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Geo-mechanical behaviour of CDW (aggregate). The use and the evaluation for a specific case.

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ABSTRACT

The last generation is concerned with the circular economy and the sustainability of several materials and manufactured products. This change is still under development for construction and demolition waste (CDW) use, despite the volumes generated in metropolis and cities.

There is no doubt that CDWs are different depending on region, city, and socioeconomic development, and each CDW presents high heterogeneity in particles (mainly, strength, shapes, composition, and grain size distribution). Thus, high complexity exists to regulate and certify material requirements.

At this moment, somewhere, the use of CDW is possible after a CDW treatment using crushing plants and providing particular distribution of the particles. However, the geotechnical requirements have to be specified. This contribution presents novel experimental studies of a CDW material focused roughly on its geo-mechanical behaviour.

The main blocky constituents of the studied CDW are mostly concrete aggregates with a particle size range between 20 and 300 mm. The experimental studies were stablished with an instrumented preloading over a CDW reclamation land and oedometer tests.

A fully instrumented preloading was designed to improve 12 m thick CDW aggregates and soft soil placed underneath. Sliding deformeters and settlement plates were installed to control vertical strain construction stages with frequent data acquisition. In the meantime, a large oedometer cell (300 mm in diameter and 300 mm high) has been used to test 100 mm particle size. Several settings of the cell have been changed to perform different tests under saturated conditions: (i) normally and overconsolidated and (ii) length duration of loading and (iii) loading level.

In both cases, time-dependent compressibility (creep) at different vertical stresses on virgin states was detected. Despite the limitation on particle size on oedometer tests, results are relevant to upscale the effects of larger particle sizes in the CDW with a particle size range typically between 20 and 300 mm). Preliminary results on CDW have shown good mechanical performance with acceptable time-dependent compressibility on loading deformations on soaking for their use in reclaimed areas.

However, geotechnical criteria for classifying and using CDW and serviceability limit states still need to be developed in codes of practice to allow comparison of the results. In this regard, the preliminary results presented in this contribution may be of undoubted usefulness.

CDW, geo-mechanical, long-term behaviour, instrumented preloading, odometers.

1 INTRODUCTION

In recent years, there has been a growing worldwide concern for the circular economy and sustainability of various materials and products, including construction and demolition waste (CDW) (Yuan et al., 2011). Despite the fact that approximately 10 billion tons of CDW are generated each year (Jain et al., 2015), the use of CDW is still under development (Menegaki et al., 2018).

CDW is highly heterogeneous in terms of composition, grain size distribution, strength, and shape, which makes it challenging to regulate and certify material requirements across regions, cities, and levels of socioeconomic development. Currently, CDW can be used after undergoing manual sorting and crushing to achieve the required particle size distribution. However, geotechnical requirements must be specified according to the intended use of the CDW.

While several tests have been conducted on CDW for various geotechnical applications, such as those described by Cardoso et al. (2016), there are still missing applications, behaviours, and parameters that need to be characterized. To facilitate the development of CDW use, this contribution presents a case history of a coarse CDW material focused on its geo-mechanical behaviour for use in fill reclamation areas.

2 CASE HISTORY

2.1 General description of the CDW plant

The CDW plant was established with the goal of reducing, reusing, and recycling materials from the Barcelona metropolitan area. It is strategically located in the Barcelona Port, where over 500,000 tons of materials are treated and reused every year.

The plant only accepts crushable CDW for treatment. The plant employs several crushing machines - as shown in Figure 1 (left)-, to produce two main products: (i) aggregates from mixed waste and (ii) aggregates from reinforced concrete. The particle size of the mixed aggregates is typically divided into two fractions: 0-20 mm and 20-300 mm (Figure 1, right).

Figure 1. *Perspective of the CDW plant (left) and CDW aggregate (right).*

2.2 20-300 mm CDW aggregate

The earthwork companies have recognized the value of these aggregates in various applications, but their usage is still limited because of the absence of regulations and certifications.

In the Barcelona Port, a large stockpile of 20-300 mm fraction CDW aggregates had accumulated, exceeding 300,000 m3. These aggregates were utilized for filling a reclaimed area. To evaluate the particle distribution and material classification, 44 representative samples (3 m^3 each) were collected. Table 1 presents the particle size distribution indexes and coefficients, where the uniformity coefficient (C_U) value for the 20-300 mm material is over 40, indicating high heterogeneity. The curvature coefficient (C_C) values are atypical, but these results are acceptable for such artificial materials. Despite initially being composed of 20-300 mm particles, the material produced a finer particle size fraction (0-20 mm) due to mobilization and ageing in the stockpile, accounting for 17-37% of the total. The fine content (FC) in the 0-20 mm fraction was less than 8%, and no plasticity was detected.

Table 1. *Basic identification, grain size distribution and classification for CDW.*

D10 (mm)	D30 (mm)	D50 (mm)	D60 (mm)	FC % (75µm)	% 0-20 mm	%20-40 Mm	% 40-300 mm
0.2-1.8	10-18	27-45	22-75	1-8	17-37	22-52	21-59

The CDW studied, in this case, is mainly composed of blocky constituents such as concrete aggregates, rock aggregates (granite and limestone), tiles, bricks, glass, and bituminous mixtures. The typical composition for the 20-300 mm aggregate is presented in Table 2, based on three parts of the total particle size distribution (0-20 mm, 20-40 mm and 40-300 mm). The majority of the material is composed of concrete particles (Rc), followed by aggregates not bounded by cement (Ru) and ceramic particles (Rb). Asphalt particles (Ra), glass particles (Rg) and impurities (X) are the secondary materials.

The specific gravity of soil particles (GS) has been calculated based on the theoretical values of density and its weight proportion, which is 2.5 Mg/m3 (with a range of 2.48 - 2.52).

Table 2. *CDW classification.*

Particle size (mm)	% X	% Rc	% Ru	% Rb	% Ra	% Rg
0-20	3-45	12-52	17-54	4-28	2-33	0-1
20-40	0-6	27-68	12-48	3-38	0-22	0-0.5
40-300	0-8	63-91	-	4-32	2-8	-

X: impurities, Rc: concrete particles, Ru: aggregates not bonded with cement, Rb: ceramic particles, Ra: asphalt particles and Rg: glass particles

Compressibility is a crucial factor that affects the geo-mechanical behaviour of CDW aggregates when used as fill material in a reclamation area. This is mainly due to the lack of knowledge about materials with (i) significant differences in particle sizes and (ii) different particle compositions. Moreover, there is more uncertainty in this specific use due to the initial macroscopic structure resulting from particle arrangement. Therefore, it is essential to characterize the primary compression (elastoplastic behaviour for virgin loading), unloading and reloading elastic behaviour, and long-term (secondary compression) behaviour of CDW aggregates.

These characteristics were evaluated for the described CDW aggregates through an instrumented preloading of CDW fill in a reclaimed area of Barcelona Port and large oedometer tests.

3 INSTRUMENTED PRELOADING

3.1 The site conditions and geotechnical instrumentation

The Barcelona Port is continuously expanding towards the sea, and a new cruise terminal was planned to be built behind the main breakwater, East dike. The first step was to create a reclaimed area (240 m × 200 m) by filling it with 20-300 mm CDW aggregates (as shown Figure 2). The fill was placed between the east dike and a quay wall consisting of concrete caissons. The soft soil layer underneath the CDW aggregates was about 40 m, which needed preloading to improve settlements under the design loads. The entire esplanade and quay wall were fully instrumented to monitor stability and consolidation processes. The study area used for the CDW aggregates' compressibility evaluation was 100 m × 80 m. In this area, settlement plates and sliding deformeters were installed to monitor relative displacements at 1 m intervals, with regular data acquisition during preloading stages.

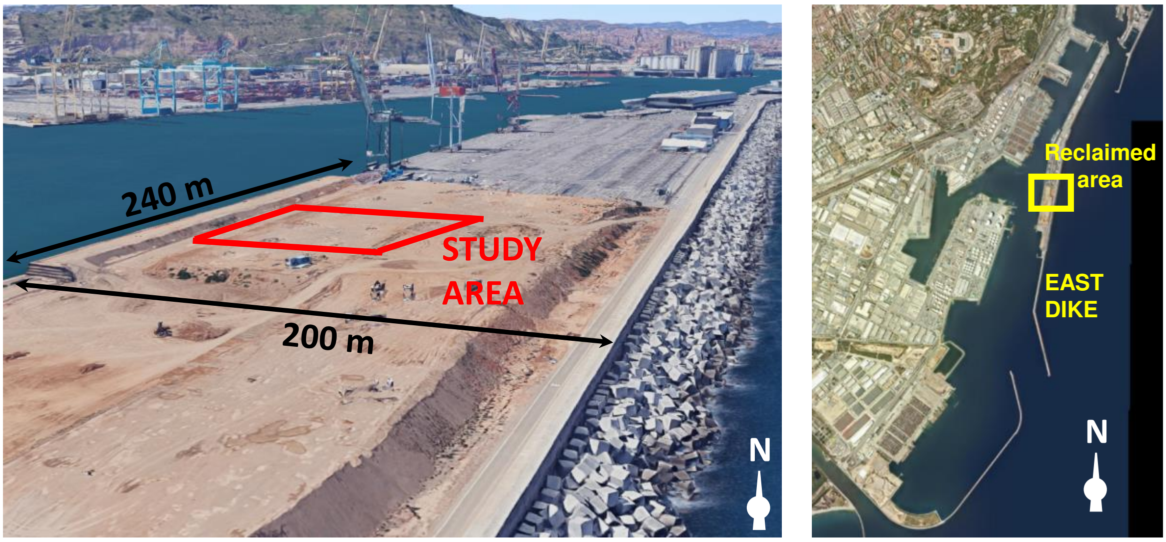

Figure 2. *Perspective of the instrumented preloading (left) and location in the Barcelona Port (right).*

Results obtained from both instruments are consistent, the total relative displacements calculated from sliding measurements and plate recordings are nearly identical. Three characteristic segments of the sliding deformeter pipe, labelled A, B, and C (Figure 3), were selected to evaluate compressibility at different depths. These control points were located below sea level, thus under saturated conditions.

The extension of the preloading and the emplacement of the control points are suitable for providing one-dimensional consolidation conditions. Therefore, compressibility results from the site can be directly compared with oedometer results.

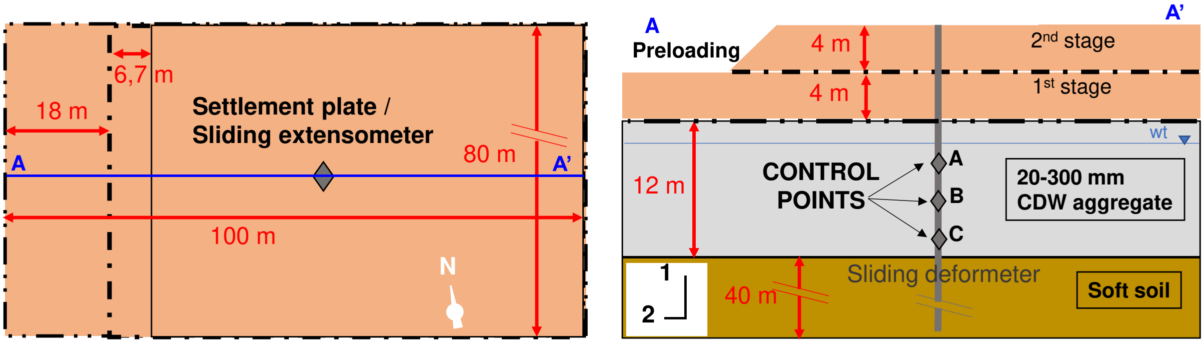

Figure 3. *Instrumentation plan: plan view (left) and cross-section (right).*

3.2 Preloading stages

The preloading was designed based on the project specifications. In order to meet the quay stability requirements of Barcelona Port, the preloading was implemented in two stages, with each stage being 4 meters in height, followed by a consolidation stage. A long consolidation period of over 2.5 years was established to allow for excess pore pressure dissipation in the natural soft soil, which is necessary to reduce long-term settlements in the existing soft soil (Alonso et al., 2000; Alonso et al., 2010). Finally, the preloading was removed and unloading was measured, followed by a consolidation period of 100 days. As is often the case in Barcelona Port esplanades, the maximum load of the preloading was higher than the design loads, resulting in an overconsolidated state for the esplanade materials.

The vertical effective stresses for each control point were estimated based on the unit weight of the CDW aggregate. These stresses changed during the preloading process due to the transmitted stresses from the preloading material (1.8 Mg/m3). The stress values for each control point are presented in Table 3.

Table 3. *Preloading description.*

Stage	**Time step (days)**	**Effective vertical stresses point A (kPa)**	**Effective vertical stresses point B (kPa)**	**Effective vertical stresses point C (kPa)**
Initial	56	74	98	114
1st preloading	27	139	163	179
Consolidation	121	139	163	179
2nd preloading	55	184	208	224
Long-consolidation	968	184	208	224
Unloading	10	74	98	114

3.3 Results

The interpretation of the sliding recordings for points A, B, and C is presented in Figure 4. The vertical strain reached at the end of the preloading ranged from 7% to 3.7%. Most of the vertical strain was achieved during the first and second preloading stages. However, significant vertical strains were also reached during the consolidation stage after loading. Although this vertical strain was not uniform, it persisted slowly until the end of consolidation, indicating the possibility of long-term behaviour.

Differences in settlements at different depths were consistent with stress levels, but the heterogeneity of CDW aggregates and the dumping method possibly caused the creation of layers with slightly different particle sizes or structures.

Non-uniform vertical strain rates were reached after both consolidation stages. This effect was clearer in the second preloading stage, where the vertical strain rate at point B was considerably higher than the rates at points C and A. This behaviour may reflect the existence of different material structures and particle sizes in depth, which led to different degrees of particle breakage (crack propagation) or rearrangement (interparticle slip and rotation).

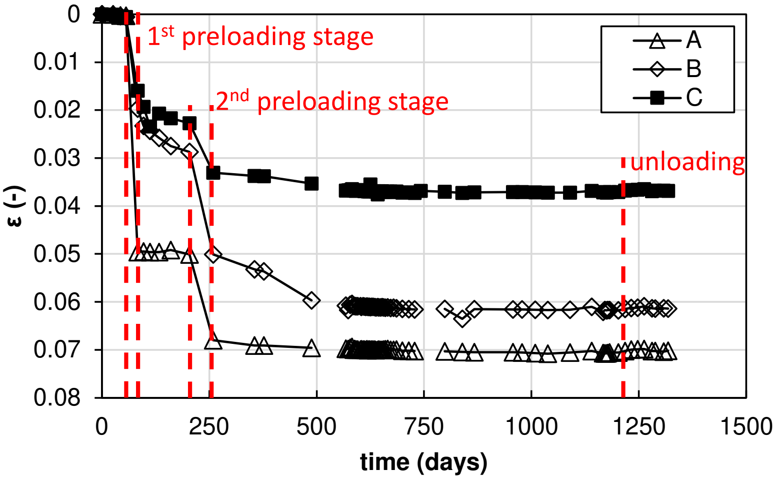

Figure 4. *Evolution of* vertical strains*, ε – t, in A, B and C.*

The consolidation lines for A, B, and C are shown in Figure 5. The consolidation lines for B and C exhibit a natural curvature of virgin consolidation lines, while the consolidation line for point A is too linear. This particular behaviour observed during the first preloading stage of point A could be attributed to two phenomena: (i) the lower initial stress at that depth and (ii) the applied stress level (2 times) and consequent particle breakage or rearrangement.

From these results, it is evident that the slope of the virgin compression line (λ) in the ε-log(σ'$_v$) plot is 0.15, 0.20, and 0.11 for A, B, and C, respectively. The unloading compression slope (κ) of the unloading-reloading line in the ε-log(σ'$_v$) plot is 8·10-4, 7·10-4, and 5·10-4 for A, B, and C, respectively.

The obtained λ values are not expected in natural coarse granular materials. The magnitude of λ is quite similar to that of the soft soil that exists below. Nevertheless, κ results are similar to those of dense granular soil. These results generate an average ratio of λ/κ = 230, which is dependent upon particle tensile strength, particle shape, and particle size distribution.

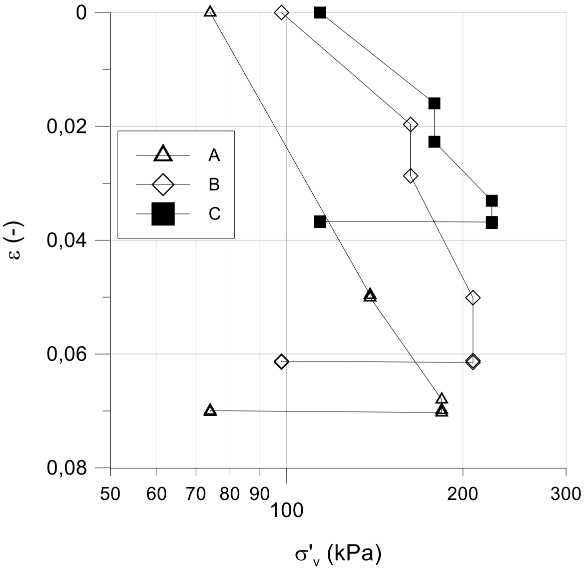

Figure 5. *Stress paths, σ'$_v$ – ε.*

The presence of long-term behaviour is particularly evident in both consolidation stages under normally consolidated states. Higher vertical strains and longer consolidation duration were observed in the Long-consolidation stage (after the 2nd preloading), as shown in Figure 6. Point B reached a vertical strain close to 0.85%, while it was lower than 0.3% for point A and reduced to 0.15% for point C. However, as previously introduced, secondary settlements during the initial 130 days were variable and represented 33%, 75%, and 45% of the total for A, B, and C, respectively. Thus, secondary compression, λ(t), was calculated according to a logarithmic function of time in the first part (from t_0=1 day to t_F=406 days) and in the last part (from t_0=443 days to t_F=735 days) for A, B, and C. The last part of the records was not evaluated due to its uncompressible noise. Finally, λ(t) of the consolidation stage just before the 1st preloading was also evaluated.

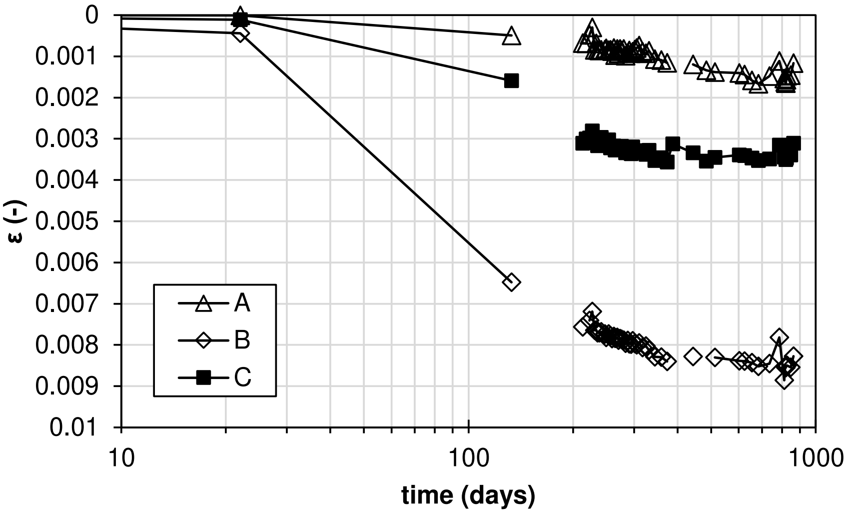

Figure 6. *Long consolidation stage, ε-t.*

The results of the secondary compression analysis show similar values, with apparently lower stress levels providing higher values (ranging from $2 \cdot 10^{-4}$ to $3 \cdot 10^{-3}$), in the same way as the first part of the Long consolidation stage (ranging from $7 \cdot 10^{-4}$ to $2 \cdot 10^{-3}$). The first part results of λ(t) are higher than the values from the second part, with the exception of point A (ranging from $8 \cdot 10^{-4}$ to 10^{-3}). These results, together with the previously described compression results, are summarized in Table 4. Although the secondary compression is not extremely high in comparison to high plasticity or organic soil - with λ(t)<0.03 - the values are similar to overconsolidated clayey soils. In the case of port fills, settlement requirements limit settlements for long time periods, i.e., 100 mm in 10 years in Spanish recommendations for maritime infrastructures (ROM.05-05). Thus, the use of CDW aggregates fills could be influenced by secondary compression, opening a new line of investigation for CDW aggregates.

Table 4. *Compression parameters for points A, B and C.*

Point	**λ**	**κ**	**Consolidation stage**		**Long consolidation stage**		
			λ(t)	**σ'v (kPa)**	**λ(t) t_F=406**	**λ(t) t_F=968**	**σ'v (kPa)**
A	0.15	$8 \cdot 10^{-4}$	$2 \cdot 10^{-4}$	139	$7 \cdot 10^{-4}$	10^{-3}	184
B	0.20	$7 \cdot 10^{-4}$	$4 \cdot 10^{-3}$	163	$2 \cdot 10^{-3}$	$8 \cdot 10^{-4}$	208
C	0.11	$5 \cdot 10^{-4}$	$3 \cdot 10^{-3}$	179	$4 \cdot 10^{-3}$	$7 \cdot 10^{-4}$	224

4 LARGE OEDOMETER TESTS

4.1 Oedometer cell description and experimental program

CDW aggregates were tested using a large oedometer cell with a diameter and height of 300 mm. The loading and unloading process was carried out using a hydraulic press with loading control. To ensure compatibility with the specimen's dimensions, the grading of particles larger than 100 mm was necessary.

Three tests were performed under saturated conditions with slightly higher stress levels than control points A, B, and C from the sliding deformeter. The tests included the following stages (Table 5): (i) specimen inundation, (ii) loading stress conditions ranging from 500 to 750 kPa, (iii) long-term stages ranging from 3600 to 14400 seconds of the loading step, (iv) unloading stage of 20 kPa, and (v) an additional stage of reloading ranging from 500 to 750 kPa.

Deaerated water was used to saturate the sample, which is chemically more aggressive than seawater. Further tests with different conditions using CDW aggregates samples from the Barcelona Port stockpile before the esplanade filling was carried out, but out of the scope of this paper.

Each sample was provided with a similar initial void ratio (e0), and the initial unit weight of oedometer specimens was approximately 1.4 Mg/m3. These values were achieved by carefully reconstituting the specimens and randomizing the emplacement of the material to account for its heterogeneity. Consistent values of void ratio were crucial to obtain reliable results despite the substantial difference between the test program and the uncontrollable dumping of CDW aggregates in the fill.

Table 5. *Test program.*

Sample	**e_0**	**Vertical stress path (kPa)**	**"Long term" stage (seconds)**
4	0.79	0 – 165 – c – 500 – c – 250 – 20 – 500	3600 – 3600
21	0.82	0 – 165 – c – 500 – c – 20 – 500	3600 – 14400
31	0.85	0 – 500 – c – 750 – 500 – 20 – 750	7200

c: creep stage

4.2 Test results

The test results for the relationship between vertical strain and vertical effective stress are shown in Figure 7. Despite the heterogeneity of the specimens (taken from different regions of the Barcelona Port stockpile), the virgin consolidation lines are quite similar. Once again, the creep stages result in secondary settlements.

As previously mentioned, λ and κ were calculated by adjusting the compression and unloading-reloading lines. The results for λ were in the range of 0.08 to 0.12, while κ was 0.003.

The vertical strain evolution lines during creep stages were similar for specimens from samples 4 and 31, whereas sample 21 exhibited an abrupt settlement during both consolidation stages (Figure 8). Sample 21 had a higher percentage of particles in the 40-300 mm range, which meant it had less protection from finer particles and was more likely to experience particle breakage or rearrangement leading to collapses.

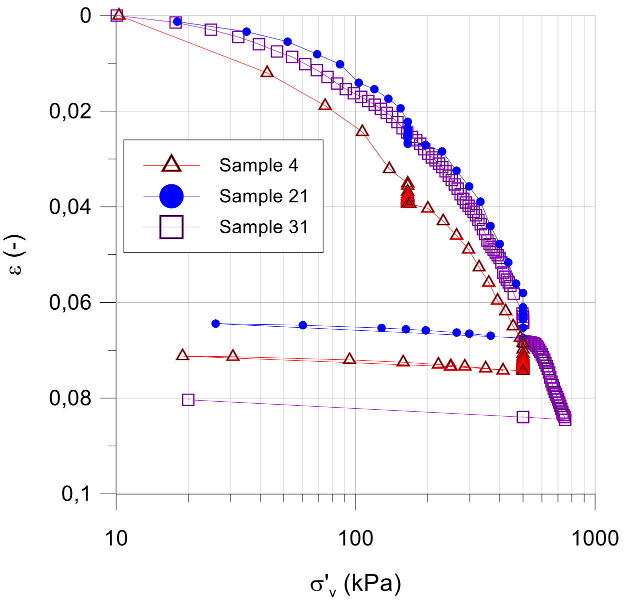

Figure 7. *Oedometer stress paths, ε – σ'ᵥ for tested samples.*

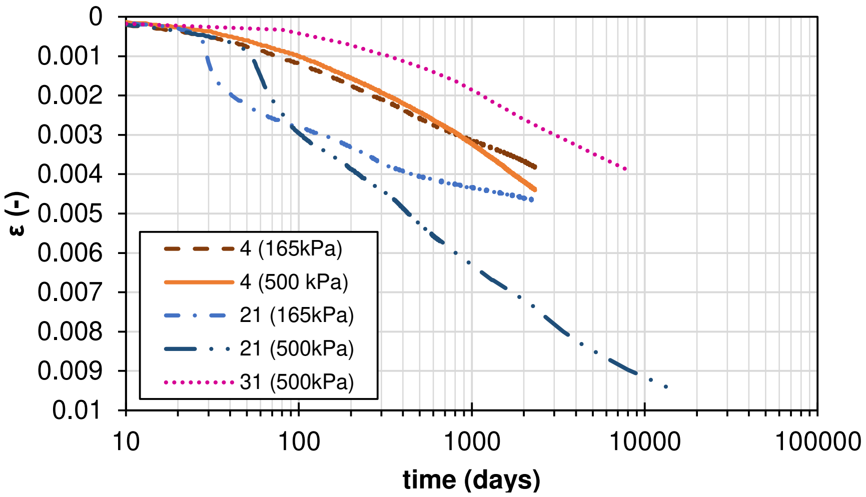

Figure 8. *Oedometer long term* vertical strain, *ε - t.*

Secondary compression was evaluated using the last part of the curves to obtain λ(t) results. These results are presented in Table 6, along with the results of previous tests. The values of λ(t) ranged from $1\cdot10^{-3}$ to $3\cdot10^{-3}$, which is equal to or close to κ.

The stress level seemed to affect the secondary compression, just as it did in the instrumented preloading; high stress levels generated less secondary settlement. It is important to note that the duration of the creep stage could also affect the results, but if λ(t) is calculated with the same assumption for t_F=3600, the results do not change.

Table 6. *Compression parameters of tested CDW aggregates samples.*

Sample	λ	κ[1]	λ / κ	λ(t) – 165 kPa	λ(t) – 500 kPa
4	0.08	0.002	40	$2\cdot10^{-3}$	$3\cdot10^{-3}$
21	0.10	0.002	50	$1\cdot10^{-3}$	$3\cdot10^{-3}$
31	0.12	0.003	46	-	$4\cdot10^{-3}$

1: for σ'ᵥ from 200 to 20 kPa.

5 CONCLUSIONS

The particle size, classification, and compressibility properties of 20-300 mm construction and demolition waste (CDW) aggregates from the stockpile at Barcelona Port were analysed. Through instrumented preloading and large oedometer testing, different compressibility characteristics were identified for both in-situ material and reconstituted specimens.

The results showed that the instrumented preloading and oedometer tests were consistent in terms of loading and unloading-reloading indexes, although slight differences were possible due to initial conditions. The dumped fill material had larger particle sizes (0-300 mm) than the oedometer samples (0-100 mm), which were denser due to gridding and thorough emplacement.

The initial differences in the dumped fill led to higher compression index values during the loading stages. However, these differences were not significant, with a variation of only $\Delta\lambda=\pm0.05$. The unloading and reloading indexes produced less clear results, as they were significantly lower than λ, with ratios between λ/κ exceeding 40. The overconsolidated state of the fill resulted in a significant improvement in compressibility. It's worth noting that the κ results of the dumped fill were one order of magnitude higher than the oedometer results.

Various factors could contribute to the observed differences. One possibility is that the initial void ratio and the presence of particles ranging from 100 mm to 300 mm, which were not included in the oedometer specimens, played a significant role. While coarse materials typically exhibit significant differences between λ and κ, the κ values obtained from the sliding micrometer were unexpectedly low. This discrepancy may have resulted from the reduced accuracy of the sliding micrometer system following compression of the pipes. Additionally, the particle rearrangement in the oedometer cell may be less representative of the fill's behaviour due to the cell's lateral confinement.

In addition, both tests detected time-dependent compressibility at different vertical stresses on virgin states, which opens up a new avenue of investigation for CDW aggregates. Although secondary compression has been studied extensively for coarse-grained materials such as rockfills by researchers like Oldecop and Alonso (2001, 2007) and Romero et al. (2013), CDW aggregates present an additional challenge due to their heterogeneity in composition and particle size. Currently, it is unclear whether the observed long-term behaviour is caused by particle breakage (crack propagation) or rearrangement (interparticle slip and rotation), and no evidence has been presented to support either hypothesis. A more thorough examination of the macrostructure and tensile strength of the particles is necessary to estimate the degree of particle rearrangement or breakage during compression.

The good agreement between the results of both compressibility tests has demonstrated that the sliding deformeter technique could be a useful tool for assessing settlements in coarse-grained materials at depth. Although the particle size limitations of the oedometer tests are a factor, the results are relevant for upscaling the effects of larger particle sizes in CDW, which typically range from 20 to 300 mm.

The results of primary and secondary compression of virgin states were not insignificant, and their use may be limited depending on project requirements, such as in port fills. It is necessary to limit the loading operability to overconsolidated states, as we suspect that time-dependent deformations can be reduced once the material is brought to an overconsolidated state, as has been observed in rockfills by Romero et al. (2013).

The preliminary results on CDW aggregates indicate that they have good mechanical performance and can be used as fills in reclaimed areas. However, geotechnical criteria for classifying and using CDW, as well as serviceability limit states, still need to be developed in codes of practice to enable meaningful comparisons of results. In this regard, the preliminary findings presented in this study are undoubtedly useful and can contribute to the development of such criteria.

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