorly-graded sand, and compared the test results with the suggested values of the German Federal Ministry of Transport [17]. This study found that the average of the E_{LWD}–RC relationships evaluated in the two sand was similar to the suggested values [17], and the results were better agreed with the suggested values [17] when the RC was greater 95%. Umashankar et al. [20] performed field tests in an expressway to assess the feasibility of using the LWD for compaction QC of the base and surface layers of pavements. The study found that the LWD modulus is highly related to the field γ_d obtained from sand-cone tests. Schwartz et al. [26] evaluated the modulus-based compaction characteristics of unbound pavement materials in a large-scale controlled test pit with three different types of LWDs. In addition, the research developed the "LWD drops on Proctor molds" method, proposing a method to determine the LWD target modulus for field considering the water content change, and performed field verification tests. Lenke et al. [18] assessed the use of the SSG as a modulus-based compaction QC device through laboratory and field tests. The study found that the SSG stiffness of base materials in the field showed a clear increase with the improvement of compaction level as evidenced by the monitoring of roller passes. Abu-Farsakh et al. [15] reported that SSG stiffness increased with respect to density increase. However, it was found that soil type and moisture content also affect the results. Meanwhile, modulus measurement may significantly vary depending on the device, even if it is used for the same soil. Meehan et al. [19] explained that the difference was caused by the inherent differences of operating principles of the devices.

Current studies described above have mainly focused on dense-graded materials. In contrast, there is no research regarding modulus-based compaction QC of OGA materials using the LWD and SSG to the authors' best knowledge. This study aims to investigate the validity of the LWD and SSG as modulus evaluation and compaction QC devices for OGA materials and for finding possible target modulus that ensures proper compaction for them.

3. Experimental Program

3.1. Materials

Five types of OGA were prepared for the test (Table 2). These materials are the same as those used in the previous study by Choi et al. [6]. Three types of rhyolite OGA were prepared in an air-dried condition before the test (Figure 3); the maximum particle sizes of these aggregates were 40 mm (D40), 25 mm (D25), and 13 mm (D13). Two additional aggregates, "D40 + D25" and "D25 + D13," were prepared by mixing their component aggregates in the same volume ratio. The mixing of the materials was conducted using a backhoe excavator, and the mixing volumes of the aggregates were controlled by the excavator bucket. The volumetric composition, basic properties, and particle size distributions of the materials are presented in Table 2 and Figure 4.

(a) (b) (c)

Figure 3. Air-dried open-graded aggregates (OGA) used for the test. The maximum particle sizes are: (**a**) 40 mm (D40); (**b**) 25 mm (D25); (**c**) 13 mm (D13) (modified from Choi et al. [6]).

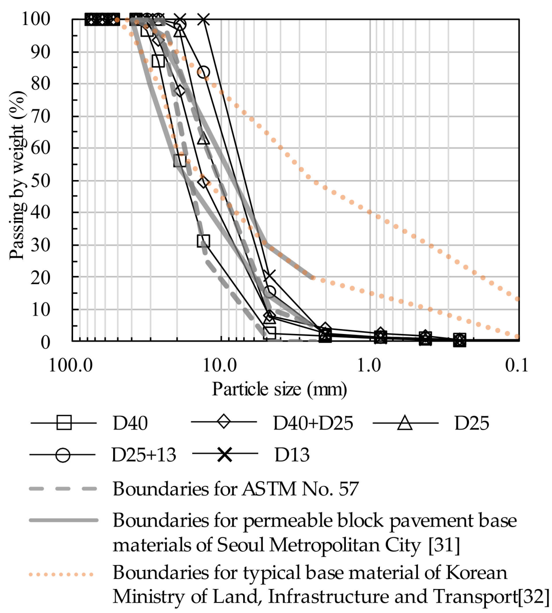

Figure 4. Particle size distribution of test materials and specifications (modified from Choi et al. [6]). Note: The particle size distributions of the test materials were obtained based on KS F 2502 [27].

Table 2. Basic information of the test materials (modified from Choi et al. [6]).

Test Material	Lithology	Material Composition by Volume (%) [1]			C_u [2]	C_c [3]	USCS [4]	G_s [5]	*W*[6] (%)	LA [7] (%)
		D40	D25	D13						
D40	Rhyolite	100	-	-	2.88	1.19	GP [8]	2.67~2.75	0.4	12.8
D40 + D25		50	50	-	2.99	1.08			0.5	9.8
D25		-	100	-	2.48	1.02			0.5	10.3
D25 + D13		-	50	50	2.84	1.16			0.5	11.2
D13		-	-	100	2.79	1.16			0.5	12.3

[1] Mixing of the materials were conducted using backhoe excavator, and the mixing volumes of the aggregates were controlled by the excavator bucket; [2] Coefficient of uniformity; [3] Coefficient of curvature; [4] Unified Soil Classification System; [5] Specific gravity based on KS F 2366 [28]; [6] Water content based on KS F 2550 [29]; [7] Loss by abrasion based on ASTM C131/C131M-14 [30]; [8] Poorly-graded gravel.

The water content of the materials was no more than 0.5%, which approximated the air-dried condition. Eisenberg et al. [5] and Smith [2] proposed ASTM No. 57 as the particle size distribution boundaries of OGA for the base layer of permeable pavements. Seoul Metropolitan City [31] also has its own specification of OGA particle size distribution boundaries for the base layer of permeable block pavements. For comparison, the boundaries are presented in Figure 4, including typically used dense-graded base materials proposed by the Korean specifications for road construction [32].

3.2. Equipment and Procedure

To obtain RC in OGAs, the vibratory hammer compaction test method [33] was used to determine the $\gamma_{d\ max}$ instead of the Proctor compaction test, and the soil chamber patterned on the Proctor mold was built to obtain the RC of compacted OGA samples and the corresponding modulus. Some details of the tests are described below.

3.2.1. Vibratory Hammer Compaction Test

To determine the $\gamma_{d\ max}$ of the OGAs, the recently developed vibratory hammer compaction test [33] was adopted. This method uses specified vibratory energy applied by a vibrating hammer and surcharge for compaction instead of impact energy that the Proctor test applies. Soil is compacted into a mold with a diameter of 152.4 mm, or 279.4 mm in three layers. Each layer is compacted with a specified compaction time for each mold. The test is conducted at two water content conditions—an oven-dried condition (dry method) and a saturated condition (saturated method)—because the $\gamma_{d\ max}$ tends to be obtained at the nearly dry or saturated condition in free-draining granular soils, rather than at an intermediate water content [13]. The $\gamma_{d\ max}$ is the larger γ_d determined from the two water contents. It can reflect field compacting effort and be applicable to the free-draining granular soils that contain large particles up to 50 mm when the 279.4 mm mold is used. It causes a minimal amount of degradation, and it produces a comparable $\gamma_{d\ max}$ with a modified Proctor test [13]. The test should be repeated at least twice with new specimens until the difference in the test results obtained from either dry or saturated method is not more than 2%.

In this study, the vibratory hammer compaction tests were conducted twice for each water content condition (dry and saturated condition), and with every test material (Table 2), using a 279.4 mm diameter mold. In the dry method, air-dried materials were used in the test instead of oven-dried material since the water content of the test materials was negligible (less than 0.5%). In the saturated method, water was continuously supplied just above the top of the layer to maintain the saturated state of the tested material, as the test standard [33] suggested.

3.2.2. Soil Chamber and Modulus Evaluation Test

The developed soil chamber for evaluating the relationship between the density and modulus of the compacted OGA is shown, with its dimensions, in Figure 5. The chamber includes a base plate, mold, and extension collar assembly, as with the Proctor mold. The base plate was for providing stable seating of the soil chamber, and the extension collar was for trimming the compacted specimen above the top of the mold evenly to make the intended height of the test sample and measure the density accurately. The height of the mold was determined higher than the stress influence depth (less than 60 cm) of the LWD and SSG [34,35]. The diameter of the chamber was determined to be large enough to perform four LWD and two SSG tests at different places.

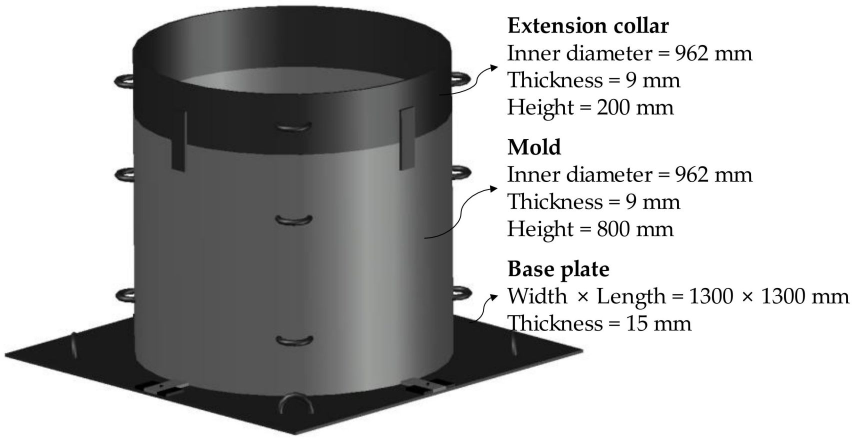

Figure 5. Schematic representation of the developed soil chamber.

The test sample was made in the soil chamber according to the following procedure. First, one of the test materials (Table 2) was compacted into the mold in three layers with approximately the same thickness, using a vibratory plate compactor (Figure 6a,b).

(a) (b) (c) (d)

Figure 6. Soil chamber and modulus evaluation test procedure: (**a**) pouring test material into the mold; (**b**) compaction with vibratory plate compactor; (**c**) modulus evaluation with LWD and SSG; (**d**) weight measurement using hoist scale.

Each layer was subjected to the same compaction time. Every edge of the mold was carefully compacted. These procedures were for making uniform sample composition. The third layer was compacted slightly above the mold into the extension collar. After the compaction of the third layer, the extension collar was removed, and the aggregate above the height of the mold (800 mm) was trimmed evenly using a straightedge. This sample height is sufficiently high for the LWD and SSG test results not to be influenced by the layer thickness, considering the influence depth of both devices mentioned above. After the compacted sample was prepared, two SSG and four LWD tests were conducted (Figure 6c) in a row to evaluate the stiffness. When conducting the tests, the test area should be 1.5 times larger than the diameter of the loading plate (30 cm) [16,34]. Accordingly, the test points were placed symmetrically as shown in Figure 7 from the center of the chamber, and the effort was made to perform the test at least 15 cm away from the wall of the chamber to secure the test area and to avoid wall effect.

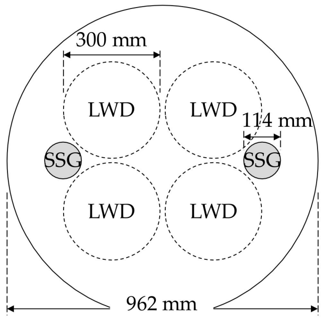

Figure 7. Layout of the test points.

For SSG tests, this study followed the test procedure presented in ASTM D6758, with certain modifications as described below. Although the test is not usually used for gravelly soils and the test standard and the manufacturer [25] strongly recommends applying a thin sand layer on the ground for the proper seating of the device if the soil surface to be tested is particularly hard or rough, seating sand was not applied here because, even if the sand were applied, the sand would pass through the large pores between the aggregate particles. However, contact between the device and the ground was strictly confirmed by rotating the SSG and checking the footprint left by the device's ring-shaped foot (Figure 8) based on ASTM D6758 [35]. Three consecutive measurements were performed at each test point.

Figure 8. Footprint left by the ring-shaped foot of the SSG.

For the LWD test, the authors generally followed the test procedure presented in ASTM E2835 [34]. Although the test procedure also recommends installing seating sand on the ground, this was not applied for the same reason as with the SSG test case; furthermore, the compacted surface of the samples was sufficiently flat, considering the size of the plate. Six drops of the falling weight were performed at each test point. The first three drops were for seating, and the next three drops were for analysis.

After the SSG and LWD tests were finished, the weight of the sample was measured by a hoist scale (Figure 6d). The aggregates were subsequently discarded before the following sample preparations and tests. Following these procedures, samples with several different densities were created, and the density–modulus correlation of each test material (Figure 10) was established. The whole test cases can be summarized as Table 3.

Table 3. Test Cases.

Material	Sample Thickness	Number of Unit Weights Considered	Number of Test Points	
			LWD	SSG
D40 D40 + D25 D25 D25 + D13 D13	80 cm	5	4 [1]	2 [2]

[1] Six drops of falling weight were done at each test point. First three drops were for seating and next three drops were for analysis; [2] Three consecutive measurements were done at each test point.

4. Results and Discussion

4.1. Maximum Dry Density of Open-Graded Aggregates

The results of the vibratory hammer compaction test are shown in Figure 9. The test was performed twice each for dry and saturated conditions of each test material. In the dry condition, the water contents of the test samples were not more than 0.5% (Table 2), and in the saturated condition, the saturation was maintained by continuously supplying water until the top of the samples during the test. The plotted values are mean values. The difference between the two test results was less than 2%, which agreed with ASTM D7382-07 [33], except D40, which was 3%. This could be attributed to its relatively large particle size. Although the difference between test results of D40 was a little higher than 2%, overall variations were not notable. It seems that the vibratory hammer compaction test produces moderately consistent test results in OGA materials. The $\gamma_{d\ max}$ was obtained only when OGAs were compacted in the dry condition (less than 0.5% of water content). In the dry method, mixed OGAs (D40 + D25, D25 + D13) showed higher $\gamma_{d\ max}$ than non-mixed OGAs (D40, D25, D13). This was because the smaller particles of the mixed aggregate filled the voids during compaction. However, this trend was not observed in the saturated condition. The reason might be because excessive pore pressure induced by the vibratory hammer disturbed the aggregates and compaction state. In the construction of a typical road base that uses dense-graded soils, wetting of the soil is important for efficient compaction. However, because the $\gamma_{d\ max}$ tends to be obtained at the nearly dry or saturated condition in free-draining granular soils, rather than at an intermediate water content [13], the test result indicates that in the laboratory OGAs should be compacted when the samples are in the dry condition not saturated.

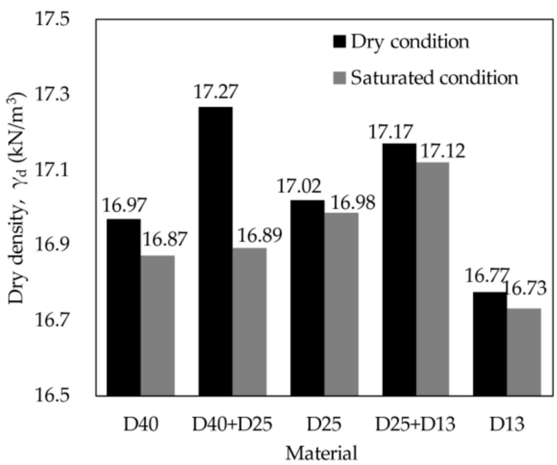

Figure 9. Results of vibratory hammer compaction tests. Note: The test was performed twice for each water content condition with each test material; Plotted values are mean values; The difference of the two test results agreed to within 2%, except for D40, which was 3%.

4.2. Relationship between Dry Density and Modulus

The relationship between dry density and modulus obtained by the soil chamber test is summarized in Table 4 and plotted in Figure 10 with the linear trend line. The symbol and error bar represent the mean value, and the maximum and minimum values of the measurements, respectively.

Table 4. Summary of relationship between dry density (γ_d), relative compaction (RC), and modulus (E_{LWD}, E_{SSG}).

Material	γ_d (kN/m^3)	RC (%)	E_{LWD} [1]				E_{SSG} [2]			
			Mean (MPa)	Max (MPa)	Min (MPa)	CV [3] (%)	Mean (MPa)	Max (MPa)	Min (MPa)	CV [3] (%)
D40	15.39	91.07	25.50	28.23	23.72	6.7%	38.20	44.23	34.78	8.6%
	15.56	92.06	27.89	30.59	24.06	9.2%	42.02	45.59	37.31	6.1%
	15.86	93.85	27.05	29.12	23.96	7.0%	41.40	45.64	39.01	7.0%
	16.03	94.85	35.78	43.49	29.56	16.2%	41.51	45.28	35.79	7.6%
	16.25	96.14	42.10	46.68	38.94	7.5%	49.18	52.00	45.58	4.5%
D40 + D25	15.28	88.92	22.59	27.93	18.16	15.5%	36.88	38.15	35.15	2.8%
	15.74	91.56	32.63	34.01	30.61	4.5%	39.08	43.15	35.04	6.6%
	15.84	92.14	28.87	31.82	27.77	5.9%	43.71	47.70	39.46	6.8%
	16.14	93.90	31.02	32.91	29.91	4.3%	44.06	47.35	40.97	6.3%
	16.22	94.39	41.75	47.92	30.31	16.3%	52.78	55.33	50.45	3.7%
D25	14.99	88.54	27.41	30.68	24.56	8.1%	38.29	41.69	35.24	6.3%
	15.34	90.61	28.31	29.94	26.70	4.3%	42.07	44.71	40.36	3.9%
	15.70	92.69	35.11	38.23	30.68	8.3%	42.98	46.07	39.92	4.2%
	15.93	94.08	39.51	40.92	37.36	3.5%	43.24	46.99	39.15	6.0%
	16.07	94.87	41.77	43.54	39.17	4.1%	47.30	50.34	44.45	4.5%
D25 + D13	15.66	91.68	27.91	29.53	25.12	6.0%	34.04	36.73	30.73	5.6%
	15.76	92.27	31.69	33.32	30.80	3.6%	37.79	43.77	34.23	8.1%
	15.86	92.86	35.96	38.37	33.52	4.8%	41.64	44.11	40.40	3.1%
	16.00	93.65	41.46	44.67	37.71	7.0%	46.21	49.96	41.17	5.9%
	16.27	95.22	36.20	38.87	31.97	8.3%	43.34	46.27	41.52	4.0%
D13	15.38	92.13	34.57	39.49	30.73	9.2%	38.47	40.60	35.70	5.4%
	15.48	92.73	37.76	45.13	33.75	11.6%	46.17	50.58	39.90	7.6%
	15.39	92.23	27.21	29.06	22.90	9.2%	38.07	38.55	37.76	0.7%
	15.61	93.54	39.42	41.74	37.36	4.0%	43.01	47.59	35.84	9.7%
	15.78	94.54	35.54	41.09	32.96	9.2%	46.50	49.23	44.08	3.7%

[1] Four measurements at each density; [2] Six measurements at each density; [3] Coefficient of variation.

E_{LWD} and E_{SSG} generally show an increasing tendency with an increase in density for all tested OGAs. These results agree with the previous research implemented for the dense-graded soils that are usually used in typical road base construction [15,18]. It seems that both the LWD and the SSG can adequately capture changes in the modulus of OGAs with density increase. In the case of the SSG test, because seating sand was not installed, contrary to the strong recommendation by the test standard and manufacturer, and because contact between the device and soil was ensured only by its footprint left by rotating its annular ring foot before the measurement, poor results were expected. Nevertheless, the device was able to capture changes in modulus with density increases well, as can be seen in Figure 10. This indicates that seating sand is unnecessary in OGAs if contact between the device and soil is well-ensured by rotating the device and checking its footprint. Variation among measurements significantly affects the reliability of the test devices. The coefficient of variation (CV) of the LWD and SSG measurements for OGA materials showed relatively low values (Table 5).

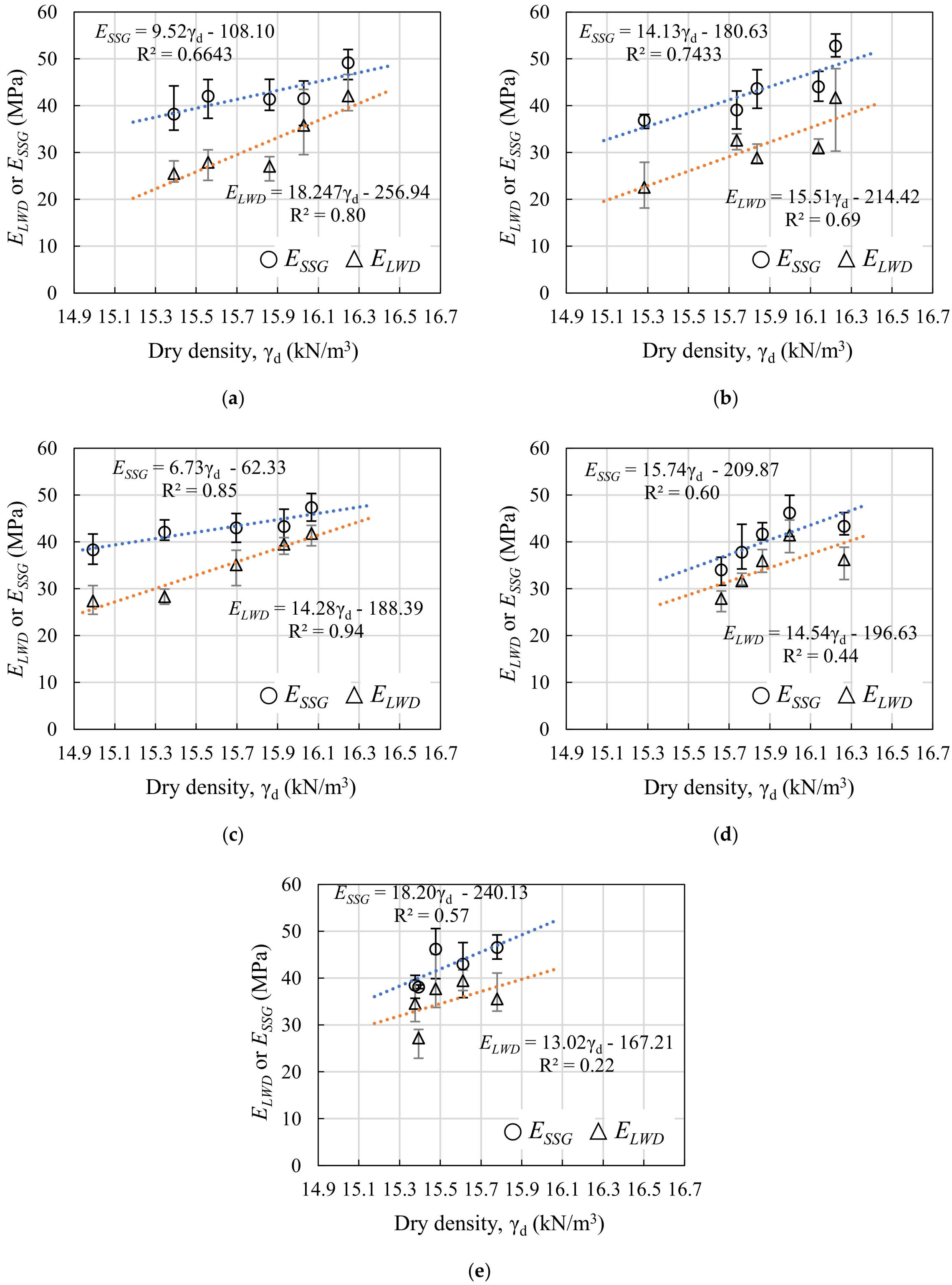

Figure 10. Relationship between dry density (γ_d) and modulus (E_{LWD}, E_{SSG}): (**a**) D40; (**b**) D40 + D25; (**c**) D25; (**d**) D25 + D13; (**e**) D13. Note: the symbol and error bar represent the mean value, and the maximum and minimum values of the measurements, respectively.

Table 5. Coefficients of variation (CV) of modulus measures.

Modulus	Coefficient of variation, CV (%)	
	Maximum	Mean
E_{LWD}	16.3	7.8
E_{SSG}	9.7	5.6

The maximum CV among E_{LWD} in this study was far lower than the value of 28% obtained by Abu-Farsakh et al. [15], conducted for dense-graded subgrade and base materials. The mean value also showed a lower level than the 17% for the poorly-graded gravel (GP) material (based on the unified soil classification system, USCS) of a previous study [14]. The mean and maximum CV among E_{SSG} were lower than those of E_{LWD}, which shows that the SSG test for OGAs produces consistent results even without seating sand. Seating sand may not be a critical factor which affects the consistency of measure data. Overall, it is considered that the LWD and SSG are valid and fairly reliable devices for monitoring the modulus change of OGA due to compaction.

The modulus measurements were highly dependent on the test device. For the same test sample, E_{SSG} showed consistently higher values than E_{LWD}, at about 6–12 MPa, even though the calculation of both moduli is based on elastic theory. It might be due to the difference of induced stress level and operating principles of the devices [19]. When the SSG is to be used to evaluate the modulus of OGA, caution should be taken because it can overestimate the modulus.

4.3. Relationship Between Relative Density and Modulus

Using the results obtained from the vibratory hammer compaction test ($\gamma_{d\ max}$) and soil chamber test (mean E_{SSG} and E_{LWD} corresponding to γ_d) (Table 4), the relationship between the RC and the modulus was plotted in Figure 11.

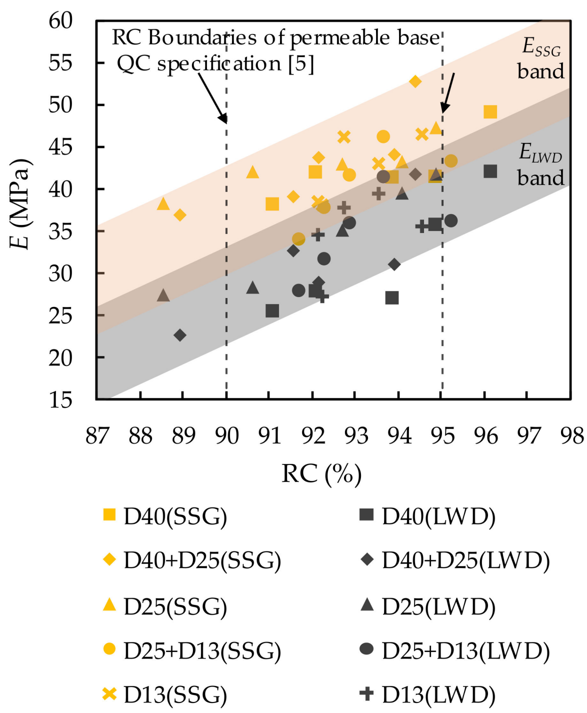

Figure 11. Relationship between relative compaction (RC) and modulus (E_{LWD}, E_{SSG}).

Expectedly, the tendency of the modulus to increase with RC increment was observed in both. However, the modulus range between E_{LWD} and E_{SSG} showed a general difference, and the range was lower than that obtained from conventional road base materials, which is dense-graded materials. The overall modulus of OGAs compacted to an RC of 88–96% was 22–42 MPa for E_{LWD} and 34–53 MPa for E_{SSG}. The results were highly dependent on the test device as stated before, rather than the test material. Although modulus values of compacted soil depend on the compaction level, when they are compared with the values of dense-graded soil, the E_{LWD} range of OGA obtained in this study (22–43 MPa) included a representative E_{LWD} of typical compacted poorly-graded gravel (41 MPa) from Nazzal [14]. In the case of the SSG, the comparison was difficult because the SSG is not usually tested for poorly-graded gravel. When the E_{SSG} range of OGA (34–53 MPa) is compared with that of sandy material instead, it is lower than that of compacted well-graded sand (50–56 MPa) [15].

During the chamber test, it was difficult to create samples of over 94% RC with all test materials. Considerable compaction efforts with the vibratory plate compactor were required. The plate compactor had to pass over the whole area of the aggregate surface more than 12 times for each layer to obtain such RC, and this required approximately 8 min of compacting time for each layer. Compacting the OGA layer with the vibratory plate compactor to over 94% RC appears inefficient. In the case of D13, because of its relatively small particle size and light weight, the movement of the plate compactor disturbed the sample and resulted in an uneven sample compaction state. Accordingly, it was hard to make samples with a sufficiently high and wide range of RC, and the results showed the most inconsistent tendency, compared to the other four test materials. The coefficient of determination (R^2) of the linear trend line shown in Figure 10 also presented the highest value among the materials. If one wants to achieve proper compaction effect and an RC value larger than about 94% during OGA base construction, it is recommended to use compaction equipment that provides larger vibratory compaction energy, such as a 10-ton vibratory roller compactor, and avoid materials which have a large proportion of small particles. If plate compactor should be used in the compaction (e.g., when the construction site is narrow), reducing lift thickness also can be another alternative for better compaction efficiency. A study to find the optimal lift thickness for the most efficient construction of OGA base layers is desired in the future.

Eisenberg et al. [5] suggested upper and lower boundaries of RC (standard Proctor) that ensure proper compaction of OGA. These were presented together with the test results (Figure 11). There are some limitations to directly adopt these RC boundaries to this research because the standard Proctor test is not compatible to OGA materials and yields smaller $\gamma_{d\,max}$ than the vibratory hammer compaction test [13] However, those were applied as reference RC boundaries in this study to identify the corresponding required modulus. According to the colored band and points in Figure 11, the minimum and maximum required modulus would be around 25 MPa and 40 MPa for LWD and 35 MPa and 50 MPa for SSG, respectively, for obtaining 90–95% RC by vibratory hammer compaction test. However, because the methods used to determine the $\gamma_{d\,max}$ in Eisenberg et al. [5] and this study are different, in order to set the required modulus of OGA materials for proper compaction in the field, it is considered that field verification tests should be performed.

When implementing compaction QC using an LWD, the German Federal Ministry of Transport [17] is frequently used as a QC specification (Table 1). However, RC-E_{LWD} correlation presented in Table 1 is inadequate to be compared directly with the test results in Figure 11, because this specification uses a standard Proctor compaction test for RC measurement, and assumes the Poisson ratio to be 0.5 to calculate the modulus for all soils Sulewska [8]. Therefore, when the correlation of GE material (Table 1), which corresponds to GP in the USCS, was directly compared with the test results, it was not comparable with the E_{LWD} band in Figure 11. However, considering that Poisson's ratio 0.35, which is more suitable for aggregates, was used in this study to calculate E_{LWD} (Equation (1)) and that the vibratory hammer compaction test yields larger $\gamma_{d\,max}$ than the standard Proctor compaction test [13], the RC would become smaller and the E_{LWD} would become bigger in the correlation in Table 1. Therefore, in this case, the correlation would be more closely plotted to the E_{LWD} band in Figure 11.

5. Limitations and Need for Future Research

The target modulus ranges proposed in this study were the moduli corresponding to the 90–95% of RC, based on the standard Proctor test. In this study, however, the moduli and corresponding RC were obtained from $\gamma_{d\ max}$ determined by the vibratory hammer compaction test. In order to verify and set the required modulus of OGAs for proper compaction in the field, it seems that real-scale field verification tests are necessary.

Other than the issues addressed in this study, there are other important issues to be considered during compacting unbound base materials on-site, for example, the lift thickness at which compactors can provide the best efficiency, and the most efficient number of passes that compactor should achieve to obtain proper compaction quality. These issues need to be addressed in further research to broaden insights of the compaction characteristics of OGAs.

6. Conclusions

For investigating the effectiveness of the LWD and SSG as modulus evaluation and compaction QC devices for OGA materials, the modulus change of compacted OGAs was investigated by LWD and SSG, corresponding to RC. Throughout vibratory hammer compaction and soil chamber tests, E_{LWD} and E_{SSG} corresponding to density of compacted OGA samples were investigated. Based on the test results, the following findings emerged:

- In the vibratory hammer compaction test, the $\gamma_{d\ max}$ was obtained when OGAs were compacted in the dry condition (less than 0.5% of water content) rather than in saturated condition. Because the $\gamma_{d\ max}$ tends to be obtained at either nearly dry or saturated condition in free-draining granular soils, rather than at an intermediate water content [13], the test result indicates that in the laboratory OGAs should be compacted when the samples are dry not saturated.
- Both the LWD and the SSG captured changes in the modulus of OGAs with density increase adequately, and the variation of each device's measurements was not significant compared to the previous studies conducted on dense-graded soils. It is considered that the LWD and SSG are valid and fairly reliable devices for monitoring the modulus change of OGAs due to compaction.
- The overall modulus of an OGA compacted to an RC of 88–96% by the vibratory hammer compaction test was 22–42 MPa for E_{LWD} and 34–53 MPa for E_{SSG}. The results were highly dependent on the test device rather than the test materials. For the same test sample, E_{SSG} showed consistently higher values than E_{LWD}. When the SSG is to be used to evaluate the modulus of OGA, caution should be taken because it may overestimate the modulus.
- During the chamber test, it was difficult to create samples of over 94% RC with the vibratory plate compactor, especially when compacting D13 samples, whose particle size is the smallest. To achieve the proper compaction effect and an RC value larger than approximately 94% during OGA base construction, it is recommended to use compaction equipment that provides larger vibratory compaction energy, such as a 10-ton vibratory roller compactor, and to avoid material that has a large proportion of small particles.
- Considering the boundaries of RC (90–95%) that ensures proper compaction of OGAs suggested in Eisenberg et al. [5], the minimum and maximum required modulus would be around 25 MPa and 40 MPa for LWD and 35 MPa and 50 MPa for SSG, respectively. However, because the methods used to determine $\gamma_{d\ max}$ in Eisenberg et al. [5] and this study are different, and in order to set the required modulus of OGAs for proper compaction in the field, it seems that field verification tests are necessary.

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