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Geomechanical Behaviour of Recycled Construction and Demolition Waste Submitted to Accelerated Wear

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Abstract: The construction industry is one of the most important sectors for economic and social development. However, it is responsible for more than 50% of the depletion of natural resources, for 40% of the energy consumption and construction and demolition waste (CDW) accounting for 30–60% of the total municipal solid waste generated worldwide. In this sense, the recycling of CDW is considered a safe alternative to the current trend, which can produce environmental and economic benefits, namely the reduction of the depletion of natural resources and the volume of waste sent to landfills. Some studies have shown promising results in the use of recycled CDW as geotechnical materials. However, the degradation performance induced by the construction procedures and weather conditions on the geotechnical behaviour of recycled CDW is still a research gap, creating an obstacle for its regular use in general engineering practice. This work evaluated the mechanical performance of recycled CDW over time when subjected to wetting–drying degradation cycles under different temperature and pH conditions. The effects of such degradation were then evaluated qualitatively (changes in particle size distribution and Proctor parameters) and quantitatively (stress–strain response and permeability). The results showed that 10 wetting–drying cycles and different compaction energies have no change in the particle size distribution of CDW compared to the original CDW. The shear strength parameters were very similar for the different degradation conditions except when different pH values were used, which may have weakened the grains and decrease the friction angle of the material. Regarding the permeability, all tested samples were classified in the same hydraulic conductivity range (very low) without significant changes induced by the degradation mechanisms.

Keywords: construction and demolition waste; sustainability; geomechanical behaviour; wetting–drying cycles; triaxial tests

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1. Introduction

The construction industry is constantly growing, which is a very relevant aspect, considering that it is characterized as one of the most important sectors for economic and social development. However, this sector is also linked with major environmental impacts [1]. The increasing development of urban areas, promoted by construction activities, results not only on the intense exploitation of natural resources but also in the generation of alarming volumes of construction and demolition waste (CDW) [2]. CDW is a by-product of the construction, renovation and/or demolition operations of buildings, accounting for 30–60% of the total municipal solid waste generated worldwide [3–5]. The inadequate disposal of this waste generates several problems, involving economic, social and environmental aspects. Furthermore, the global demand for construction materials is increasing day by day, which is associated with higher extraction volumes of natural resources and with an increase in energy consumption [6].

The construction industry is currently responsible for more than 50% of the natural resources depleted worldwide, and for 40% of the energy consumption [1,7]. In this sense, the recycling of CDW is considered as a sure alternative to the current trend, one which can certainly, if properly implemented, produce environmental and economic benefits, namely the reduction of the depletion of natural resources and, also, of the waste volumes sent to landfills [8].

Some studies have shown promising results in the reuse of CDW as a geotechnical material, such as in slopes, retaining structures, base and subbase layers of pavements, soils improvement and railways. Hidalgo et al. [4] investigated the behaviour of two soil types stabilized using alkali-activated brick dust; the unconfined compression strength at different curing temperatures and moistures and the use of different types and concentrations of alkaline activators were investigated. It was found that the addition of brick dust resulted in an increase in the soil strength of between 1.7–2.3 times with respect to the non-stabilised material, suggesting that the resulting materials will find practical applications in construction.

Cristelo et al. [9] analysed, using consolidated-drained triaxial tests and geoenvironmental (leaching) tests, a fully characterized batch of recycled mixed construction and demolition waste (CDW); the results showed that the analysed CDW batch was environmentally sound and in accordance with the European Directive 2003/33/EC; and the mechanical behaviour was consistent with that of natural soil, reaching strength envelops and elastic stiffness values competitive with those obtained with a natural granular material with a similar particle size distribution.

Arulrajah et al. [10] conducted a comprehensive laboratory assessment of the geotechnical and geoenvironmental properties of five types of CDW materials: recycled concrete aggregate (RCA), crushed brick (CB), waste rock (WR), reclaimed asphalt pavement (RAP) and fine recycled glass (FRG). In terms of usage in pavement subbases, RCA and WR revealed geotechnical properties equal or superior to quarry granular subbase materials. The behaviour of CB, RAP and FRG has shown that these materials may be improved with additives or mixed in blends with high quality aggregates to enable their usage in pavement subbases. In addition, Arulrajah et al. [11] performed small-strain static triaxial tests on five types of recycled CDW materials and discovered that RCA and WR are similar to natural aggregate (NA).

Vieira [12] evaluated the possibility of using fine grain CDW recycled materials as backfilling of geosynthetic reinforced structures (embankments and retaining walls), replacing the soils typically used in the construction of these structures. The authors proved that the use of CDW materials as a filling material in the construction of geosynthetic reinforced structures is a feasible solution and, thus, contributes to broadening the application of these recycled materials, particularly their fine portion (below 10 mm) with lower value to other applications, such as the concrete production or base layers of transportation infrastructures.

However, despite several studies published in the literature, the degradation performance, induced by the construction procedures and weather conditions, of this alternative material, is a major concern and a barrier to their use in some European countries. The breakage of CDW particles is commonly pointed out as an issue in the use of these recycled materials as geotechnical material of earth structures, such as pavements, structural embankments, slopes and base layers of transport infrastructures, for example.

Some studies have been carried out on the effects of use recycled aggregates on the durability of concrete (Guo et al., 2018). Studies regarding the degradation behaviour of recycled aggregates in geotechnical applications are very scarce, creating an obstacle for its regular use in general engineering practice, considering that, in such engineering applications, the materials are exposed to different sets of physical and chemical degrading agents and not least to the structural loads that are also always present. In this sense, this work aims to contribute to the study of the mechanical performance of CDW over time. The effects were simulated by imposing the degradation of the material, through wetting–drying cycles, under different controlled conditions of temperature and pH. The effects of such degradation were then assessed qualitatively (changes in the particle size distribution and Proctor parameters) and quantitively (stress–strain response and permeability).

2. Materials and Methods

2.1. Materials

The recycled CDW used in this work (Figure 1a) was collected from a recycling plant, located in the central region of Portugal and was produced mainly by the demolition or rehabilitation of residential buildings, as well as from illegal landfills. During the recycling process, the CDW went through a sorting process to remove light contaminants, such as plastic, rubber, and wood, followed by a process of separation of their particle size fractions and, finally, by the griding of the particles larger than 30 mm. The batch of recycled CDW used is this research was a fine-grain material.

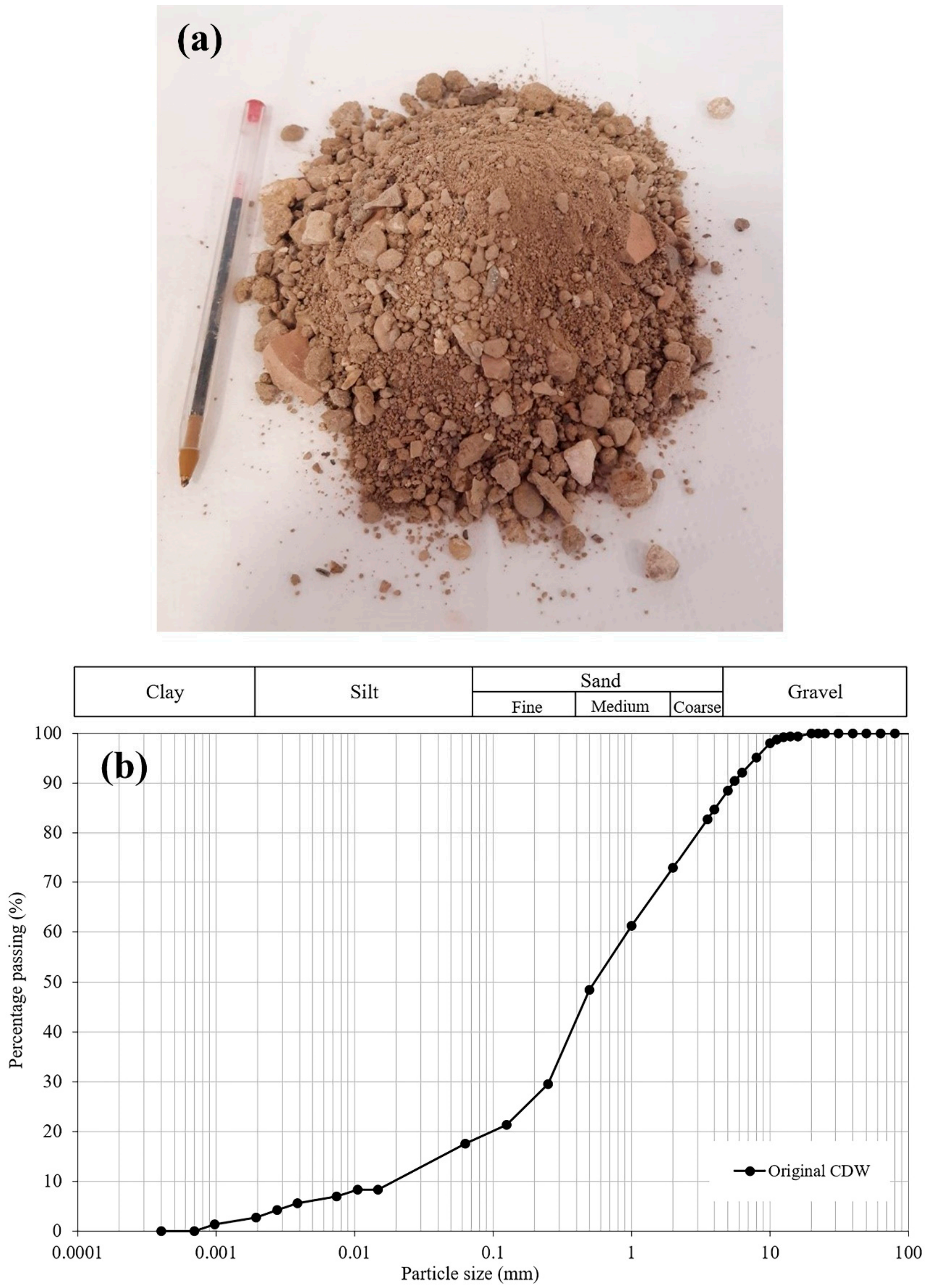

Figure 1. Recycled construction and demolition waste used in this study. (**a**) Material as received; (**b**) particle size distribution.

The recycled CDW was initially characterized according to its physical and mechanical properties. The particle size distribution (Figure 1b) was analysed through sieving and sedimentation, according to the standard ASTM D7928 [13], the constituent analyses were developed based on the EN 933-11 [14]. Particle size distribution allowed the classification of the material as a silty sand (SM), according to the Unified Soil Classification System [15]. The particle density (Gs) was obtained following the procedures of ASTM D854 [16]. The maximum and minimum void ratios of the material were established according to ASTM D4253 [17] and ASTM D4254 [18]. Proctor tests were performed using either standard effort [19] or modified effort [20], generating the respective optimum water content (ω_{opt}) and maximum dry unit weight (γ_{dmax}) for each effort. The results are shown in Table 1.

Table 1. Properties of the recycled CDW.

Property	Value
D_{10} (mm)	0.02
D_{30} (mm)	0.26
D_{60} (mm)	0.91
Fines content (%)	17.5
Uniformity Coefficient, C_U	45.5
Curvature Coefficient, C_C	3.71
Minimum void ratio, e_{min}	0.30
Maximum void ratio, e_{max}	0.64
Particle density, Gs (g/cm^3)	2.47
Optimum water content (%)	11.2
γ_{dmax} (kN/m^3)	19.8
Concrete, concrete products, mortar, concrete masonry units, R_c (%)	41.67
Unbound aggregate, natural stone, hydraulically bound aggregate, R_u (%)	20.42
Clay masonry, calcium silicate masonry units, aerated non-floating concrete, R_b (%)	19.92
Bituminous materials, R_a (%)	1.82
Glass, R_g (%)	2.12
Other materials, X * (%)	14.05
Floating particles, FL (cm^3/kg)	4.97

* Materials that do not fall into the above categories (e.g., gypsum drywall, cork, non-floating wood and soils resulting from the washing process).

Recycled CDW consisted mainly of unbound aggregates, crushed concrete (concrete products, mortar, concrete masonry units) and masonry (clay masonry units, calcium silicate masonry units, aerated non-floating concrete). A significant percentage of soils was also recorded in recycled CDW, as can be seen in Table 1. This composition is considerably different from commercially available natural soils usually used in earth structures. Natural silicious sand, for example, shows quartz as the main component with around 90% silicon dioxide (SiO_2) in its mineralogical composition [21]. The possibility of reusing these residues is not hindered by these differences in particle composition, since the material grain size distribution is equivalent to a granular geotechnical material.

2.2. Material Degradation with Compaction

Compaction is one the most effective procedures to control the quality of the compaction of embankments made from granular material. The possible grain breakage of the recycled CDW has generated uncertainties regarding its performance, thus hindering its application as an alternative material to natural soils. In this sense, Proctor tests were performed with different compaction efforts, following the recommendations of the ASTM D1557 [20] and ASTM D698 [19] standards. After being submitted to the Proctor tests, the material that originated the point corresponding to the maximum dry unit weight for each energy set of points was submitted to a particle size distribution (PSD) analysis [13], which was then were compared with the PSD of the original CDW.

2.3. Material Degradation with Wetting-Drying Cycles

To simulate the practical conditions of earth structures, such as pavements, shallow foundations and slopes, the material was also submitted to several sets of 10 wetting–drying (W–D) consecutive cycles, in order to evaluate their potential effect of on the particle size distribution (Figure 2a). Different conditions of controlled temperature and pH were used for each set of cycles, considering three different temperatures for the drying stage—51, 71 and 91 °C. For the 71 °C set, chemical reagents were used to produce two additional pH values for the wetting solution, namely 4 (citric acid) and 11 (sodium hydroxide). In every other case, the pH of the wetting solution was approximately neutral (tap water), i.e., pH natural. Each cycle began with the immersion of the material in solution for a period of 5 h (Figure 2b), ensuring its complete saturation, followed by oven-drying for 48 h (Figure 2c). The influence of the degradation conditions imposed on the material by these cycles was evaluated through the influence on their particle size and, also, on the mechanical and physical response, which was assessed using triaxial and permeability tests, respectively.

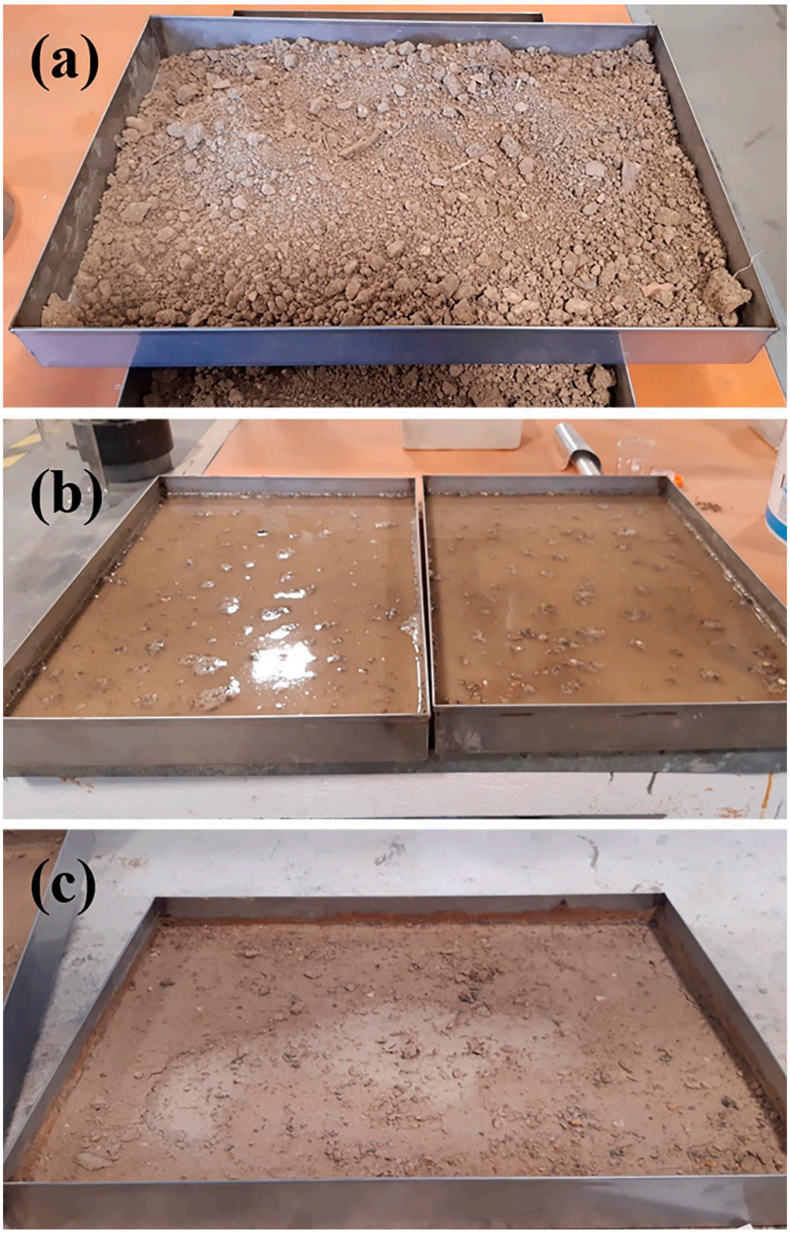

Figure 2. Wetting–drying cycles. (**a**) Material preparation; (**b**) immersion stage for 5 h; (**c**) oven-dried material, after 48 h.

2.4. Permeability and Triaxial Compression Procedures

To determine the degradation of the CDW imposed by the W–D tests in its shear strength, isotropically-consolidated drained triaxial tests (CID) were performed, under different effective confining stresses (p′) of 25, 50 and 100 kPa. These tests followed the procedures of ASTM D7181 [22] and were performed on cylindrical specimens of 70 mm in diameter and 140 mm in height and moulded with the values obtained in the Normal Proctor Tests (Section 2.1). It is known that, to avoid inappropriately large grain sizes inside the triaxial specimen, the specimen diameter should be at least equal to six times the largest particle size; however, due to the limited size of the equipment available, a smaller specimen diameter was utilized. In addition, considering that all specimens were moulded with equal sizes, this influence was disregarded.

The samples were saturated until a B-value [23] of 0.99 was obtained. A displacement control servo-hydraulic load frame was used to apply an axial load at 0.01 mm/min. The axial load and axial strain were measured by a 5 kN load cell and a linear variable differential transformer (LVDT), respectively. Each test was carried out up to an axial strain of 15%. The volumetric strain was measured by an Imperial College-type volume gauge. In the calculation of the deviator stress, area and membrane corrections were applied, as recommended by [24].

During the triaxial tests, hydraulic conductivity (or permeability) tests were also performed, as disposed in the Clause 6 of standard BS1377 [25] and described by [26]. In this test, the sample is subjected to a known effective stress under the application of a back pressure and a constant hydraulic gradient is applied. The permeability coefficient is determined by measuring the water volume passing through the sample during a predetermined time frame.

3. Results and discussion

3.1. Influence of Compaction on the PSD

Figure 3 shows the compaction curves of the CDW for the different Proctor energies. As expected, the increase in Proctor energy leads to an increase in the maximum specific dry unit weight and a decrease in the optimum moisture content, from 19.8 to 20.8 kN/m^3 and from 11.2 to 9.2%, respectively.

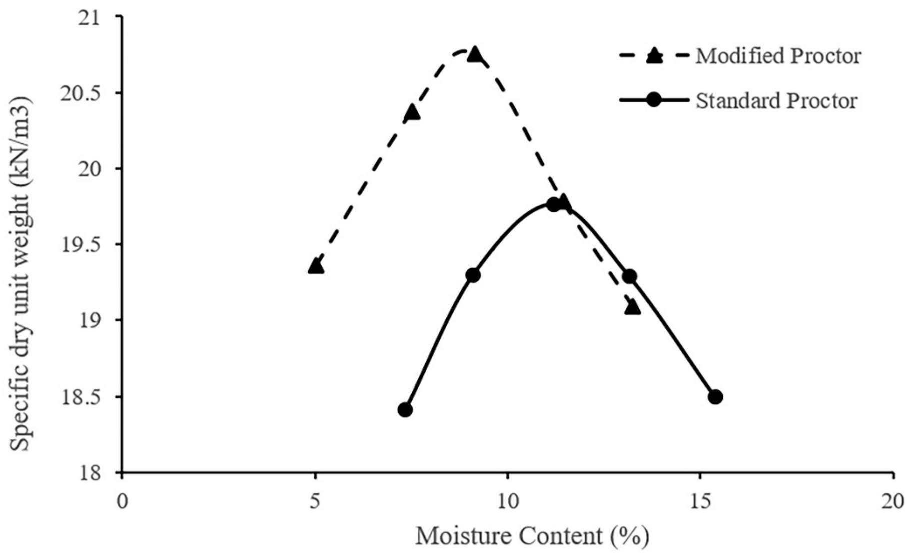

Figure 3. Compaction curves for each energy considered.

Figure 4 shows the particle size distribution obtained after the standard and modified energy Proctor tests, along with the soil particle size distribution obtained in the characterization test. All curves were extremely similar, as shown in Table 2, indicating that different compaction energies had no significant influence on particle size distribution, even for the modified energy Proctor test. This demonstrates the feasibility of using recycled CDW as a backfill material even when compacted with higher compaction energies. The small discrepancy of the curves was attributed to the heterogeneity of the recycled CDW and the variability of the test itself.

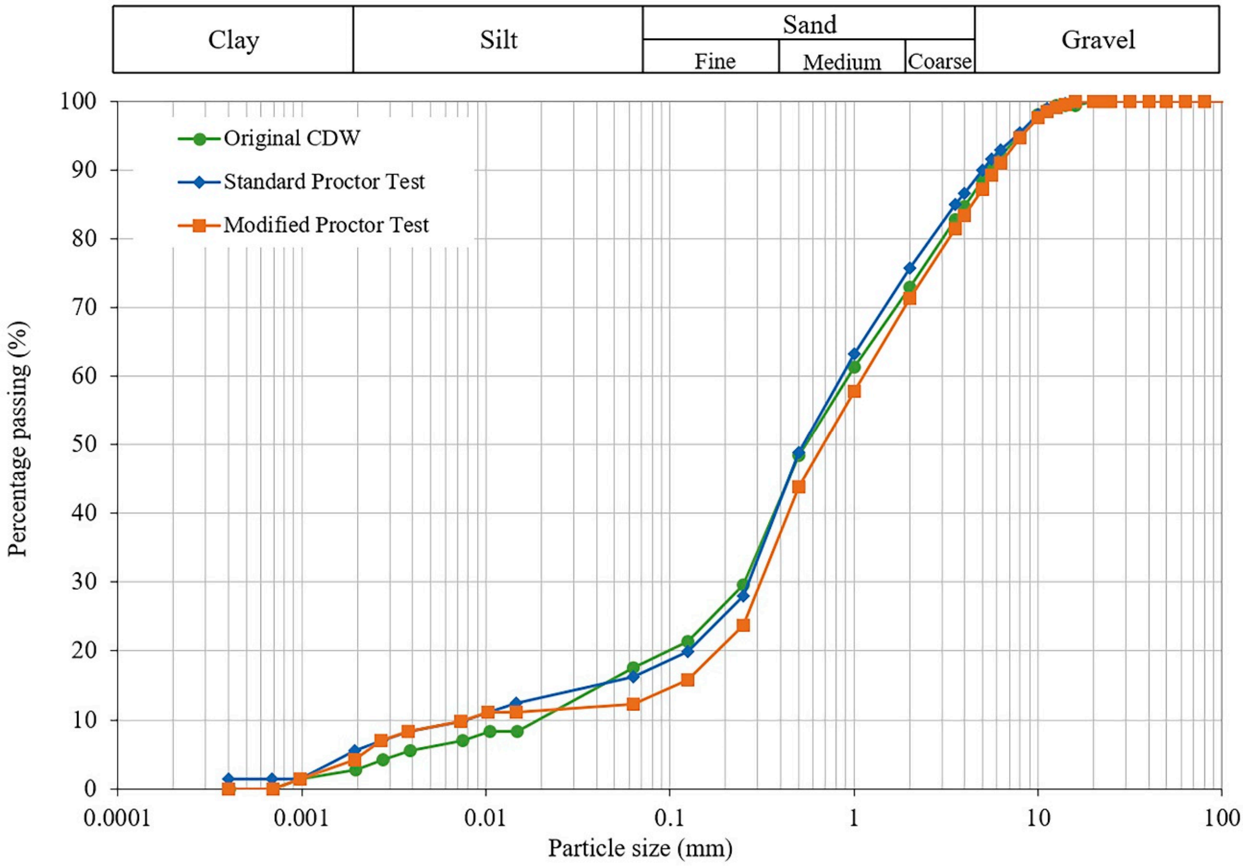

Figure 4. PSD at different compaction energies.

Table 2. PSD of the samples after the Proctor tests.

Particle Size	Original (%)	After Standard Proctor (%)	After Modified Proctor (%)
Gravel (>4.75 mm)	13	13	16
Coarse Sand (2.0 mm to 4.75 mm)	15	14	16
Medium Sand (0.425 mm to 2.0 mm)	29	35	34
Fine sand (0.075 mm to 0.425 mm)	25	22	21
Silt (0.002 mm to 0.075 mm)	15	11	8
Clay (<0.002 mm)	3	5	5
Classification (ASTM D2487)	SM	SM	SM

Other authors [27] also evaluated the effect of compaction energy on particle breakage of a CDW and found no differences in the particle size of material compacted at normal and modified energies. These authors also point out that higher moisture contents led to greater lubrication between the grains, during the compaction process, allowing the overall densification with less breakage.

3.2. Influence of Temperature and pH on PSD

Figure 5 shows the particle size distribution and Table 3 presents the percentage values of CDW after the degradation induced by the wetting–drying cycles. The results show that only slight variations of the PSD were produced. Regarding the changes in the respective Unified Classification, all samples maintained the original SM, indicating that the imposed degradation conditions were not aggressive enough to modify the particle size of the CDW during the 10 cycles. Other authors [28] performed wetting–drying cycles, under a controlled temperature of 60 °C, also concluding that the effect of these cycles on the physical properties of the recycled CDW aggregate are not significant, which suggests that these harsh conditions are not capable of altering the dimensions of these recycled particles, although this does not mean its physical structure and mechanical performance are not affected.

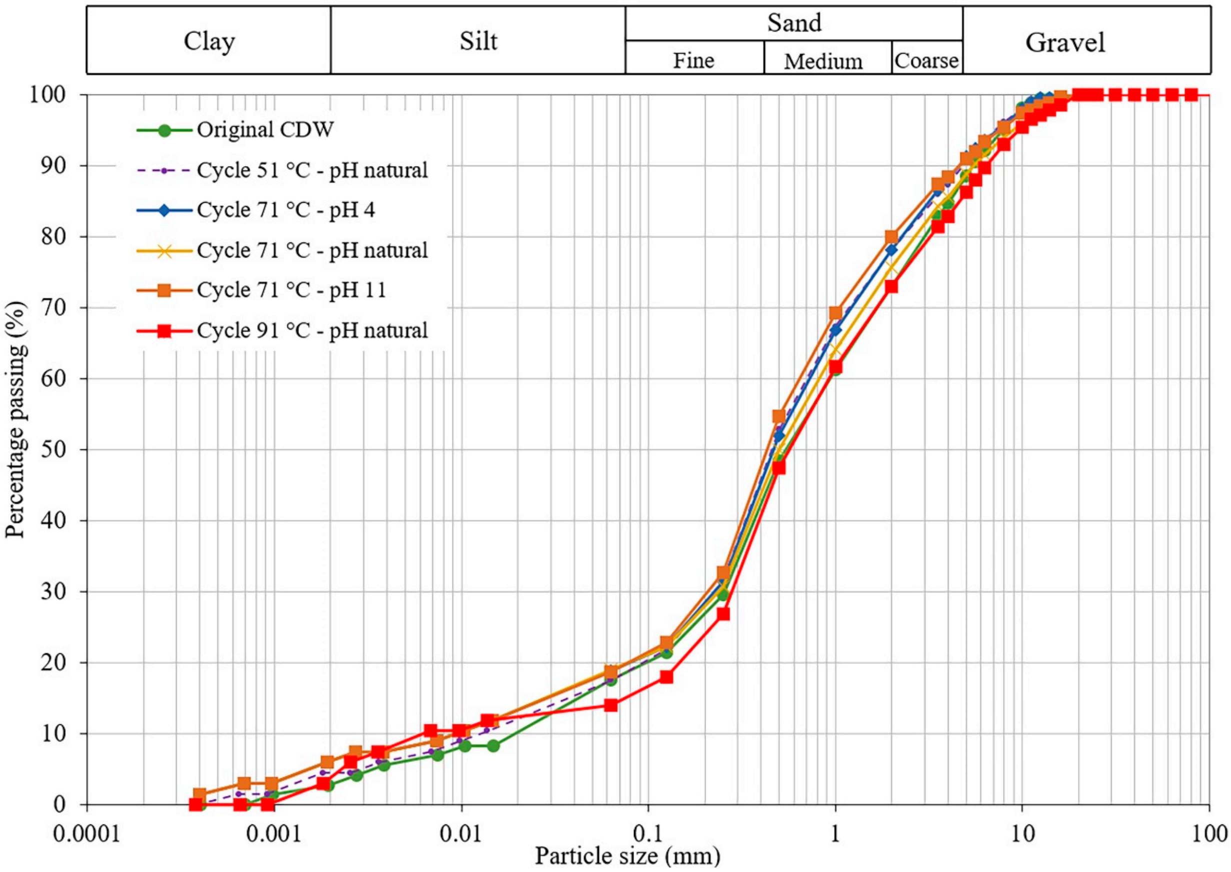

Figure 5. CDW particle size distribution after degradation cycles.

Table 3. Particle size after degradation cycles.

Particle Size	Original	51 °C		71 °C		91 °C
	(%)	pH Natural (%)	pH 4 (%)	pH Natural (%)	pH 11 (%)	pH Natural (%)
Gravel (>4.75 mm)	13	11	9	12	9	14
Coarse Sand (2.0 to 4.75 mm)	15	11	13	13	11	13
Medium Sand (0.425 to 2.0 mm)	29	31	31	35	30	32
Fine sand (0.075 to 0.425 mm)	25	29	27	25	30	26
Silt (0.002 to 0.075 mm)	15	13	13	13	13	10
Clay (<0.002 mm)	3	5	7	7	7	5
Classification (ASTM D2487)	SM	SM	SM	SM	SM	SM

3.3. Triaxial Tests

The results of the triaxial tests show the stress–strain behaviour for each degradation condition to which the CDW was subjected during the W–D cycles. Figures 6–9 show the deviator stress (q) versus the axial strain (ε_a) and volumetric strain (ε_{vol}) for each confining pressure (25, 50 and 100 kPa) and for the different W–D conditions as well; Figure 6 shows the drained response for the original CDW; Figure 7 shows the results of CDW under degradation to a cycle of 51 °C; Figure 8a shows the response to a cycle of 71 °C, pH 4; Figure 8b shows the response to a cycle of 71 °C with a neutral pH; and Figure 8c shows the results of a cycle of 71 °C with pH 11. Figure 9 presents the drained response of CDW to degradation cycles of 91 °C.

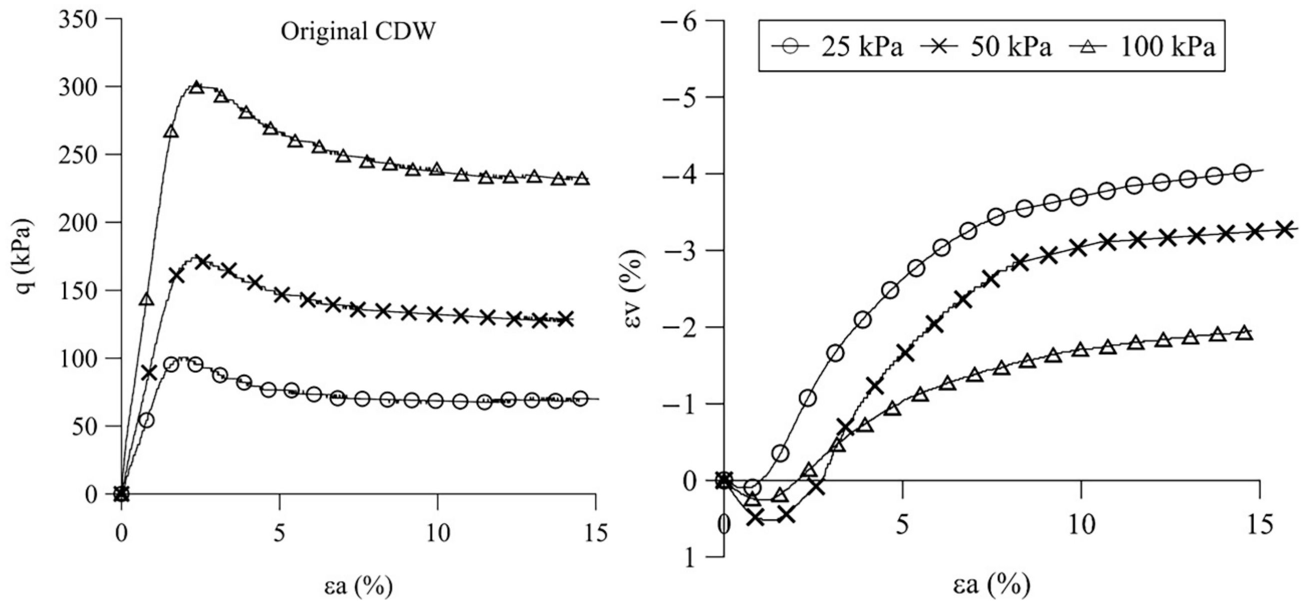

Figure 6. Drained response of CDW at different confining stresses for original CDW.

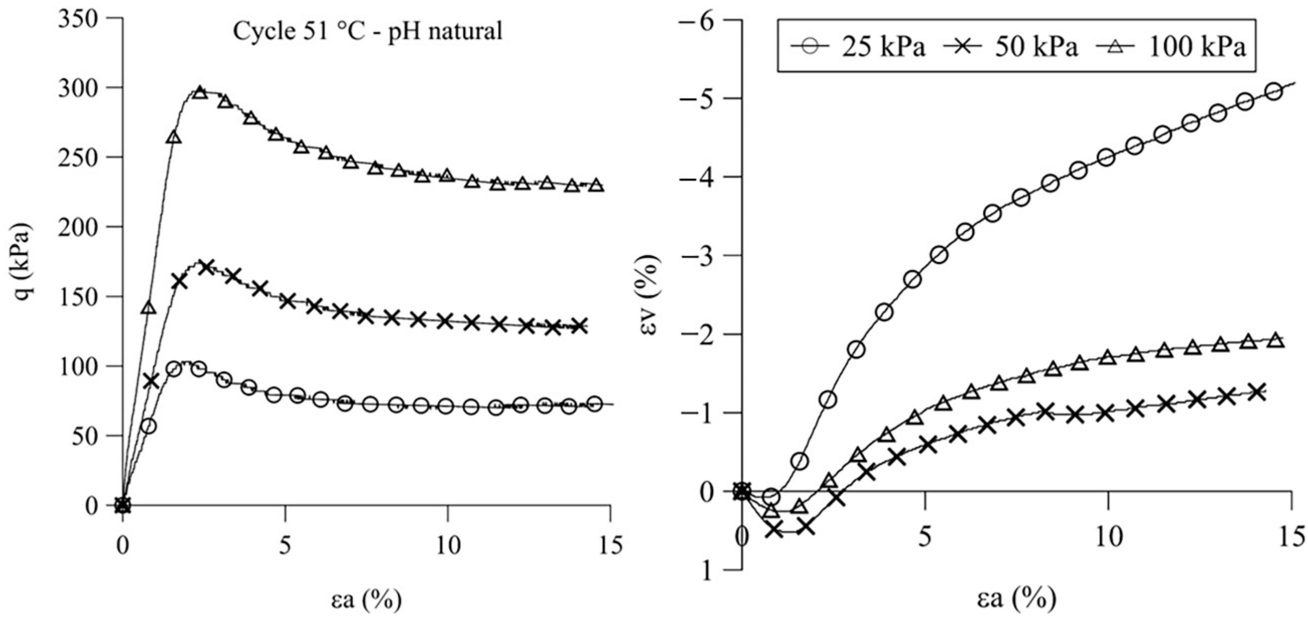

Figure 7. Drained response of CDW under degradation cycles at different confining stresses for a cycle of 51 °C.

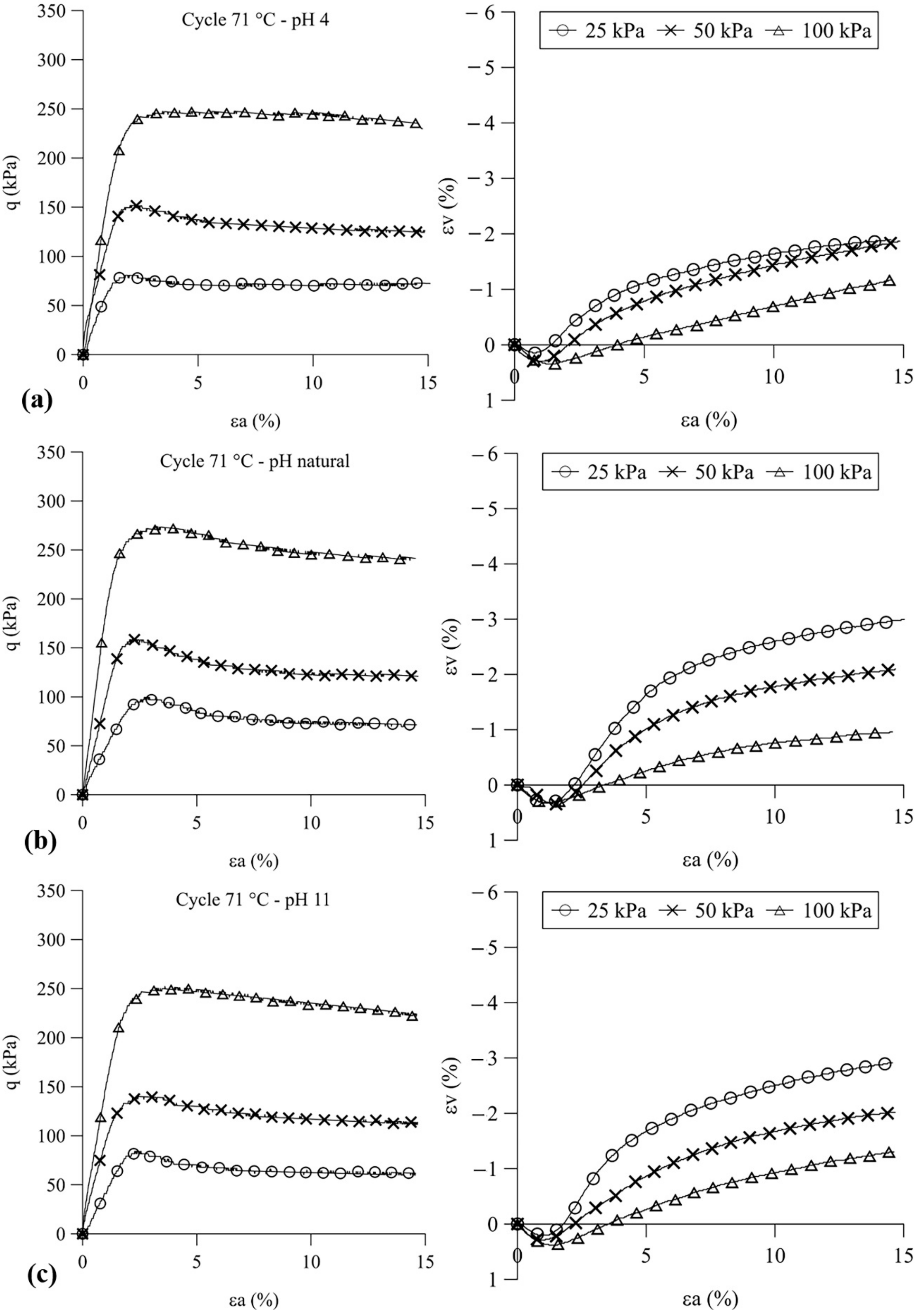

Figure 8. Drained response of CDW under degradation cycles at different confining stresses (**a**) a cycle of 71 °C at pH 4; (**b**) a cycle of 71 °C at pH natural; (**c**) a cycle of 71 °C at pH 11.

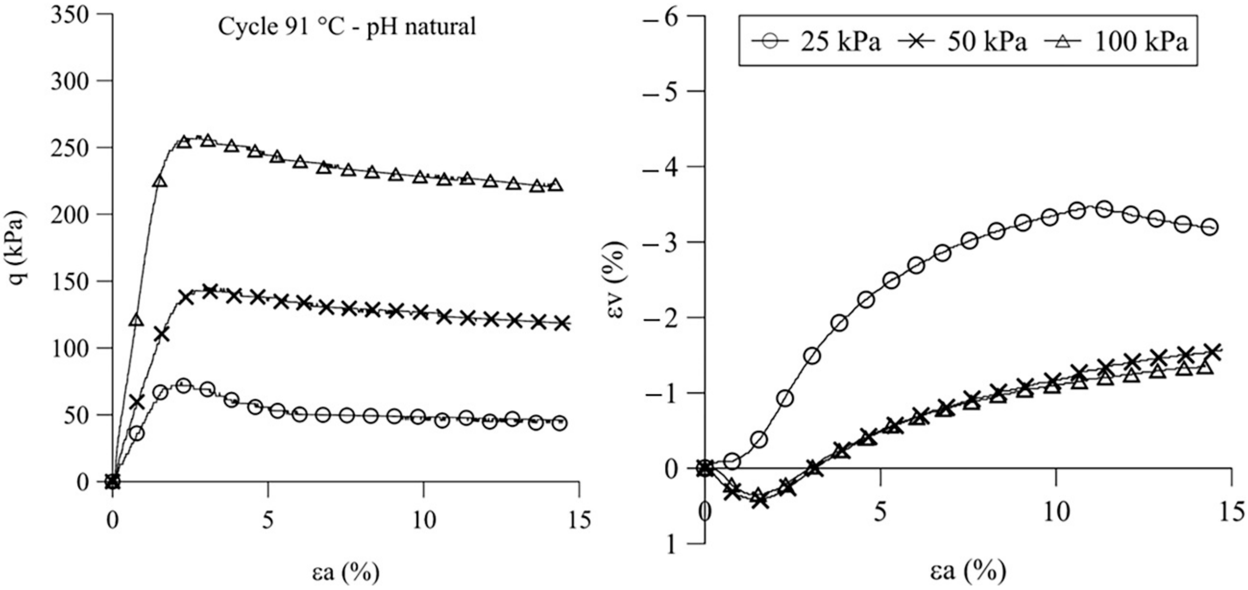

Figure 9. Drained response of CDW under degradation cycles at different confining stresses for a cycle of 91 °C.

In general, all samples produced similar stress–strain behaviours, with a pronounced strength peak and subsequent strain-softening, with the highest peak and stiffness of the material being evidenced for the highest confining stress. The volumetric variation indicated an initial compressive behaviour followed by the dilatancy of the material—the lower the confining stress, the higher the dilatant behaviour. These stress–strain characteristics are in accordance with what is described in the literature regarding several classical soil materials, such as dense sand, in which a well-defined failure peak is followed by strain-softening, with dilatant behaviour at low confining stresses [29].

The elasto-plastic strength parameters—cohesive intercept (c′) and friction angle (ϕ′)—were defined with basis on the failure envelopes (Figure 10). The strength peak values were considered as the failure of the material. It can be seen that, for samples submitted to the degradation cycles with the natural pH and regardless of the respective temperature, the strength parameters are very close to those obtained for the original CDW (Table 4), indicating that the temperature increase has no influence on the particle strength. The slight variation on these parameters is once again attributed to the material's heterogeneity.

Table 4. Strength parameters for CDW.

Sample ID	q_{peak}			ϕ′	c′
	25 kPa	**50 kPa**	**100 kPa**	**(°)**	**(kPa)**
Original CDW	100.5	175.0	302.4	34.5	10.1
51 °C, pH natural	103.1	173.9	299.4	34.0	11.2
71 °C, pH 4	80.8	151.7	248.3	31.3	9.0
71 °C, pH natural	99.6	158.6	274.1	32.8	9.8
71 °C, pH 11	84.2	140.0	252.3	31.7	7.7
91 °C, pH natural	74.4	145.0	258.8	33.2	4.7

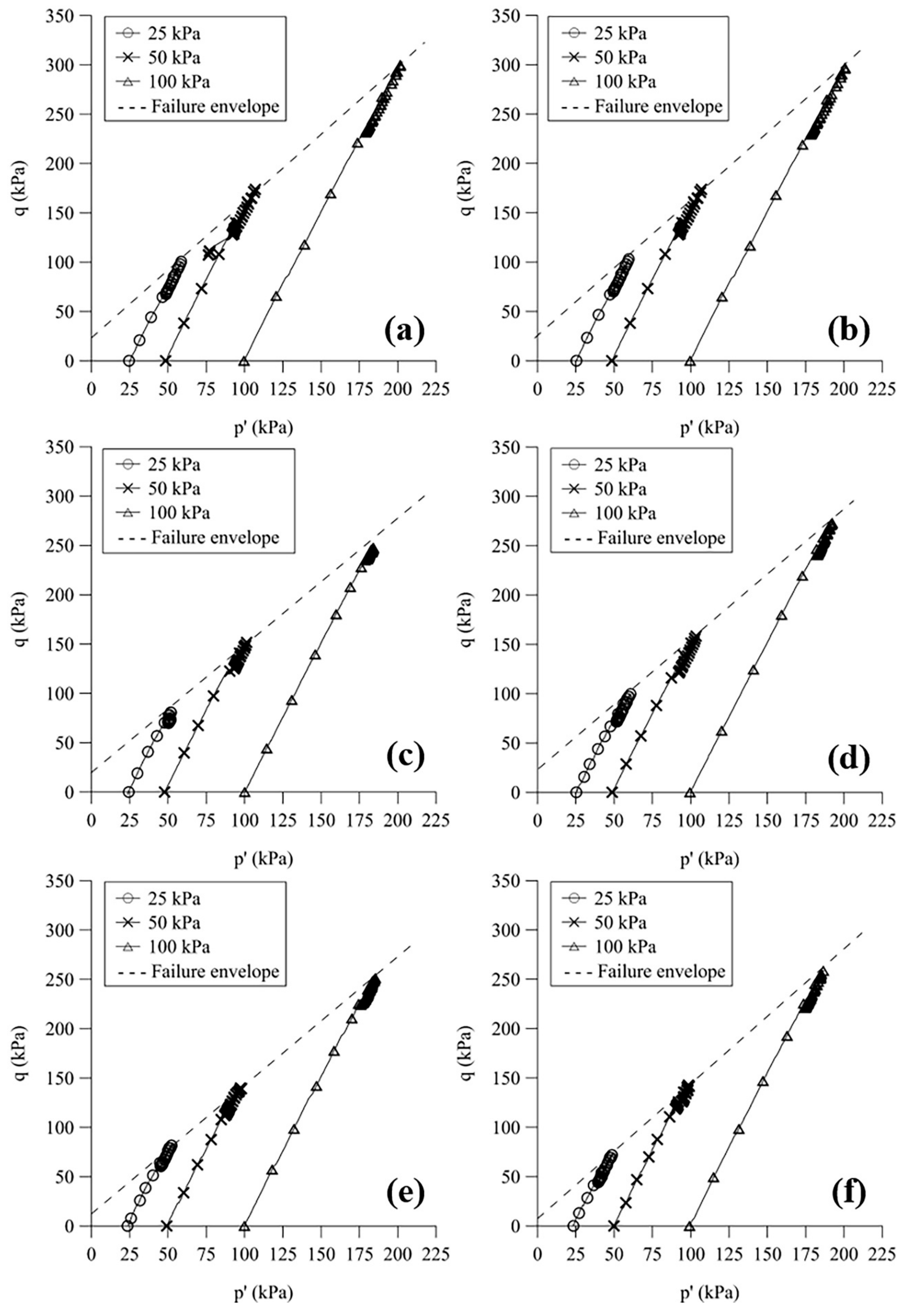

Figure 10. Failure envelopes for the CDW after being submitted to the following conditions: (**a**) original CDW; (**b**) 51 °C, pH natural; (**c**) 71 °C, pH 4; (**d**) 71 °C, pH natural; (**e**) 71 °C, pH 11; (**f**) 91 °C, pH natural.

However, the recycled CDW samples submitted to different pH environments (4 and 11) during the cycles showed a significant reduction in the friction angle values compared to the ϕ' value found for the original CDW (Table 4). This effect of the acid and alkaline environments is, most likely, related to the compositional changes of the minerals forming the soil grains, promoted by the harsh conditions imposed during these tests. The stress–strain curves obtained during these tests showed also that an increase in confining stress produces a less pronounced post-peak decrease. Nevertheless, the stress–strain behaviour remained similar to that of the original CDW.

In addition, can be seen that the mechanical behaviour is consistent with that of natural soil, reaching strength parameter values competitive with those obtained with a natural granular material, with a similar particle size distribution (for example, above 30° for sands) [29].

These results corroborate the results found by Arulrajah et al. (2012), who performed small-strain static triaxial tests on five types of recycled construction and demolition materials and discovered that recycled concrete aggregate (RCA) and waste rock (WR) are similar to natural aggregate. Through small-strain triaxial tests, Cristelo et al. (2016) found that the mechanical properties of CDW mixtures are similar to those of natural soil. Senetakis (2016) investigated the geotechnical characterization of two uniform fractions of recycled concrete aggregates, and they found an angle of shear strength of about 31° for saturated samples.

3.4. Hydraulic Conductivity

Figure 11 shows the results of hydraulic conductivity of the recycled CDW subjected to different W–D cycles (the results presented are the average of three samples). The range for the different hydraulic conductivity classification levels of soils, as proposed by [29], is also graphically represented for comparison purposes.

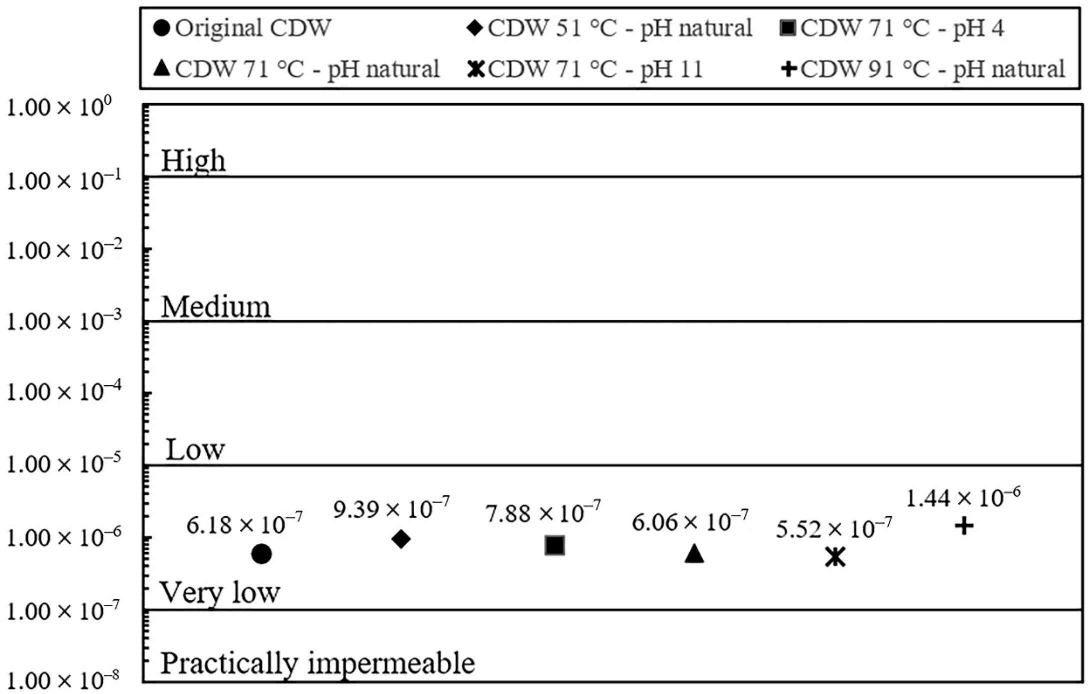

Figure 11. Hydraulic conductivity of the recycled CDW.

Since permeability results were extremely similar, all tested samples were classified in the same hydraulic conductivity range—*very low*. This finding is corroborated by the particle size distribution results. Considering that the size of the grain remained the same for all samples, the permeability of the materials was not expected to change, since it is highly influenced by grain size [10]. In addition, [30] state that coarse-grained soils are more susceptible to long-term degradation cycles, while fine-grained soils (such as the case of this CDW) are less affected, as shown by the aforementioned results.

4. Conclusions

The present work assessed the geomechanical behaviour of recycled CDW subjected to degradation with wetting–drying cycles under different conditions of temperature and pH. From the results obtained for this specific type of material, it was possible to draw the following conclusions:

(a) Regarding the influence of the compaction mechanism on particle size distribution, different compactions energies, standard and modified, have no influence on the particle size of the recycled CDW when compared to original CDW. The small discrepancy between the curves may be related only to the heterogeneity of the material;
(b) Temperature and pH showed no significant changes on the particle size distribution after the 10 wetting–drying cycles. All samples maintained the same soil classification, sand with silt (SM);
(c) The effects of the wetting–drying cycles on mechanical properties of the CDW are not relevant. The triaxial tests showed that the stress–strain behaviour was similar for all CDW samples, with a pronounced strength peak and subsequent strain-softening behaviour, with the highest peak and stiffness for the highest confining stress tested. All samples showed an initial compressive behaviour followed by a dilatant one, in accordance with the behaviour described for classical soil material, such as dense sand at low confining stresses. The strength parameters, c' and ϕ', were close to the original CDW, except for those of the samples submitted to cycles with different pH, 4 and 11, which presented a reduction in the value of ϕ', and it is believed that the acid or basic environments wakened the grains; in addition, the mechanical behaviour of the CDW is consistent with that of natural soil, reaching strength parameters values competitive with those obtained from a natural granular material;
(d) The hydraulic conductivity of the material subjected to the cycles of degradation showed values extremely similar to the original CDW, all staying within the same very low hydraulic conductivity classification range, attesting the results found for the particle size distribution.

This research demonstrated that this particular type of CDW waste presented good degradation performance induced by the construction procedures (compaction mechanism) and weather conditions. Thus, it has a high potential for reutilization as geotechnical material in applications like road and railway base and subbase layers or embankments. This can produce environmental benefits, namely the reduction of the depletion of natural resources and the volume of waste sent to landfills.

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Data Availability Statement: Some or all data, models, or code generated or used during the study are available from the corresponding author by request (full experimental results are available).

Conflicts of Interest: The authors declare no conflict of interest.

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