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Stress dependent behaviour of unbound layers of unselected construction and demolition waste aggregates by lightweight deflectometer tests

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Abstract

The use of construction and demolition waste (CDW) aggregates in unbound road pavement layers is increasing. However, the lack of data on performance in the field has spurred this investigation into their in-situ properties. A lightweight deflectometer (LWD) is a fast and simulative testing device for estimating the elastic modulus of unbound pavement layers. A field test pit was built to run LWD measurements on an unbound subbase layer containing CDW aggregates compacted at different energy levels. To assess their stress-strain non-linear behaviour, several LWD drops were performed on the same location by varying (i) the loading mass, (ii) the drop height, and (iii) the plate diameter. A stress-hardening behaviour of in-situ CDW aggregates was observed, consistent with the stress dependent evolution of resilient modulus of granular material commonly recorded in laboratory tests. The LWD modulus was found to be dependent on the level of compaction energy but also sensitive to the mechanical response of the layer below. The outcomes at this test pit suggest it would be wise to consider the rational evaluation of the in-field stress dependent behaviour of unbound CDW granular materials at both the design stage and when devising quality acceptance procedures. Nonetheless, to have a comprehensive interpretation of LWD results a greater uniformity of material properties and a stronger control of construction procedures will be desired, especially when heterogenous materials such as CDW aggregates are investigated.

Keywords: construction and demolition waste aggregates; unbound pavement layers; lightweight deflectometer; non-linear response; stress-dependant behaviour.

1. Introduction

The use of recycled aggregates from construction and demolition waste (CDW) in road constructions is gradually spreading worldwide thanks to their proven environmental and economic benefits with respect to natural resources (Rosado et al., 2017; Zhao et al., 2021). In the European framework, the implementation of the Green Public Procurement policies and the release of the New Circular Economy Action Plan (European Commission, 2020) will provide a further boost to the promotion of CDW aggregates in the near future (Nadazdi et al., 2022).

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Several investigations revealed the adequate mechanical and durability properties of CDW aggregates and their viability as a replacement to natural ones (Cerni et al., 2012; Bassani and Tefa, 2018; Tavira et al., 2018) in the formation of embankments and unbound road pavement layers (subgrade and subbases). Structurally sound subbase layers are of vital importance for loading support and for the durability of the upper pavement structure. To reach adequate density and bearing capacity, granular materials are moistened and compacted with rollers. The mechanical and volumetric properties of the whole subbase layer are strongly related to both the properties of the granular materials employed in its formation (i.e., gradation, fine content, shape and strength of grains) and the compaction procedure (i.e., moisture content, energy of compaction, type of compaction) (Cheung and Dawson, 2002; Bassani et al., 2021). These aspects assume even greater importance when CDW recycled materials are employed because of their strong heterogeneity (Bassani et al., 2017; Reis et al., 2021).

1.1 Problem statement

Current technical specifications require an assessment of the quality of laying and compaction operations of the subbase layer before the construction of upper bounded layers. Sand cone and static plate loading tests (PLT) are traditionally carried out to evaluate density and bearing capacity respectively (Yoder and Witczak, 1975). With static PLT, the surface modulus (M_{PLT}), i.e., the ratio of an applied static vertical stress to the top of the layer to the resulting vertical deflection, is estimated. This value is representative of the bearing capacity of the layer but cannot be used as a stiffness parameter for the stress-strain pavement analysis (Nikolaides, 2014). Conversely, non-destructive dynamic plate loading tests with light weight deflectometer (LWD) are gaining popularity thanks to the possibility of estimating fundamental material properties (Fleming et al., 2000). LWD is a portable device and consists of (i) a falling mass that transfers a dynamic load via a plate to the layer, and (ii) geophones or accelerometers that measure the surface deflections (Guzzarlapudi et al., 2016; Bilodeau and Doré, 2014).

Despite its increasing acceptance and popularity, there are still some issues with the interpretation of LDW tests results, such as (i) the poor correlation with the degree of compaction (Elhakim et al., 2014; Duddu and Chennarapu, 2022), (ii) the marked spatial variability of results (Hossain and Apeagyei, 2010), and (iii) the unexplored stress dependency of LWD moduli on the stress conditions (Tirado et al., 2017). Moreover, there is a limited background on LWD test outcomes of unbound layers containing CDW recycled materials.

1.2 Study objective

In this experimental study, a field test pit was built with unbound CDW aggregates compacted at three different energy levels to evaluate the expected dependency of the LWD modulus to compaction. On the same testing point, several LWD drops were performed by varying (i) the loading mass, (ii) the drop height, and (iii) the plate diameter to evaluate the stress-strain non-linear behaviour of CDW materials. The LWD test results were interpreted with the support of in-situ density and static PLT outcomes.

2 Materials and methods

2.1 Problem statement

The field test pit was built on February 23rd, 2022 (sunny day, air temperature 2-18°C, RH = 40%, average wind speed of 15 km/h) in La Loggia (Turin, Northwest of Italy), close to the CAVIT SpA headquarter which produced and supplied the CDW aggregates employed in this study. In the CAVIT plant, CDW composed of waste material from the demolition of buildings and road pavements is treated to produce recycled aggregates in the 0-40 mm size fraction. The material employed in this field test is composed of concrete (20.5%), bricks (6.8%), bituminous mixtures (20.4%), rocks, and excavated soils (52.3%). In accordance with EN 1097-6 (European Committee for Standardization, 2013), a sample of the CDW material used was tested and revealed a particle density of grains value equal to 2597 kg/m^3 and a water absorption value of 3.7%.

The field test pit had an extension of 45 m in length and 10 m in width and was divided into three sections characterized by different levels of compaction of the upper 30 cm-thick layer (1st layer, Figure 1). The stratigraphy was selected to minimize the spatial variability of LWD measurements carried out on the compacted laying surface (3rd layer) made up of natural soil. The 3rd layer was compacted with 4 passes of a dynamic roller. The 2nd layer of 40 cm was built with CDW aggregates with compaction operations at the optimum moisture content (OMC). The material was compacted with 8 passes uniformly distributed over the entire extension of the test pit. The top layer (1st layer) of 30 cm was finally compacted at the OMC with different passes (4, 8, and 12) to create three different sections characterized by a low, medium, and high compaction level. A vibrated compaction method was always applied, apart from the last pass, which applied a static compaction to produce a smooth layer surface.

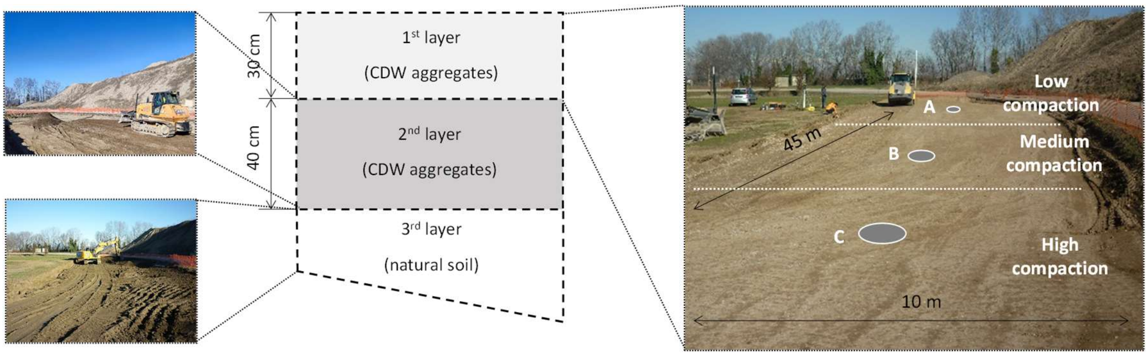


Figure 1: Layout and layered scheme of test pit with indication of compaction sections and testing points.

2.2 Problem statement

A preliminary Proctor compaction study was conducted to measure the optimum moisture content (OMC) and the maximum dry density (MDD) following the modified procedure according to the EN 13286-2 (European Committee for Standardization, 2010). The in-situ density of compacted layers was measured as per the sand cone test method according to the CNR 22/1972 (Consiglio Nazionale delle Ricerche CNR, 1972) and compared with the MDD. A double-cycle static 300 mm plate loading test (PLT) was performed according to the CNR 146/1992 (Consiglio Nazionale delle Ricerche CNR, 1992) to obtain the surface moduli M_{PLT} and M'_{PLT}. During the 1st cycle a load increment of 0.10 MPa was applied with a 200-kN hydraulic jack from 0.05 to 0.35 MPa. The plate was then unloaded and a 2nd loading cycle was performed with steps of 0.10 MPa from 0.05 to 0.25 MPa to obtain M'_{PLT}. For each loading increment, the settlement was constantly monitored and recorded with three dial gauges arranged at 120° on the plate. The deformation moduli M_{PLT} and M'_{PLT} were obtained as the ratio between Δp (increment of load pressure from 0.15 to 0.25 MPa) and Δs (increment of settlement from the corresponding 0.15 to 0.25 MPa pressure) obtained during the 1st and 2nd loading cycle respectively.

A Dynatest 3032 LWD, equipped with a built-in plate loading cell and a central geophone to measure the load and displacement time histories respectively, was employed to estimate the in-situ stiffness of investigated unbound layers. To evaluate the stress-dependent behaviour of unbound CDW materials, 18 different values of vertical pressure were applied by changing the falling mass (10, 15, and 20 kg), the drop height (33, 58, 84 cm), and the plate diameter (300 and 150 mm). Eight consecutive drops were performed for each loading combination. The measured deflection peak and maximum load were employed in Bousinnesq's elastic theory to calculate the surface LWD modulus (E_{LWD}), assuming a Poisson's ratio of 0.35 and a stress distribution shape factor equal to 2 (Senseney and Mooney, 2010; Alshibli et al., 2005). All tests were performed immediately after compaction of each layer. Table 1 summarizes the configurations and the details of performed tests for each location.

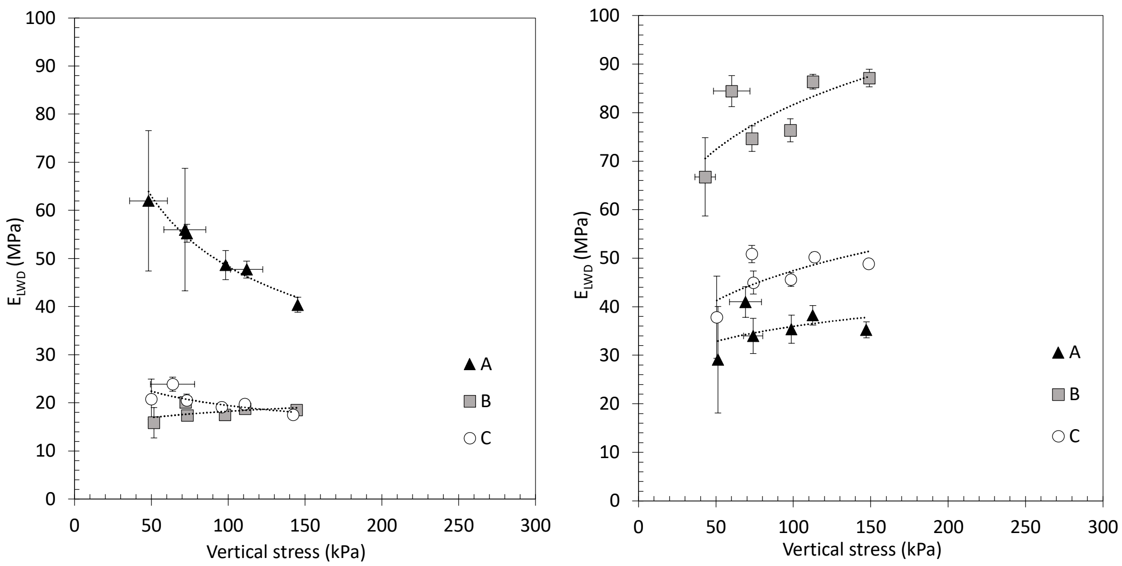
Table 1: Summary of configurations and tests carried out for each location of the test pit.

Layer	Test point	Test type and configuration
Laying surface (3rd)	A, B, C	LWD (mass: 10, 15 kg; height: 33, 58, 84 cm; plate: 300 mm)
2nd	A, B, C	LWD (mass: 10, 15 kg; height: 33, 58, 84 cm; plate: 300 mm)
1st	A, B, C	Density, PLT, LWD (mass: 10, 15, 20 kg; height: 33, 58, 84 cm; plate: 150, 300 mm)

3 Results and discussion

3.1. LWD tests on 3rd and 2nd layers

Figure 2 compares the evolution of the surface LWD modulus (E_{LWD}) as a function of the vertical applied stress in correspondence to the A, B, and C points on both the 3rd and 2nd layer. Consistent with previous research, the LWD stiffness of the laying surface (Figure 2-a) was found to be relatively heterogeneous due to the natural cohesive soil (Anjan Kumar et al., 2016; Apeagyei and Hossain, 2010).



(a) (b)

Figure 2: LWD test results on (a) 3rd and (b) 2nd layer as a function of vertical stress. Error bars indicate one standard deviation.

Apart from point B, an increment in vertical stress resulted in a slight decrease of the E_{LWD}, a finding which was consistent with the common stress-softening behaviour of natural cohesive fine soils (Thompson and Elliott, 1985; Rahim and George, 2005).

As previously mentioned, to reduce the effect of high spatial variability and the stress-softening behaviour of the laying surface (3rd layer), a 40 cm thick additional layer (2nd layer) made up of compacted CDW aggregates was inserted between the 3rd and the 1st layer (Figure 1).

3.2. Sand cone density and plate loading tests on the 1st layer

The results of the sand cone density (SCD) test carried out on the three sections of the 1st layer are reported in Table 2. The increase in the number of roller passes from 4 to 12 led to an increase in material densification from 1994 to 2094 kg/m^3. Comparing the SCD with the Proctor maximum dry density (MDD) of 2128 kg/m^3, the low compacted area (4 passes) reached a density equal to 93.7% of the Proctor MDD. In the case of medium (8 passes) and high (12 passes) compaction levels, the SCD/MDD ratio rose to values of 97.7 and 98.4% respectively. It is worth mentioning that the Proctor MDD was obtained with an OMC equal to 8.2%, while lower water contents were recorded at site (Table 2). The variation in the moisture content in the three sections was due to the construction operations: CDW material was transported by truck and spread with a dozer starting from zone C to zone A. Despite being spread with a water content close to the OMC, CDW aggregates dried lying down before being compacted since the 1st layer was compacted starting from zone A to zone C. Therefore, the material in section C remained exposed to the sun and air (Section 2.1) for longer thus losing the highest amount of water. This also explains why the higher number of roller passes in section C (12 passes) did not lead to a significantly higher densification than that in section B which was compacted with 8 roller passes.

Table 2: Results of sand cone density test on the 1st layer

Compaction level	Sand cone density, SCD (kg/m^3)	At site moisture content (%)	SCD/MDD (%)
Low (near point A)	1994	6.2	93.7
Medium (near point B)	2079	5.6	97.7
High (near point C)	2094	4.9	98.4

Note: MDD = maximum dry density measured as per the Proctor test equal to 2128 kg/m^3 with an OMC equal to 8.2%

Table 3 shows the results for the static PLT conducted on the three sections of the 1st layer subjected to different levels of compaction. The M_{PLT} increased by 32% when passing from the low and the medium compacted area, while the section compacted with 12 passes (high compaction level) exhibited an M_{PLT} value almost equal to that of area B.

Focusing on the values of M'_{PLT}, a clear reduction from 289.4 to 125.5 MPa from the low to high compaction level was observed. Therefore, the M_{PLT}/M'_{PLT} ratio increased from 0.14 to 0.23 passing from low to medium compaction, while it reached a value of 0.42 in the case of 12 passes, thus demonstrating an effective enhancement of the quality of compaction of the 1st layer when moving from 4 to 12 roller passes. According to the CNR 146/1992 (Consiglio Nazionale delle Ricerche CNR, 1992), the M_{PLT}/M'_{PLT} ratio is an indicator of the quality of compaction: values close to the unit denote that the layer experienced a small permanent strain during the 1st loading cycle and low extra-compaction occurred during the 2nd cycle, thus the M_{PLT} and M'_{PLT} values are similar; vice versa, when the degree of compaction is low, the M_{PLT}/M'_{PLT} ratio assumes low values because of the higher permanent strains (i.e., compaction) accumulated during the 1st loading cycle, which results in M_{PLT} values significantly lower than M'_{PLT}.

The surface PLT modulus at point C was similar to that at point B because of the low mechanical response of the layers below section C, which likely contributed to the deformation of the entire layered system. In fact, E_{LWD} at point C at depth of 2nd and 3rd layer was significantly lower than that at point B (Figure 2).

Table 3: Results of static plate loading test on the 1st layer.

Compaction level	M_{PLT} (MPa)	M'_{PLT} (MPa)	M_{PLT} /M'_{PLT} (-)
Low (near point A)	39.3	289.4	0.14
Medium (near point B)	51.9	229.0	0.23
High (near point C)	52.1	125.5	0.42

Note: M_{PLT} = deformation modulus at the 1st loading cycle, M'_{PLT} = deformation modulus at the 2nd loading cycle.

3.3 LWD tests on the 1st layer

The results of the LWD tests on the 1st layer with different loading configurations are shown in Figure 3. Each point is the average value of eight drops with the same loading configuration (Section 2.2). For all investigated locations, an increment in the applied vertical stress was followed by an increase in the surface LWD modulus (E_{LWD}). This outcome suggests that the non-linearity of CDW granular materials has an influence on the LWD response, thus it needs to be taken into account as well as the stress dependent evolution of resilient modulus of granular material commonly recorded in laboratory tests (Uzan, 1985; Lekarp et al., 2000).

The stress-hardening behaviour was more pronounced in the A and B sections, compacted with 4 and 8 passes respectively. In the case of point C, E_{LWD} is less dependent on the vertical stress. These aspects can be quantitatively appreciated by considering the power law relationship of Equation 1, which was employed to fit the experimental results:

$$E_{LWD} = a \cdot (\sigma_v)^b \tag{1}$$

where σ_v is the vertical stress, while a and b are regression coefficients. In particular, the b coefficient quantifies the influence of the σ_v on the LWD stiffness. The higher values of b for points A and B testify to the greater stress-hardening effect with respect to point C. It is worth noting that Equation 1 fitted the non-linear behaviour at points A and B with determination coefficients (R^2) of 0.75 and 0.89 quite well, while it was less effective in fitting the experimental results of point C ($R^2 = 0.57$). A considerable discontinuity in the measured E_{LWD} (in point C) when passing from 300 to 150 mm plate configuration was recognised, thus partially justifying this low value of R^2. Kim et al. (2007) stated that at low stress values, the influence of σ_v is not significant because of the small deflection response of the material.

Figure 3 shows that the increase in compaction energy level contributed to the increase in the E_{LWD} value. For all LWD loading combinations, the area compacted with 12 passes (point C) exhibited an elastic modulus which was 40% higher on average than the area compacted with 4 passes. This result is consistent with previous research (Sulewska, 2012) and with sand cone density and PLT modulus tests (Section 3.2).

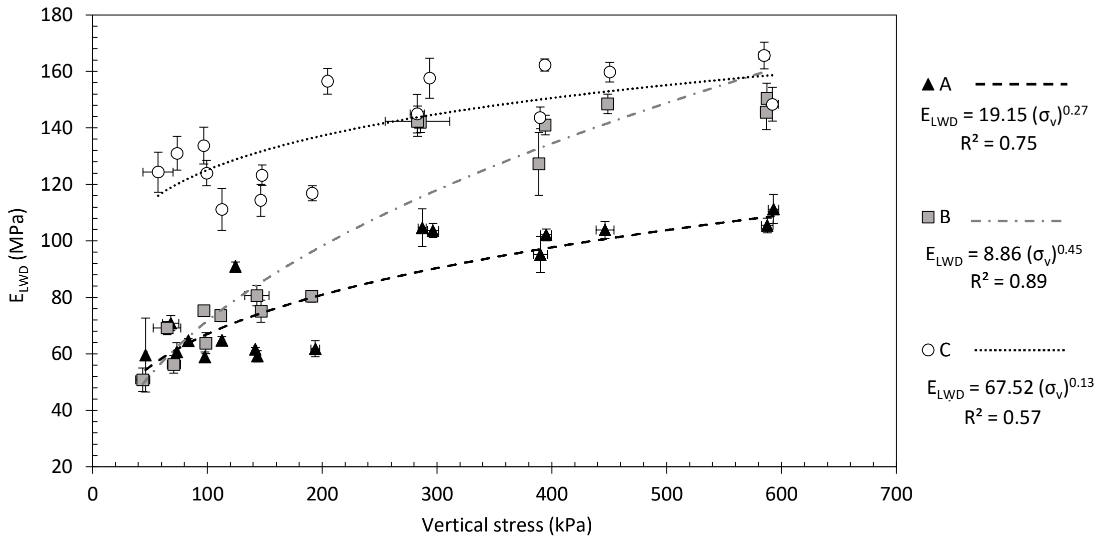


Figure 3: LWD test results on A, B, and C points of the 1st layer as a function of vertical stress. Error bars indicate one standard deviation.

Considering the testing point B, LWD drops led to intermediate values of E_{LWD} between point A and C. However, at low vertical stresses (300 mm plate), the LWD moduli of point B were close to that of point A, thus suggesting that 8 roller passes instead of 4 did not lead to a significant increase in the stiffness of the layer. However, at high vertical stresses (LWD configuration with 150 mm plate), the E_{LWD} values for area B were markedly higher than those for area A, almost reaching the values measured at point C. This result may be ascribed to the higher stiffness of the 2nd layer in point B with respect to points A and C (Figure 4), which contributed to the overall LWD modulus recorded in point B (Benedetto et al., 2012). This effect was only evident at high stresses because they tend to involve a greater depth below the loading plate.

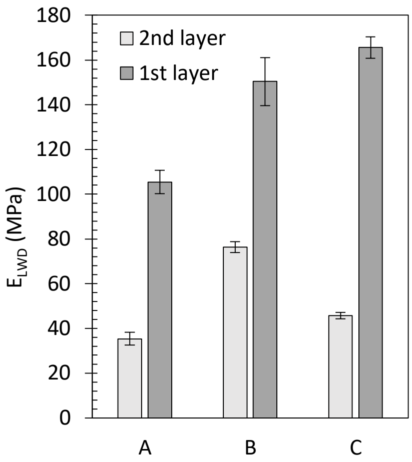


Figure 4: Comparison of LWD moduli at specific loading configurations (10 kg falling mass, 84 cm of height, 300 mm plate for 2nd layer; 15 kg falling mass, 84 cm of height, 150 mm plate for 1st layer) for the three testing points. Error bars indicate one standard deviation.

4 Conclusion

In this study, an experimental field test pit was built to evaluate the mechanical response of a subbase layer containing CDW aggregates as per the LWD testing method. To assess the stress-strain non-linear behaviour of the CDW materials, several LWD drops were performed on the same location by varying (i) the loading mass, (ii) the drop height, and (iii) the plate diameter, i.e., by varying the applied vertical stress.

This approach allowed us to evaluate the stress-dependent behaviour of CDW granular material and determine the stress-hardening behaviour of LWD modulus. A general increment in the surface E_{LWD} in response to an increase in the level of compaction energy was observed, which was in line with expectations and corroborated the sand cone density and PLT outcomes. At high vertical stresses involving a greater depth below the loading plate, the stiffness of the layer below the 1st layer (i.e., the 2nd layer) had an influence on the deflection response of the LWD tests. It suggests that the interpretation of LWD test results should require a clear knowledge of the mechanical contribution of the layers below the investigated one.

The outcomes of this experimental test pit suggest a need to consider the stress dependant behaviour of CDW aggregates that affect the LWD modulus. The stress-hardening behaviour of in-situ CDW aggregates is consistent with the stress dependent evolution of the resilient modulus of granular material commonly measured in laboratory tests and should be considered for the rational evaluation of unbound layers at both the design stage and in quality acceptance procedures. Nonetheless, a better interpretation of LWD results should be accompanied by a greater uniformity of material properties and greater control of construction procedures (thickness of layer, humidity), especially when heterogenous materials such as CDW aggregates are investigated.

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