Consistency of the Casagrande Liquid Limit Test

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ABSTRACT

The liquid limit test is one of the most widely used tests in soil mechanics, with the value obtained being correlated against a variety of soil properties such as soil strength. The percussion test for liquid limit originally described by Casagrande (1932) is the standard test for liquid limit in much of the world. The apparatus to be used is described in many design codes including ASTM D4318-10e1. While it is well known that two classes of these devices exist, those with hard and soft bases, the true picture is more complex; International design codes contain a great variety of specifications for the devices, some much more prescriptive than others.

This paper uses the analysis described by Haigh (2012) to investigate the effects of base hardness and resilience on specific strength at liquid limit. A survey of devices in use worldwide was also carried out, indicating that both the variability in national design standards and potential degradation of bases over time leads to a large variability in the specific strength observed at liquid limit when different devices are used.

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KEYWORDS: Plasticity, Identification and Classification of Soils, Texture Plasticity and Density Characteristics of Soils

INTRODUCTION

Atterberg (1911) first proposed a test for measuring the water content at which soil changed from a plastic to a liquid state, involving striking a porcelain bowl containing soil in which a groove has been cut on the palm of the hand. This test was subsequently standardized by Casagrande (1932) who developed equipment to drop a brass cup containing soil through which a standardized groove had been cut through a fixed distance onto a hard rubber base; the liquid limit being the water content at which 25 blows were required to close the groove. While the plastic limit test, (determined by thread rolling as described in ASTM D4318-10e1 determines a genuine observable transition in soil behaviour from a plastic to semi-solid state, as discussed by Haigh et al. (2013), the liquid limit is essentially arbitrary in nature; no distinct change in soil behaviour being observable at this water content. The liquid limit of a soil is thus dependent on the precise characteristics of the method and device used to determine it.

It has been widely recognised that different procedures for determining liquid limit may result in different values being obtained for the same soil. Casagrande (1958) recognised that since its inception 26 years earlier the liquid limit device that he had invented had evolved differently in different countries, those in use in the USA having hard Micarta bases and those in the UK having softer rubber bases, base hardness not having been rigidly determined in the original specification. These differences in specification have persisted since, with the added complexity of liquid limit being determined using fall-cone methods in much of Europe. The influence of these three testing methodologies, (hard base cup, soft base cup and fall-cone) have been investigated widely to determine the differences in liquid limit measured. A synthesis of investigations by Norman (1958), Sridharan and Prakash (2000) and Dragoni et al. (2008), resulting in the 35 data points shown in Figure 1, shows the soft-base cup to give a higher liquid limit value than the hard-base cup, a linear regression to the data yielding equation 1.

$$w_{L\,hard} = 0.904\, w_{L\,soft} + 0.44\% \qquad [1]$$

The cone penetrometer has been shown to give broadly comparable results to the hard-base cup for soils with low liquid limits but to diverge substantially for high liquid limit soils, (Wasti and Bezirci 1986), the liquid limit measured by the fall cone test being substantially lower than that measured using the Casagrande cup. Haigh (2012) analysed the Casagrande liquid limit test by measuring the acceleration of the cup during impact on the base of a hard-base device and using this as an input to a Newmarkian sliding block analysis (Newmark 1965) of the slopes of the groove through the soil. This analysis showed the liquid limit to be associated with a value of specific soil strength (ratio of strength to density) of approximately 1 m^2/s^2, comparable with reported strength in the literature for vane shear strengths at liquid limit. This explained the observed trend in strength data such as that by Youssef et al. (1965), in which strength at liquid limit decreased with increasing liquid limit and hence also the divergence between cone and cup liquid limit values. The data from multiple sources still, however, showed a large degree of scatter, especially when comparing data from different sources. This raised questions as to the similarity between liquid limit devices in operation worldwide and hence to the replicability of liquid limit test results between different countries and laboratories.

WORLDWIDE SPECIFICATION OF CASAGRANDE LIQUID LIMIT APPARATUS

As most large countries worldwide rely on their own design standards, there are a plethora of descriptions available describing the precise specification of a Casagrande liquid limit device. The specifications from 15 countries for which this data was collected are summarised in Table 1. The base hardnesses for these devices are specified using one of three scales; Shore

A, Shore D or IRHD. Whilst these hardnesses are uniquely defined only by the method used to derive them, approximate conversions from each of the hardness scales to Young's Modulus are given by Gent (1958) and Hertz and Farinella (1998). These were used to calculate the comparable stiffness values in Table 1.

It can be seen that while there are two major classes of liquid limit device, those with hard and soft bases, the precise nature of a device within each of these categories is not rigidly defined. More worryingly, two countries, New Zealand and Switzerland, either give no guidance as to the base hardness or give such a broad range of hardness values as to essentially cover both types of device, (an IRHD value of 100 corresponding to a rigid material). The French code NFP94-051 (1993) is also peculiar in defining the base characteristics based on compressive strength and density, which will have only an indirect relationship to the shock loading experienced by the cup.

In addition to the base hardness, the base resilience is also an important parameter in determining the nature of the impact between the cup and the base. The resilience is defined as the ratio between the rebound height and the initial height of a ball-bearing dropped vertically onto the base. This ratio is typically close to 90% for hard-based devices with relatively rigid plastic bases such as those defined by ASTM, and around 30% for the rubber bases of soft-based apparatus, for example those defined by the British standard.

EFFECT OF BASE HARDNESS ON LIQUID LIMIT

The impact between the cup of the Casagrande device and the base could be approximated as the impact of a spherical body on an elastic half-space. This problem was investigated analytically by Hertz (1881) from whose work it can be shown that the force F exerted on a rigid sphere of radius R indenting an elastic half-space with Young's modulus E and Poisson's ratio v is related to the indentation d by:

$$F = \frac{4E\sqrt{Rd^3}}{3(1-\nu^2)} \quad [2]$$

By integrating this equation and noting that the kinetic energy of the cup at impact with the base of the liquid limit device K is constant regardless of the device specification (drop height always being defined as 10 mm), it can be shown that the maximum penetration d_{max} is given by:

$$d_{max} = \left[\frac{15K(1-\nu^2)}{8E\sqrt{R}}\right]^{\frac{2}{5}} \quad [3]$$

And hence the maximum acceleration is given by:

$$a_{max} = \frac{F_{max}}{m} = \frac{4E\sqrt{R}}{3m(1-\nu^2)}\left[\frac{15K(1-\nu^2)}{8E\sqrt{R}}\right]^{\frac{3}{5}} = \frac{1.944}{m}\left[\frac{E^2K^3R}{(1-\nu^2)^2}\right]^{\frac{1}{5}} \quad [4]$$

$$a_{max} \propto E^{\frac{2}{5}} \quad [5]$$

Numerical solution of the equation of motion for the cup results in the acceleration pulse that the cup is subjected to having a normalised shape as shown in Figure 2. As the integral of the acceleration is equal to the change in velocity of the cup through the bounce, stiffer bases will typically exhibit higher maximum accelerations a_{max}, but lower durations T in order to keep the integral approximately constant. Changes in the resilience of the base may alter the rebound velocity and hence change the value of the integral. The assumption of a purely elastic behaviour of the base results in an implied base resilience of 100%, a reasonable assumption for hard-based apparatus but excessive for soft-base devices. The effects of this assumption will be discussed later.

It can be seen from Table 1 that the prescribed base stiffness in the liquid limit test apparatus ranges from 8-500 MPa, dependent on the precise code being utilised. Utilising the acceleration pulse shown in Figure 2, the analysis described by Haigh (2012) involving a Newmarkian sliding block analysis of slope failure within the liquid limit test device can be carried out. The peak acceleration measured by Haigh (2012) of 310 g for an ASTM device is utilised as the value of a_{max} at the centre of the range of stiffnesses prescribed for an ASTM device in Table 1 (353 MPa). It can be seen from figure 3 that while hard base devices exhibit a specific strength at liquid of 0.98 ± 0.05 m^2s^{-2}, soft base devices exhibit a specific strength of 0.58 ± 0.07 m^2s^{-2}. Values calculated by measurement of the acceleration pulse using new hard and soft based devices were found to be 0.932 and 0.376 m^2s^{-2} respectively, Haigh & Vardanega, (2014), showing good agreement for hard base devices but an overestimate for soft devices where the base resilience is lower.

EFFECT OF BASE RESILIENCE ON LIQUID LIMIT

In order to quantify the effect of base resilience on liquid limit, the acceleration pulse shown in Figure 2 was modified such that less than 100% of the stored energy was returned to the cup as it rebounded from the base. This was achieved by leaving the loading portion of the pulse unchanged, but increasing the unloading stiffness by the reciprocal of the resilience. This has the effect of compressing the time axis on the unloading portion of the pulse, as shown in Figure 4.

The analysis was then repeated for resilience values from 10-100%. The results of these analyses can be seen in Figure 5. It can be seen that resilience has a profound effect on the predicted specific strength at liquid limit, an increase from the 30% value typical of soft-base devices to the 90% value typical of hard-base devices increasing the specific strength at liquid limit by around 80%. The predicted specific strengths at liquid limit can be adequately predicted by:

$$\left(\frac{c_u}{\rho}\right)_{LL} = 0.254(\log_{10} E + 0.1391)(r + 0.1448) + 0.1892 \qquad [6]$$

Where E is the base Young's modulus in kPa and r is the resilience.

The shaded areas on Figure 5 indicate the combinations of base stiffness and resilience specified by typical hard and soft-base design codes. It can be seen that once the effect of resilience is incorporated into this analysis the specific strengths at liquid limit are 0.86 ± 0.09 m^2s^{-2} and 0.35 ± 0.07 m^2s^{-2} for hard and soft-base devices respectively. The values experimentally measured for these devices, 0.932 and 0.376 m^2s^{-2} respectively, fall within these tolerances.

SURVEY OF DEVICES IN-USE WORLDWIDE

In order to study the veracity of this analysis, impact acceleration traces were measured for twenty-nine Casagrande devices of all types in laboratories in four countries, (UK, India, Turkey & Singapore). A high degree of variability was found between devices, even those which were nominally identical. The eighteen soft-based devices studied showed specific strengths at liquid limit ranging from 0.30 – 0.66 m^2s^{-2} with an average value of 0.47 m^2s^{-2} and a standard deviation of 0.11 m^2s^{-2}. The eleven hard-based devices tested showed specific strengths at liquid limit ranging from 0.61 – 1.12 m^2s^{-2} with an average value of 0.87 m^2s^{-2} and a standard deviation of 0.16 m^2s^{-2}. The standard deviation for both species of liquid limit device is thus approximately 20% of the average. It is noteworthy that a set of five devices purchased from the same manufacturer gave three almost identical results of 0.87 m^2s^{-2} with two outliers at 0.63 m^2s^{-2} and 1.12 m^2s^{-2}.

Whilst the sample size is relatively small, there is some evidence that soft-based devices tend to give increased specific strengths with age whereas hard-based devices tend to give lower specific strengths. This variation in the properties of Casagrande devices over time emphasises the need to follow the procedure set out in ASTM D4318-10e1 to check the resilience of the base and its hardness as part of the annual check of the liquid limit device's "wear and critical dimensions" mandated under ASTM D3740-12. These checks are often not explicitly mandated at regular intervals under other national standards.

IMPACT OF BASE CHARACTERISTICS ON LIQUID LIMIT VALUE

As changing the base characteristics changes the specific strength implied by requiring 25 blows for groove-closure (i.e. the liquid limit), different devices will give different liquid limits for the same soil. In order to convert from the changes in specific strength at limit for different devices described earlier to changes in implied liquid limit water content, certain assumptions have to be made with regard to the variation of soil strength and density with water content. Vardanega and Haigh (2014) based on a large database of fall-cone tests on a variety of soils demonstrated that close to the liquid limit the strength variation of soils could be estimated using:

$$c_u = c_L 35^{(1-I_L)} \qquad \text{(where, } c_L = 1.7\text{kPa)} \qquad 0.2 < I_L < 1.1 \qquad [7]$$

$$I_L = \frac{w - w_p}{w_L - w_p} \qquad [8]$$

It can also be shown that the density of a saturated soil varies with water content according to:

$$\rho = G_s \rho_w \frac{1 + w}{1 + G_s w} \qquad [9]$$

Utilising the values of specific strength at liquid limit for the different apparatus measured by Haigh and Vardanega (2014) with typical values of liquid and plastic limits of soils, it can be shown that the relationship between liquid limits with hard and soft-based devices can be approximated by:

$$w_{L\,hard} = 0.845\, w_{L\,soft} + 4.7\% \qquad [10]$$

It can be seen from figure 6 that within the range of most soils' liquid limits, equations 1 and 10, (the observed and predicted relationships respectively), both pass through the centre of the available data.

Similarly, a variation of 20% in the specific strength at liquid limit, (the standard deviation found for a given species of Casagrande equipment) would result in a change in the measured liquid limit by approximately 2.6% of its value, very similar to the 2-3% standard deviation reported in ASTM D4318-10e1 as the results of multi-laboratory triplicate tests on clay liquid limits. Much of this reported error may thus be due to the variation between devices used in practice.

CONCLUSIONS

While the Casagrande liquid limit test has been accepted as the standard method of determining liquid limit for over 80 years, international variations in both codal provisions and the devices themselves can have significant effects on the liquid limit measured.

Both the hardness and resilience of Casagrande device bases have been shown to be very important in determining the value of the liquid limit of a soil determined using that device. Analysis based on the work of Haigh (2012) using an acceleration trace derived from Hertzian contact mechanics has been shown to adequately model the variation of specific strength at liquid limit predicted using devices with different characteristics.

In order to achieve consistent results between laboratories, both base hardness and resilience should be controlled. It is hence troubling that the specification of liquid limit devices in international standards is so variable, even within each of the two classes of device (hard and soft-base) and that regular base testing, as mandated in ASTM D4318-10e1 is not a part of many international design codes. In the absence of further information on the rate of change of base properties, annual checking of the base hardness and resilience to ensure proper performance is recommended.

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Table 1: Specifications for Casagrande liquid limit test devices

	Country	Code	Base Hardness	Equivalent Young's Modulus[1] (MPa)	Resilience	Other
Hard Base	USA	ASTM D4318 (2010)	80-90 D	260-446	77-90 %	
	Canada	CAN/BNQ 2501-090 (2005)	Micarta or hard rubber	-	75-85%	
	Brazil	NBR6459 (1984)	ebonite	~500	74-92 %	
	Germany	DIN18122-1 (1997)	>80 D	>260	80-90 %	
	Sweden	SS27119 (1989)	ebonite	~500	-	Superseded by ISO/TS 17892-12 (2004) Fall-cone test
	Spain	UNE 103103 (1994)	80-90 D	260-446	75-90 %	
	South Africa	SANS3001-GR10 (2013)	Hard rubber	-	80-90 %	
		TMH1 (1986)	85-95 D	340-585	-	
Soft Base	South Korea	KSF2303 (2000)	83-93 A	11-31	-	
	Japan	JIS A1205 (1999)	83-93 A	11-31	-	Resilience typically 15-40% (Kazama and Shimobe 1997)
	UK	BS1377-2 (1990)	84-94 IRHD	11-28	20-35 %	Fall-cone test preferred
	Australia	AS1289.3.1.1 (2009)	86-94 IRHD	13-28	-	
	India	IS2720 (1985)	86-90 IRHD	13-18	30-40 %	
Either	New Zealand	NZS4402 (1986)	79-99 IRHD	8-221	-	
	Switzerland	SN670345a (1989)	Not specified	-	-	
	France	NFP94-051 (1993)	Not specified	-	-	Density 1250-1300 kg/m3 Compressive strength 180-220 MPa

[1] Equivalent Young's Modulus values are estimated from rubber hardness using formulae from Gent (1958) for durometer hardness and Hertz and Farinella (1998) for IRHD.

Figure 1: Comparison of measured hard and soft base liquid limits

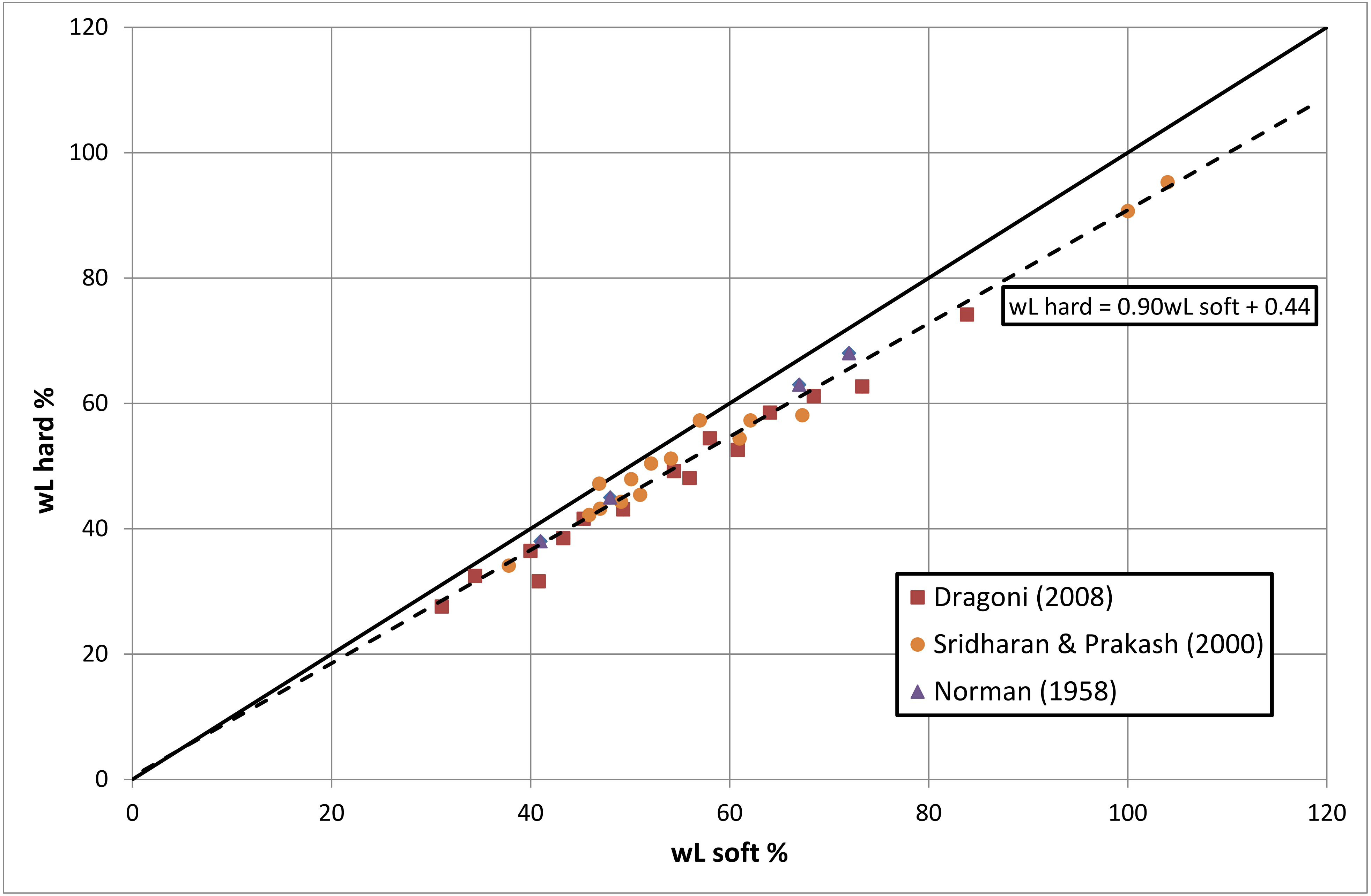
Figure 2: Vertical acceleration predicted during impact with base.

Figure 3: Effect of base stiffness on specific strength at liquid limit with 100% resilience

Figure 4: Effect of resilience on applied acceleration pulse.

Figure 5: Influence of base resilience on specific strength at liquid limit.

Figure 6: Prediction of liquid limit variance using equation 10.


wL hard %
wL soft %
0
20
40
60
80
100
120
wL hard = 0.90wL soft + 0.44
■ Dragoni (2008)
● Sridharan & Prakash (2000)
▲ Norman (1958)

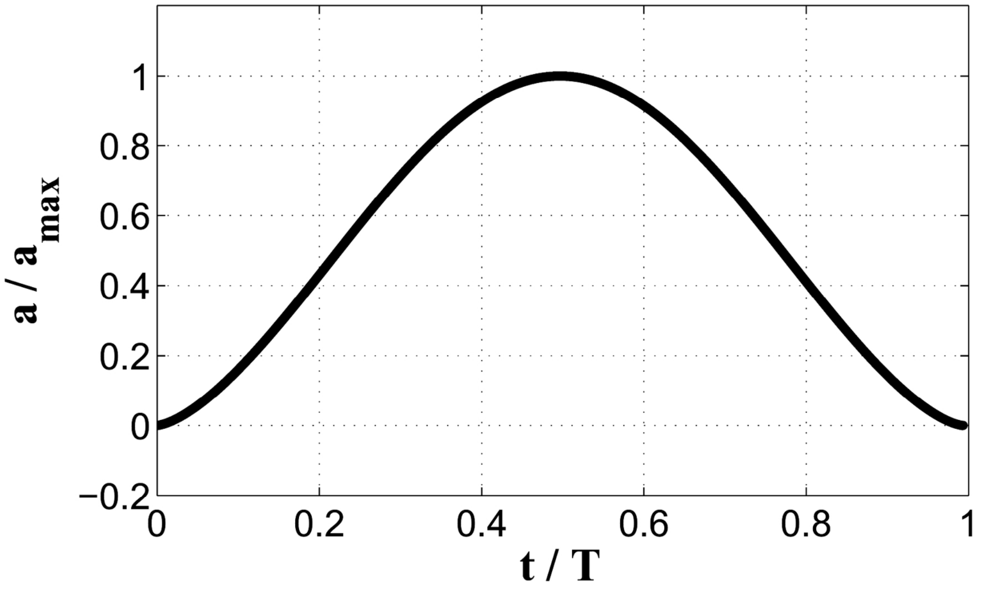


Figure 2: Vertical acceleration predicted during impact with base.
153x91mm (300 x 300 DPI)

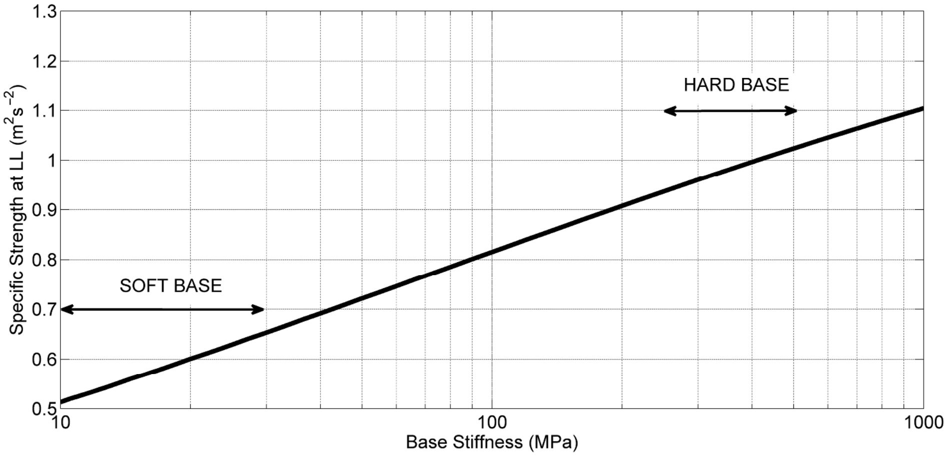


Figure 3: Effect of base stiffness on specific strength at liquid limit with 100% resilience
306x151mm (300 x 300 DPI)

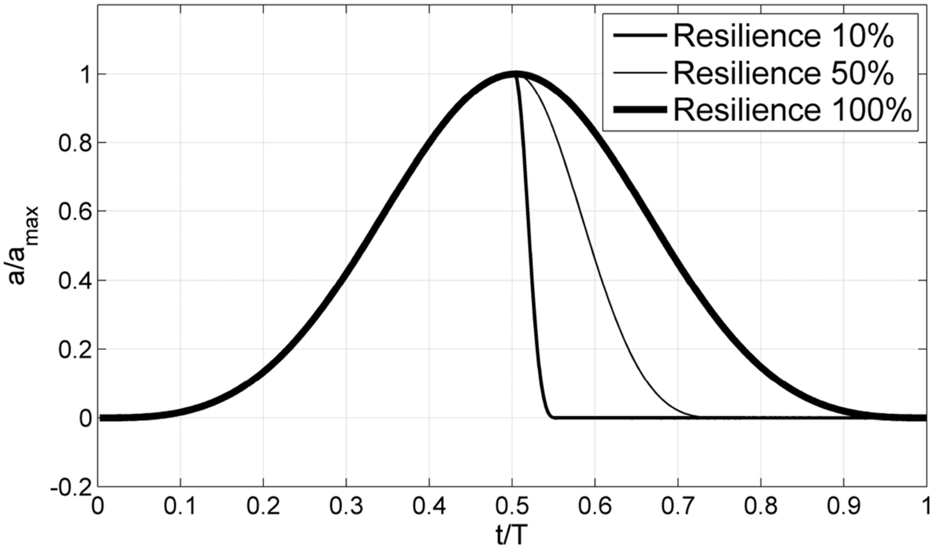


Figure 4: Effect of resilience on applied acceleration pulse.
114x65mm (300 x 300 DPI)

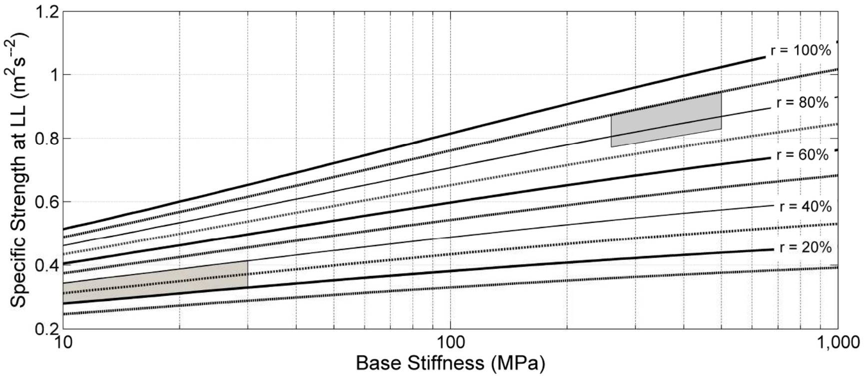
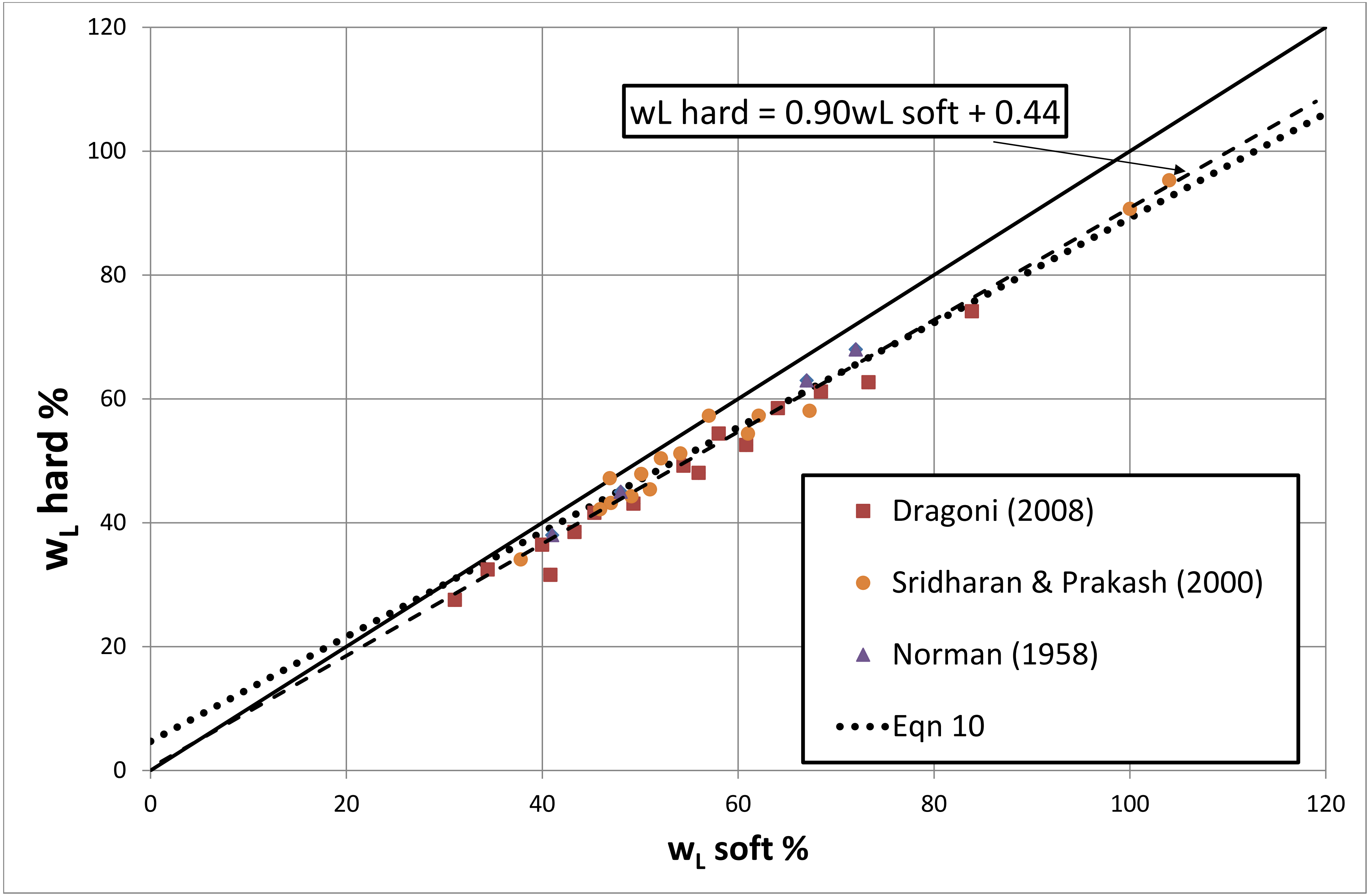


Figure 5: Influence of base resilience on specific strength at liquid limit.
211x159mm (300 x 300 DPI)


wL hard = 0.90wL soft + 0.44
w_L hard %
w_L soft %
0
20
40
60
80
100
120
0
20
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120
■ Dragoni (2008)
● Sridharan & Prakash (2000)
▲ Norman (1958)
•••• Eqn 10