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INFLUENCE OF COMPACTION AND LOADING CONDITIONS ON THE DYNAMIC PROPERTIES OF A SILTY SAND

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ABSTRACT

Elastic properties of a compacted silty sand were measured in a precision triaxial cell at the Ecole Centrale de Paris in the range of very small strains (between 10^{-6} and 10^{-4}), using improved Hall effect-based local strain gauges and data acquisition system. The dynamic properties of the soil were also derived from resonant column tests at the IST, in Lisbon, as functions of shear strain, compaction water content and confining pressure. Elastic limits as low as 5.10^{-6} were found in both devices, with Poisson's ratio from triaxial tests ranging from 0.05 at very strains ($< 10^{-4}$) to 0.37 at larger strains. Comparison between quasi-static and dynamic values were found to be in good agreement, with a reasonable value of Poisson's ratio, despite the complex properties of this soil such as viscosity, ageing effects and anisotropy.

INTRODUCTION

The dynamic characterization of soils has been studied extensively over the past 40 years. It is generally expressed in terms of shear wave velocity, shear modulus and damping ratio. These properties are evaluated by different techniques in laboratory and in the field, where tremendous recent advances have taken place. However, many of these studies were performed in dry or saturated soil conditions, despite the widespread use of unsaturated soils in compacted materials in civil, mining and environmental engineering. Furthermore, the stress-strain behaviour in the domain of small to intermediate strains (pre-failure domain) has not been deeply investigated.

In this paper, the emphasis is placed on the comparison between resonant column and precision triaxial compression test results obtained on a silty sand compacted with different water contents and dry densities on both sides of the optimum. These compaction conditions lead to different structures (“fabrics”) and consequentely to different hydraulic and mechanical properties (Fleureau *et al.*, 1999). In this paper only the mechanical properties will be discussed. These two types of tests apply different loading conditions. The resonant column test applies a dynamic (torsional) loading where the acceleration is a major controlling factor and material properties are determined by the dynamic properties (resonant-frequency) of the system including the specimen. In the precision triaxial test the monotonic or cyclic loading (axial or/and horizontal stresses) is applied at a relatively slow strain rate for which the effect of inertia can be ignored. So, the material properties obtained will be compared to evaluate the sensitivity of the material tested to the effects of loading conditions.

It must be emphasized that the parameters derived from the resonant column are the shear modulus (G) and the damping ratio (D) in function of the amplitude of the shear strain (10^{-6} to 10^{-4}). In the precision triaxial test, the Young’s modulus and Poisson’s ratio are obtained in function of the vertical strain (ε_1) or volumetric strain ($\varepsilon_v = \varepsilon_1 + 2\,\varepsilon_3$). These parameters can be easily converted in terms of shear modulus and shear strain by eq. (1) if it is assumed that the material behaves in an elastic and isotropic way.

$$G=\frac{E}{2\cdot(1+\nu)} \text{ and } \gamma=(1+\nu)\cdot\varepsilon_1 \qquad (1)$$

However, the results could also be analysed by an existing cross-anisotropic hypo-quasi-elastic model (Tatsuoka *et al.*, 1999) considering inherent and stress state induced anisotropy.

BACKGROUND ON SMALL TO MEDIUM STRAIN BEHAVIOUR OF COMPACTED SOILS

Despite the fact that compacted soil is a common construction material, there is a lack of experimental data on its behaviour at small to intermediate strains. Moreover, compacted soil with different water contents will produce different structures (“fabrics”) and consequently its response in this strain domain should be strongly influenced.

Wu *et al.* (1989) and Quin *et al.* (1991) have investigated the small strain range behaviour of partially saturated soils. Very recently Picornell and Nazarian (1998) have investigated the effect of matric suction on the small strain range of fine to coarse grained reconstituted soils. Further research have also been carried out by Cabarkapa *et al.* (1999) and by Vinale *et al.* (1999). The former presents the behaviour of the Metrano silty sand under saturated conditions for specimens compacted at the optimum water content and on the dry and wet sides of the optimum. Refering the data to the same strain amplitude, strain rate and ageing time, Vinale *et al.* (1999) conclude that: i) the specimens compacted at the optimum water content have a large initial shear modulus compared to the dry and wet specimens; ii) the specimens with higher initial shear modulus also have higher damping ratios. However, they emphasize the need of further studies to explain why stiffer structure obtained when the soil is compacted at the optimum water content also has higher dissipation properties.

Vinale *et al.* (1999) reported very interesting data on the same soil obtained in resonant column-torsional shear device with the capability of working under suction-controlled conditions. Tests results obtained on specimens compacted at modified Proctor optimum and wet of optimum water content show that the initial shear modulus increases with suction until a threshold value that depends on the net mean normal stress. This same trend was also observed by Gomes Correia *et al.* (1996) for the Fontainebleau sand. Vinale *et al.* (1999) remarked that wet compaction induces a weaker soil fabric with respect to optimum, showing that increasing water content causes a strong reduction in the initial shear modulus of the Metrano silty sand, both in resonant and torsional shear tests. The authors emphasize that the soil fabric resulting from compaction water content conditions is the key regulator of soil behaviour, since the other factors like ageing, stress state and history or suction were unchanged.

MATERIAL AND METHODS

Tests were performed on a residual silty sand, hereafter called Perafita sand, resulting from weathered granite, which has been used as a building material for a road in the north of Portugal. Its mean properties related with grain size distribution are shown in Table 1.

Table 1. Mean properties of Perafita sand

d_{10}	d_{30}	d_{60}	d_{60}/d_{10}	<80μm	γ_s/γ_w
mm	mm	mm		%	
0.036	0.192	0.604	16.8	18	2.66

The standard and modified Proctor curves are shown in Fig. 1. The preparation of specimens is the same for all the tests : the soil is sieved to avoid the presence of aggregates, then it is mixed up with the right quantity of water; after that, it is placed in a sealed plastic bag for 24 hours to allow the hydric equilibrium to establish. Finally, compaction is made in 3 layers in a small mould (70 mm in diameter, 140 mm high) by a 24 N weight falling from a 305 mm height, with 24 blows per layer. The compaction curve and the points corresponding to the studied water contents are also shown in Fig. 1.

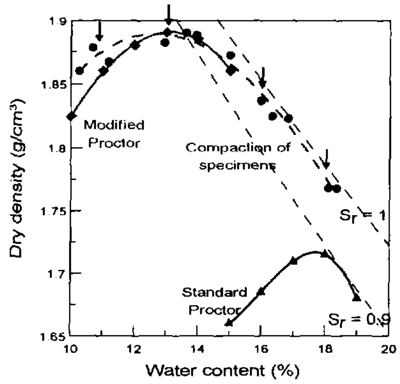

Fig. 1. Compaction curve in the ∅70 mm mould, compared to the Standard and Modified Proctor curves

After compaction, the specimen is placed in the triaxial cell and allowed to consolidate under the first isotropic stress during one day (in the hereafter-called "standard conditions"). Then, a deviator loading is applied up to 10^{-4} axial strain, in order not to damage the sample. Then, the confining pressure is increased until the second consolidation stress level, and so on for the other levels. For the last confining pressure, *i.e.* 79 kPa, the specimen stays in consolidation for 3 days (ageing) before the test. At the end of all the tests, a larger cycle is made, up to a few 10^{-3} axial strain. The drainage system remains open during all the tests.

EXPERIMENTAL DEVICES

Resonant Column device

The resonant column test (RCT) is one of the most accurate and repetitive way of determining the small strain shear modulus (Lo Presti et al., 1999). The apparatus used is of the fixed-free type, in which the top end (free end) is vibrated in torsion mode by means of an electromagnetic drive system (SEIKEN - model DTC-158). The frequency of excitation is adjusted until the first mode of resonance of the specimen is established. Measurements of the resonant frequency, acceleration and amplitude of the applied vibration excitation are made at the free end. These measurements, combined with the apparatus characteristics, are used to calculate the shear modulus and damping ratio of the specimen. The equipment used at the Geotechnical laboratory of IST in Lisbon was completely automated for test running and for data acquisition and analysis. The test results are presented in terms of shear modulus and damping ratio in function of the shear strain amplitude.

Despite its simplicity and accuracy, this test method has the following drawbacks:

- the applicable maximum shear strain is rather small, and usually not larger than 0.1 %;
- the loading frequency or the strain ratio is too large for most geotechnical engineering problems and is not constant during testing. This fact can have a non negligible influence on the shear modulus and on the damping ratio of some soils and consequently must be taken into account correctly (Bray *et al.*, 1999; Gomes Correia, 1999; Lo Presti *et al.*, 1996; Tatsuoka *et al.*, 1997).

Precision triaxial tests - Hall effect-based local strain measurement gauges

Hall effect-based local strain measurements principles are well documented in Clayton and Khatrush (1987). Lo Presti *et al.* (1994) compared the performance of LVDT, LDT and Hall effect strain gauges and concluded that Hall effect measurements exhibit the smallest resolution and the largest scatter in comparison with the two other transducers. They also showed that Hall effect strain gauges exhibit poor stability in the measurements made at room temperature (20 ± 2 °C) and that they are the most sensibly affected by electrical noise. In a personal communication Lo Presti showed the importance of the relative position between Hall effect sensor and magnet casing during a calibration test. He also noticed some stick-slip behaviour, which is typical of a system with some friction as is the case of Hall effect setting. To overcome these drawbacks, a lot of improvements have been realised in the system used at the laboratory of ECP.

The basic instrumentation was bought from GDS Instruments in the UK to be used with specimens of 140 mm high and 70 mm in diameter (Fig. 2). Three Hall effect devices were used: two 80 mm-long axial gauges were attached to the central part of the sample and one radial calliper was attached to two opposing points of a diameter in the middle section of the sample.

As referred, many parameters can lead to significant measurement errors. Temperature variations are the main source of errors. They have an influence on the thermal expansion of the pendulum arms and the calliper (the thermal expansion ratio of aluminium being $23\ 10^{-6}\ K^{-1}$). The gains of the Hall chips can also vary due to temperature drift ($\approx -0.05\ \%\ K^{-1}$), and this is relevant if there is an initial offset in the output voltage. The magnets flux drops with the temperature elevation ($\approx -0.5\ \%\ K^{-1}$ for ferrite magnets), which leads to the same potential problem. The acquisition device as well is temperature-dependent. There are also some indirect effects of temperature such as the possible variation of the confining pressure. The pressure also depends on the incoming or outgoing volume of the piston. The average pressure controller has a 1 kPa tolerance range, but when working with a material, the E_{max} of which is about 100 MPa, this means a 10^{-5} strain imprecision. Besides, other more practical matters may affect the quality of the result, like the good or bad alignment of the two parts of the gauge (calibration gave approximately 7% of gain change per degree of misalignment), or like the lack of knowledge regarding the behaviour of the latex membrane under the pads supporting the diametrical calliper. The issue of the centring of the piston, which is usually guaranteed by a hollow in the sample cap, appeared to be non-negligible.

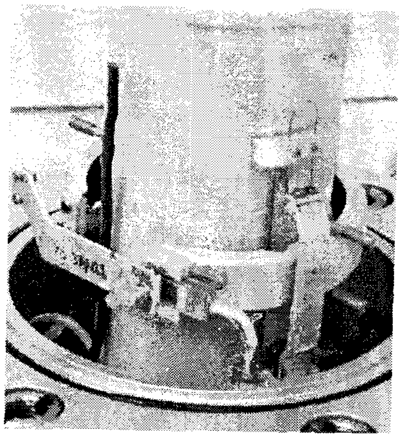

Fig. 2. Hall effect-based local strain gauges used in the precision triaxial tests

To reach the desired precision, some precautions had to be taken and some modifications applied, such as: working in a basement to avoid temperature changes and vibrations; using a compressed air tank as a pressure buffer to compensate the movement of the piston into and out of the cell; using a very high precision voltage source (HP 3245A) and multimeter (HP 3458A); replacing the ferrite magnets with Sm-Co magnets, which are much stronger and more temperature-stable ($0.035\ \%\ K^{-1}$) and allowed to increase the overall gain by a factor 10; adding to the lower pad a screw that allows to precisely set the initial relative position of the sensor and the magnet and thus reducing the offset; adding a pointing system that allows to precisely set the alignment of the upper and the lower part of the strain gauge; modifying the attachment pad of the lateral strain calliper to eliminate the membrane deformations; replacing the hinges of the calliper with flexible wire springs in order to get rid of the play; etc.

The enhanced equipment was tested with a dummy brass specimen: the resulting precision in axial strain was as low as a few 10^{-7}. Finally, on soil specimens, Young's modulus can be measured with a good accuracy over a $5\ 10^{-6}$ strain range.

RESULTS AND DISCUSSION

Results from resonant column tests

Only a few typical results will be presented about the shear modulus. The usual representation of the shear modulus degradation curve in function of the shear strain shows that the elastic threshold is around 5.10^{-6}. The influence of the increasing isotropic consolidation stress is reflected in an increase of the shear modulus. Concerning the influence of water content, Fig. 3 shows no influence when the degradation curve is normalized using in ordinates the shear modulus (G) divided by its maximum value (G_{max}). No influence is either observed on the very small shear strain modulus (G_{max}), when normalized with a function of void ratio (Iwasaki *et al.* 1978):

$$f(e)=(b-e)^2/(1+e) \quad \text{with b = 2.17} \qquad (2)$$

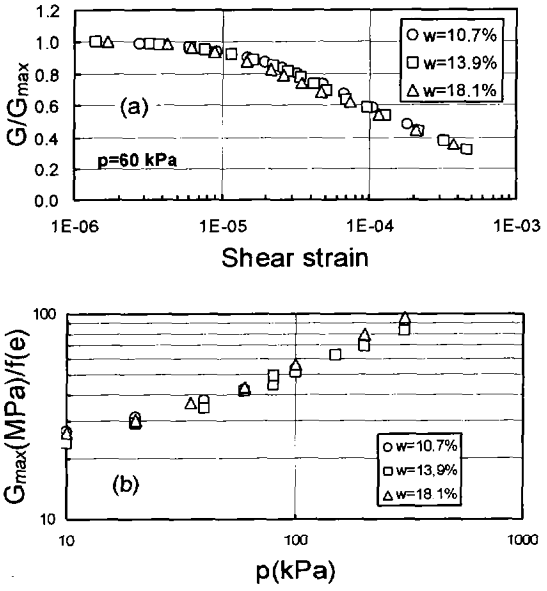

Fig. 3. Influence of moulding water content on: a) normalized shear strain degradation curve; b) maximum shear modulus normalized by a function of the void ratio.

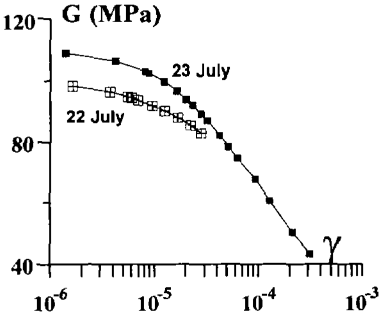

Fig. 4. Influence of ageing.

The effect of consolidation time was observed in a resonant column test (w = 18,1%) for an ageing of about one day and a consolidation stress of around 50 kPa (Fig. 4).

Results from precision triaxial tests

Figure 5a shows the changes in deviator versus axial strain in the range from $\varepsilon_1 = 0$ to $1.2 \cdot 10^{-5}$. The regularity and continuity of the curve highlight the good quality of the measurements, which is confirmed by the reversibility of the first cycle. At the beginning of data acquisition, the distance between the experimental points is as small as 10^{-7}. For larger cycles (Fig 5b), irreversibilities are observed but, whatever the irreversible strain level, the small strains unloading-reloading moduli remain constant. On Fig. 5c, the secant modulus was calculated as the ratio of the deviator to the corresponding axial strain in a monotonic test. Under a 5.10^{-6} strain, the secant modulus appears to be constant, with a maximum value of about 100 MPa. Above this value, the modulus drops, with a change in the convexity of the curve in the semi-log graph at approximately $\varepsilon_1 = 10^{-5}$. In the usual triaxial domain (for ε_1 = 0.1 %), the modulus comes down to 17 MPa. Figure 5d presents the changes in radial versus axial strains during a large cycle. Between 10^{-3} and $2.5 \cdot 10^{-3}$, the slope of the curve shows a Poisson's ratio of 0.37. It is interesting to notice that, at small strains (below 10^{-4}), the Poisson's ratio tends towards a much smaller value (0.05). This was confirmed in several other tests.

Influence of consolidation time and strain rate. In order to compare the results of precision triaxial tests carried out at relatively low strain rates and resonant column tests, in which the loading frequency reaches around 100 Hz, the influence of strain rate has been examined. In the range of strain rates (from $5 \cdot 10^{-9}$ to 10^{-7} s^{-1}) and for the water content (w = 13.7 %) investigated in the triaxial, it seems that this parameter has little effect on the maximum modulus, but the dispersion is relatively high (Fig. 6a). Moreover, the shape of the unloading curves in the [ε_1 , q] diagram highlights that the strain keeps increasing a little after the deviator starts to decrease: this is clearly a viscous behavior which could be related to the relatively high proportion of fines contained in the sand (18% < 80 µm). Some of the tests have been performed after different consolidation times and it was useful to study the influence of this factor on the results: the confining pressure (13 kPa) was applied on day 0 on the sample at w = 13.7 % and measurements were carried out on days 1, 3, 7 and 14. Figure 6b shows a general increase in the maximum modulus, of about 10 % between the initial and the final measure. This effect, which should be confirmed by tests at different water contents and confining pressures, has already been mentioned by Santucci de Magistris *et al.* (1998).

Influence of confining pressure and compaction water content on Young's modulus. Precision triaxial tests have been performed under confining pressures of 13, 26, 53 and 79 kPa on samples compacted at water contents of 11.1, 13.7, 16.4 and 18.0 %. To compare the results at the same void ratio, the moduli were corrected using eq. 2.

For the tests carried out in the standard conditions, at the two lowest water contents, Fig. 7a shows a quasi-linear increase in the maximum modulus with the confining pressure. In the other two cases, at w = 16.4 and 18 %, observed maximum moduli are slightly too high and drop for the highest confining pressure. Non-standard consolidation times are responsible for these discrepancies: at w = 16.4 %, the consolidation times were, respectively, 3 days, 2 days, 1 day and 1 day and at w = 18 %, 1 day, 8 days, 5 days and 1 day. It has been previously observed that this factor plays an important part and could account for the high moduli values measured after longer ageing times.

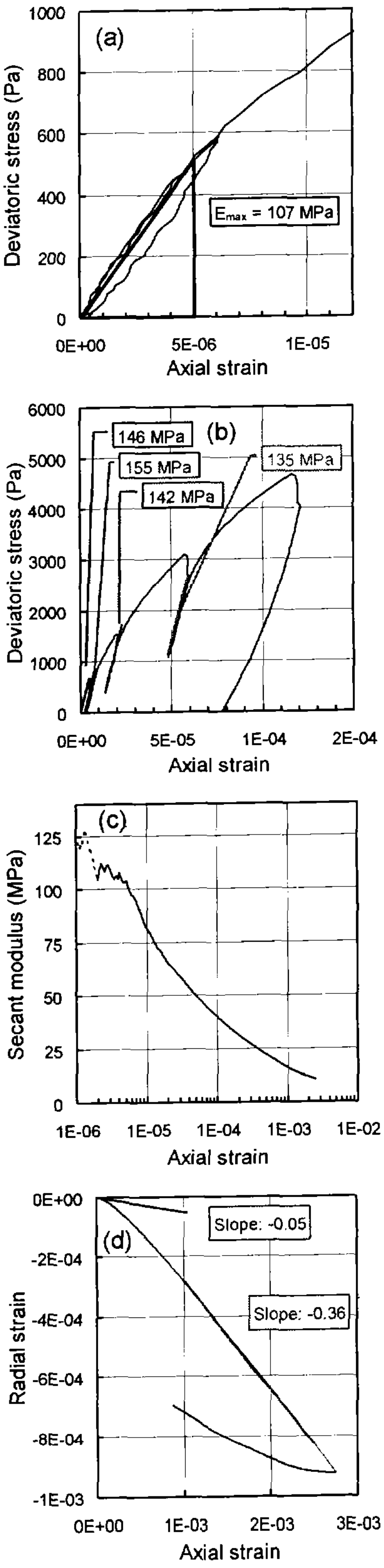

Fig. 5. Deviatoric stress paths: (a), (c) & (d) w=13.9 %, σ_3=13.7 kPa, e_{ini}=0.48, 14 days of consolidation, strain rate of 10^{-8} s^{-1}, beginning of the loading; (b) w=11.1 %, σ_3=51.1 kPa, e_{ini}=0.50, 1 day of consolidation, strain rate of 10^{-8} s^{-1}, larger cycle with small strain unloadings-reloadings and their moduli.

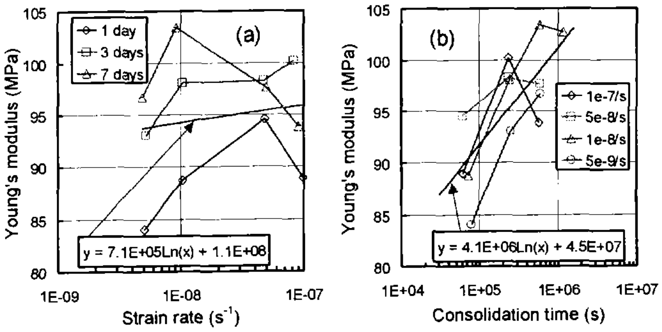

Fig. 6. Young's moduli E_{max} calculated from series of deviatoric tests and corrected to the same void ratio of 0.5 with Hardin's formula, w=13.9 %, σ_3=13 kPa, e_{ini}=0.48; (a) influence of the strain rate at different consolidation times; (b) influence of consolidation time at different strain rates.

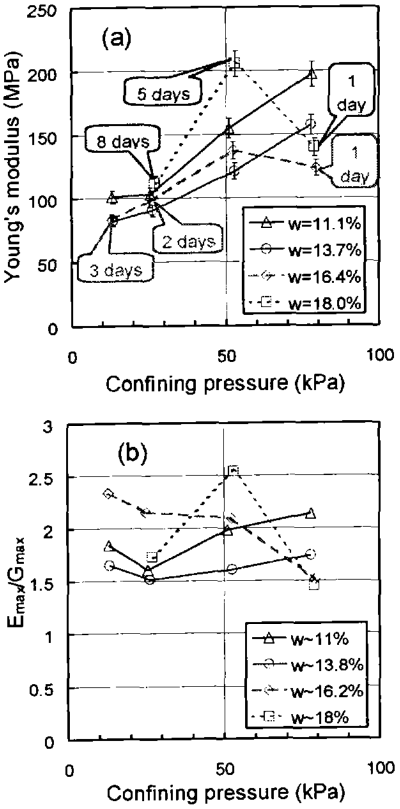

Fig. 7. Normalized elastic moduli calculated from series of deviatoric tests; (a) influence of the confining pressure on E_{max} for different initial water contents — non-standard consolidation times are reported; (b) comparison of triaxial tests and resonant column tests with the ratio E_{max}/G_{max} against confining pressure for each water content.

In standard conditions, at a given density and total confining pressure, the modulus increases when the compaction water content decreases from 13.7 % to 11.1 %. This result is explained by the increase in the negative pore-water pressure that results in an increase in the effective isotropic stress. However, this effect is of lesser importance than the ageing of the material in the two non-standard tests.

Comparison between the results of precision triaxial tests with those of column resonant tests

Figure 7b presents the ratio of maximum moduli derived from precision triaxial tests to those from resonant column tests versus confining pressure: the mean value appears to be independent from the confining pressure and close to 2. For an isotropic material, Poisson's ratio derived from E_{max} and G_{max} is close to 0. This value is confirmed by the experimental data of Fig. 5d for small strains. However, this conclusion should be considered carefully, given the anisotropy that could derive from compaction.

CONCLUSION

The improvement of a Hall effect gauges system to carry out sample strain measurements in triaxial tests led to reliable values of Young's modulus and limits in the range of strains from 10^{-6} to a few 10^{-3}. Elastic limits as low as 5.10^{-6} were found for a compacted silty sand from Portugal. Poisson's ratio varying from 0.05 at very low strains to 0.37 at larger strains were measured in these tests.

The experimental results on a compacted silty sand (residual soil of granite) show that water content has no influence on the shear modulus in the strain range from 10^{-6} to 10^{-4}. Comparison between moduli obtained by precision triaxial tests and those from resonant column tests showed a good agreement between experiment and theory with a reasonable value of Poisson's ratio, in spite of the complex properties of this soil such as viscosity, ageing effects and anisotropy. Therefore, for very small strains, very similar elastic properties can be obtained using different loading systems. This shows that these properties are "quasi-intrinsic" properties that can be used both for dynamic and static analysis.

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