Electronic hammer for nondestructive determination of compaction characteristics of fine-grained soils

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Abstract.- Obtaining physical and mechanical parameters of soil are mostly obtained in laboratories or by field tests. The main goal of this research is to determine compaction characteristics of fine-grained soils (clayey soils or Kaolinite) using an invented electronic hammer without the necessity of sampling and its complexity. To verify the accuracy of the invented device, first, using the modified Proctor compaction test introduced in AASHTO standard, is prepared compacted soil with different ratios. Induced shear waves increase resistance and voltage of strain gauge and force sensor. These values are transmitted to the AVR microcontroller using an ADC and finally, the soil strength is computed and displayed on the LCD. Comparing the results of the electronic hammer with direct shear test device leads to obtaining numerous correlation relations. Several soil samples with different compaction percentages and specific weights are evaluated and just with an impact of the hammer on the surface and using the correlation relations, compaction percentage or specific weight is estimated. The results show values less than 2 hammer reading are equivalent to compaction percentage less than 75% and more than 3 hammer reading values are equivalent to compaction percentage more than 90%.

Keywords: RH[2] Impact Hammer; compaction behavior; unsaturated clayey soils.

Martillo electrónico para la determinación no destructiva de características de compresión de suelos de grano fino

Resumen.- La obtención de parámetros físicos y mecánicos del suelo se obtiene principalmente en laboratorios o mediante pruebas de campo. El objetivo principal de esta investigación es determinar las características de compactación de los suelos de grano fino (suelos arcillosos o caolinita) utilizando un martillo electrónico inventado sin la necesidad de un muestreo y su complejidad. Para verificar la precisión del dispositivo inventado, primero, usando la prueba de compactación Proctor modificada introducida en el estándar AASHTO, se prepara tierra compactada con diferentes proporciones. Las ondas de corte inducidas aumentan la resistencia y el voltaje del medidor de deformación y el sensor de fuerza. Estos valores se transmiten al microcontrolador AVR utilizando un ADC y, finalmente, la resistencia del suelo se calcula y se muestra en la pantalla LCD. La comparación de los resultados del martillo electrónico con el dispositivo de prueba de corte directo conduce a la obtención de numerosas relaciones de correlación. Se evalúan varias muestras de suelo con diferentes porcentajes de compactación y pesos específicos y solo con un impacto del martillo en la superficie haciendo uso de las relaciones de correlación, se estima el porcentaje de compactación o el peso específico. Los resultados muestran que los valores de lectura del martillo inferiores a 2 son equivalentes al porcentaje de compactación inferior al 75 % y los valores de lectura del martillo superiores al valor 3 son equivalentes al porcentaje de compactación superior al 90 %.

Palabras clave: martillo de impacto RH[2]; comportamiento de compresión; suelos arcillosos insaturados.

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1. Introduction

In soil science, determining soil strength and deformation parameters are highly important. Specifying the bearing capacity of the soil, calculating the dimensions of foundations, controlling stability against slip and wedge failure, determining

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external bearing capacity on the soil structure and controlling soil settlement and permeability can be done using these parameters.

Grisso [1] conducted lots of researches about the electronic conductivity of clayey soils, sand and silt to obtain the Cation Exchange Capacity (CEC), check the values of pore water pressure in deep clay soils, determine layer thickness and some similar parameters by automated machines like pulling truck equipped with electronic conductivity sensors. Sharma [2], determined P-wave velocity, impact strength index, slake durability index and UCS for seven rock types using various standard methods in the laboratory. Based on the obtained results, they proposed reliable empirical equations for the determination of the given parameters by knowing the P-wave velocity. Weidinger [3] calculated parameters such as the percentage of humidity, temperature degree and the shrinkage rate in the coarse-grained soils only by time-domain reflectometry sensor and transmitting waves. Hemmat [4], using cone penetration testing (CPTu) and electronic probes, determined the special weight, density, pore water pressure, soil friction angle, and cohesion. Harb [5], using Real-Time Kinematic GPS (RTK-GPS), measured the shear strength of soils at various depths in the field. Law [6] determined the soil hardness parameters at deep hole drilling in the Kenny Hill area and the correlation of Standard Penetration Test (SPT) was assessed by Plaxis software and hardening soil method. Lin [7], using the cone index experiment and dual-sensor vertical penetrometer (DSVP), compared and assessed the relationship between humidity content and bulk modulus of the soil in the field. Also, Keller [8] applied Boussinesq stress distribution method at a depth of 30 to 70 cm from ground level and calculated parameters such as Poisson's ratio, vertical stresses, modulus of elasticity and special weight in the range of elastic behavior of the soil. Rao [9] introduced a method to determine the compressive strength of decaying materials (i.e. falling soil). This method was based on shear wave velocity measurements at the location. After analysis, some cement added to increase the strength of break zones. El Abassi [10] proposed a new ultrasound method for measuring the physical and mechanical properties of rocks. They found that good linear correlations can be found between the longitudinal velocity and other physical rock properties, such as the transverse velocity, Young's modulus, Poisson's ratio, and bulk density. Therefore, based on the correlations suggested by them, estimations of the mechanical rock properties from the sole measurement of longitudinal velocity can be possible. Khalil [11] summarized the elastic moduli and geotechnical parameter relationships as derivation of VP, VS, and density values. Then, they obtained geotechnical parameters from seismic measurements in the two fields which were located in Egypt and Saudi Arabia. In this way, by gathering both VP and VS using refraction data, and the density of rock samples, they drew contour maps for geotechnical parameters such as Poisson's Ratio and Young's Modulus in the area of the project.

Obviously, determining the shear strength and bearing capacity of soil as well as the elastic settlements with field and laboratory data are very important. Taking samples of field soil, transferring the samples to the laboratory and testing is very time-consuming and need high cost as well as high level of skill and precision to obtain acceptable results. Due to errors of non-calibrated devices and human errors, accuracy of the results will reduce that can cause egregious errors in designs and decisions of experts and geotechnical engineers [12].

As this paper aims to present an innovative electronic device with high sensitivity, compaction parameters of soil can be calculated just with few impacts on different points of fine-grained soil. This new device is called RH hammer and its dimension is like a Schmidt hammer and it will be used as a non-destructive test to calculate the mechanical parameters of the soil. This new device works on materials with stiffness much less than concrete. It is notable that the average compressive strength of soil on average is about 100 to 300 kilograms per centimeters squared and for concrete is about 1 to 3 kilograms per centimeters squared.

2. RH Impact Hammer Design

Because of the soft structure of soils compared to rocks, it is not possible to use Schmidt hammer for calculating the compressive strength of soil. In this section, a newly designed device called RH impact hammer, shown in Figure 1, is introduced. This hammer is designed based on the analog Schmidt hammer with softer internal spring and lighter internal mass so that smaller impact is applied on the soil surface. It can calculate parameters such as compaction or specific weight surfaces by a sensor that is mounted to its end. Therefore, the compaction characteristics of the material can be obtained by applying a few impacts and reading the hammer numbers in horizontal and vertical directions.

Figure 1: Electronic impact hammer.

Firstly, it is necessary to introduce the details of the RH impact hammer and then, explain the process of the experiment. Highly-sensitive sensor, called force-sensing resistor (FSR), with an electric circuit is used at the end of the invented hammer that produces electronic potential proportional to the applied pressure. The sensor is displayed in Figure 2. The output of the FSR sensor is resistance that after converting to a voltage and filtering, it is first read with an ADC (Analog Digital Converter) of the AVR microcontroller and then, after integrating acceleration-time graph and some mathematical calculations, the compressive strength that is proportional to stiffness of the soil, is computed and shown on LCD display [13].

Figure 2: FSR Sensor.

RH impact hammer is schematically shown in Figure 3 in three different states. In the state 1, no pressure is applied and the internal spring is in its relaxed state. If the end bar of the hammer is contacted with soil and pressure is applied, then, the internal spring is stretched and finally, the device is set in state 2. In the final stage of state 2, the pawl is opened and the weight is delivered and in a fraction of the second, the internal spring is contracted and hammer inters state 3 and exerts an impact on the soil surface.

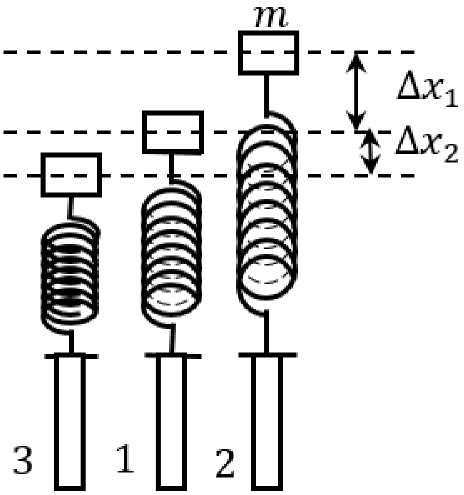

Figure 3: Schematics of the impact hammer in three different states.

Parameters of the impact hammer are as follows: Spring constant: 30 N/m, Internal mass: 50 g, Maximum stretch: 8 cm, Maximum compaction: 4 cm.

The working process of the impact hammer can be briefly explained such that it is first contacted with the soil surface and then, with the graphical interface, the execution command is generated. By applying the pressure on the hammer, an impact is imposed on the soil surface using its internal weights. The resistance and voltage sensors of the hammer calculate the value of the inserted impact. The value is converted to standard output by electric circuits. The standard output is given to the microcontroller unit with ADC convertor and the microcontroller calculates the compressive strength using the sensor results and finally, compressive strength is shown on the LCD display by the microcontroller.

In continuation, the velocity, acceleration, and energy of the internal mass of the hammer in state 3 (during application of the impact on the soil surface) are considered. To do so, the conservation of energy is used: The total energy of state 3 = Total energy of state 2

Depending on the horizontal or vertical usage of the hammer, energies can be considered in two forms. In the horizontal form, assuming the internal mass's center of gravity in the state 1 as the potential origin, we have: Potential energy saved in the stretched spring is equal to Kinetic energy of internal mass plus Potential energy saved in the compressed spring.

$$\frac{1}{2}k\Delta x_1^2 = \frac{1}{2}mv^2 + \frac{1}{2}k\Delta x_2^2, \quad (1)$$

$$f = k\Delta x_2 = ma \quad (2)$$

Using specifications of the impact hammer, we have $k = 30$ N/m; $m = 0,05$ kg; $\Delta x_1 = 0,08$ m and $\Delta x_2 = 0,04$ m, are obtained the parameters in Table1 using equation (1) and equation (2).

Table 1: Parameters of the impact hammer in horizontal form

Velocity, v [m/s]	Energy, E [J]	Acceleration, a [m/s^2]
1,7	0,1	5g

g: 10 m/s^2

In the vertical form, assuming the internal mass's center of gravity in the state 3 as the potential origin, we have:

The potential energy of internal mass with respect to origin plus potential energy saved in the stretched spring are equal to kinetic energy of internal mass in motion plus Potential energy saved in the compressed spring.

$$mg\left(\Delta x_1 + \Delta x_2\right) + \frac{1}{2}k\Delta x_1^2 = \frac{1}{2}mv^2 + \frac{1}{2}k\Delta x_2^2 \quad (3)$$

Therefore, are obtained the parameters in Table2 using equation (3) and equation (4).

$$f = k\Delta x_2 + mg = ma \quad (4)$$

Table 2: Parameters of the impact hammer in vertical form

Velocity, v [m/s]	Energy, E [J]	Acceleration, a [m/s^2]
2,3	0,16	6g

g: 10 m/s^2

As can be seen, compared to horizontal form more energy is transmitted to the soil surface in the vertical form.

3. Calibrating the RH Impact Hammer

To calibrate the number that is obtained from the hammer impact, it is necessary to compare it to the other well-known tests. To do so, a series of modified AASHTO density test is conducted to gain compaction and maximum specific weight of the clay sample. After that, in the different compaction rates, samples are built to conduct the direct shear test and hammer impacting in different test boxes. In this way, the number shown by the hammer is compared and calibrated with the direct shear result.

In other words, after conducting experiments to determine the compaction and maximum specific weight, 21 different laboratory samples are made in the range of 0 to a maximum of 15% humidity and compaction of 71,86 % to 100 % in sampling box with dimensions of 10 by 15 by 15 centimeters for hammer test and box with dimensions of 6 by 6 by 1,6 centimeters for direct shear test.

3.1. *Modified AASHTO Density Test*

The first and the most important test on the clayey soil is the modified AASHTO density test (method C: AASHTO T180 – 70 & ASTM D1557 – 70 [14]). To have both wet and dry soil it is necessary to use soil with different humidity percent from 0% to about 20%. In this way, we can have different compaction ratios from low to high density.

The result in Table 3 and Figure 4 shows that in the 15,63 % optimum humidity for clayey soil, the dry special weight is 1,64 grams per cubic centimeter and the wet special weight is 1,9 grams per cubic centimeter. The sub-conclusion of this study is that we can analyze clayey soils in a dry mode, having special weight from 1,3 up to 1,7 grams per cubic centimeter and in wet mode, having special weight from 1,35 up to 1,9 grams per cubic centimeter using RH impact hammer.

Other experiments have been conducted to determine the behavior of clayey soil are soil density test, Atterberg Limits test, direct shear test, grading test, X-RAY test, and RH impact hammer test.

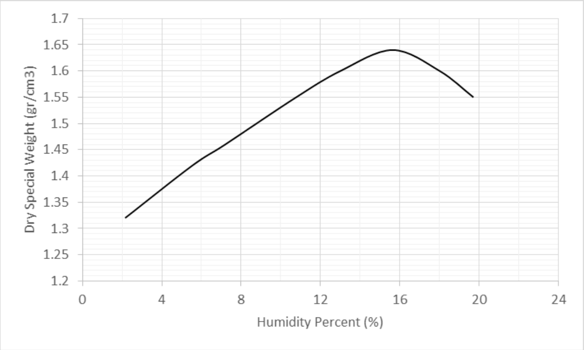

Figure 4: Dry special weight vs Humidity percentage.

3.2. *Hammer Impact Test Results*

In hammer impact test, with the help of a piezoelectric sensor that is sensitive to the impact, the stress and strain values generated at the soil surface are measured and plotted and then, by integrating the area under this curve and knowing the volume of soil, the amount of energy can be calculated. According to the plastic behavior of the soil, acceleration-time, speed-time, and displacement-time curves are obtained [3].

Because of the flexibility of clayey soils, the waves generated by the impacting the soil are damped quickly and therefore, it is necessary to record and analyze reflected data in the first wavelength. The equation (5) shows the first wavelength before damping.

$$\lambda = \frac{v_s}{f} \tag{5}$$

Replacing values v_s = 80,38 and f = 618 in equation (5) is obtained λ = 13 cm.

3.3. *Analysis of Direct Shear Test Result*

The standard direct shear test was carried out on 21 samples. The stress-strain graph for the first sample among 21 samples is shown in Figure 5.

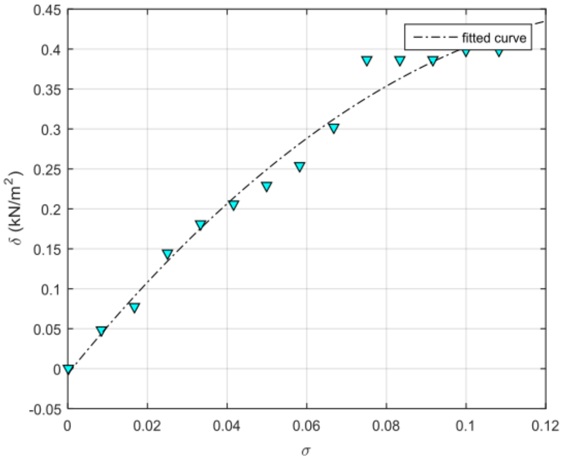

Figure 5: stress-strain graph in the laboratory.

By integrating the fitted stress-strain curve and multiplying the result in the volume of the soil sample, the total consumed energy will be obtained [15]. In Figure 5, integrating between strain values 0 to 0,1083; the area under the curve is found as $A = 0,0267\ kg/cm^2$. By mathematic calculations, the equivalent hardness for displacement is in hand:

$$Soil\ Volume : V = 6 \cdot 6 \cdot 1,6 = 57,6\ cm^3$$

$$Energy : E = A{\cdot}V = 1.537 kg{\cdot}cm \approx 0,15 N{\cdot}m = 0,15$$

Table 3: The results of AASHTO Density Test (method C)

	Sample Number							
	1	2	3	4	5	6	7	8
Box and soil weight, [g]	4700	4850	4910	5060	5150	5235	5223	5190
Wet Special weight, [g]	1,35	1,5	1,56	1,72	1,81	1,90	1,89	1,85
Wet sample and container weight, [g]	59,30	59,50	48,50	80,00	53,50	91,80	89,40	45,70
Dry sample and container weight, [g]	58,50	57,50	46,30	75,00	49,00	83,50	80,40	40,40
Sampling container weight, [g]	21,40	21,40	15,70	28,60	14,40	30,40	30,40	13,50
Humidity percent, [%]	2,15	5,54	7,19	10,77	13,00	15,63	18,00	19,70
Dry Special weight, [g]	1,32	1,42	1,46	1,55	1,60	1,64	1,60	1,55

Box weight: 3400 g
Box volume: 965,81 cm^3

$$E=\frac{1}{2}kx^2 \rightarrow k=\sqrt{\frac{2E}{x^2}} \xrightarrow{x=0,00649} k=7298,1\frac{N}{m}$$

For the other samples, the same calculations are done and the results are presented in Table 4. In this way, based on experiments on the specific materials, clayey soil, the relationships between specific weights, horizontal and vertical numbers of RH hammer, compaction, are shown in some graphs. The best curves also are fitted to the data in each case.

4. Analysis and results

Figure 6 shows a more specific weight results in a higher number of RH hammer both in vertical and horizontal modes.

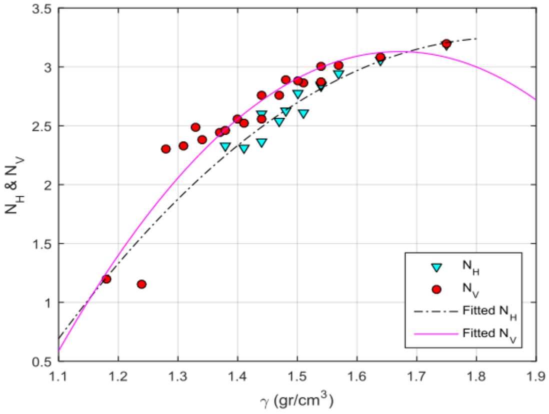

Figure 6: Vertical and horizontal numbers of RH hammer as a function of special weight

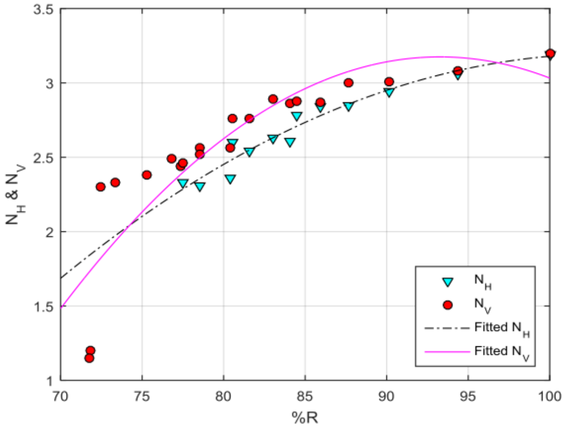

Figure 7: Vertical and horizontal numbers of RH hammer as a function of compaction

In Figure 7, as the compaction of the samples increases, the obtained number of RH hammer also increases. It is noteworthy that for samples with low compaction, the experiment in the horizontal state was not possible because of collapse after the hammer's impact, so there is no NH number for compaction under 75%.

As Figure 8 shows, when the compaction is more than 90%, the NV to NH ratio is about one; it means that for compaction more than 90%, both numbers of RH hammer are almost equal.

Based on Figure 9, there is a direct relationship between compaction and specific weight.

Figure 10 shows the energy of the direct shear test is somehow increasing with the hardness increase.

Based on the results of the direct shear test device and RH hammer on the 21 samples and 7 final

Table 4: Relationship among characteristic parameter of soil and RH hammer number

No.	Sample No.	N_H	N_V	Special Weight γ $[g/cm^3]$	Compaction R [%]	Humidity Percent ω [%]	Energy $[kg \cdot cm]$	K $[kg/cm]$
1	1A	-	1,20	1,180	71,86	0,00	1,537	7,298
2	2F	-	2,49	1,328	76,79	2,00	2,063	7,219
3	3A	-	1,15	1,240	71,74	1,50	2,280	10,826
4	4A	-	2,30	1,280	72,47	2,00	2,511	11,918
5	5F	-	2,44	1,370	77,34	3,50	2,050	7,908
6	5A	-	2,33	1,310	73,38	5,50	2,626	12,440
7	6F	-	2,56	1,403	78,56	5,70	2,088	6,364
8	6A	-	2,38	1,340	75,27	6,40	1,906	9,021
9	7F	2,60	2,76	1,435	80,57	8,15	2,142	4,953
10	7A	2,33	2,46	1,380	77,52	8,40	1,710	8,119
11	8F	2,63	2,89	1,478	83,00	6,10	2,157	4,510
12	8A	2,31	2,52	1,410	78,56	5,29	1,612	7,644
13	9F	2,61	2,86	1,510	84,10	9,29	2,142	4,590
14	9A	2,36	2,56	1,440	80,39	8,12	2,413	7,531
15	10F	2,84	2,87	1,540	85,93	9,10	2,159	4,570
16	10A	2,54	2,76	1,470	81,60	8,19	1,658	5,156
17	11A	2,78	2,88	1,500	84,47	10,11	2,021	6,312
18	12A	2,85	3,00	1,540	87,69	9,92	2,021	8,244
19	13A	2,94	3,01	1,570	90,13	8,05	2,874	11,714
20	14A	3,06	3,08	1,642	94,39	13,69	2,056	8,367
21	15A	3,19	3,20	1,750	100,00	15,00	2,851	11,632

Table 5: Proposed relationship between RH hammer number and soil compaction parameter

No.	Compaction R [%]	N_H	Special Weight γ $[g/cm^3]$	Results of [R%] in test	Results of N_H in test	Range of moisture ω [%]	Range of γ $[g/cm^3]$
1	72	1,25	1,18	70,80	1,29	0 ~ 2	1,15 ~ 1,20
2	74	1,69	1,25	74,20	2,11	0 ~ 3	1,21 ~ 1,30
3	76	1,75	1,35	76,37	2,30	3 ~ 6	1,31 ~ 1,40
4	82	2,40	1,45	82,00	2,80	6 ~ 8	1,41 ~ 1,50
5	88	2,73	1,55	87,00	2,90	8 ~ 13	1,51 ~ 1,60
6	94	3,10	1,65	93,00	3,00	13 ~15	1,61 ~ 1,70
7	98	3,25	1,73	99,00	3,16	13 ~15	1,71 ~ 1,75

samples, results presented in Table 4 and Table 5 are obtained. The privilege of these tables is that by having only one item, all other parameters can be estimated.

It is noteworthy that for 1A to 6A in Table 4, there are samples with low compaction that the experiments in the horizontal state were not possible for them because of collapse after impact of the hammer.

5. Conclusion

This paper introduces a new device called the RH impact hammer. Using this new device, just by a single impact, compaction parameter of the soil can be achieved, precisely. As it was presented, the results of this new hammer were calibrated by the direct shear test device. The following list summarizes the results of this study.

The increase in the output number of impact hammer has a direct relation to the specific weight and compaction of the soil.

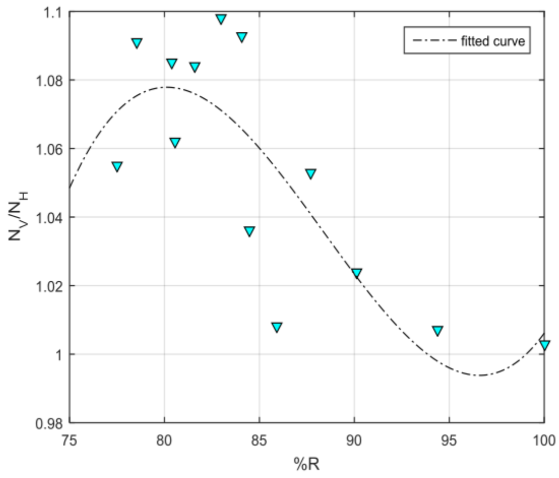

Figure 8: Vertical and horizontal numbers ratio of RH hammer as a function of compaction

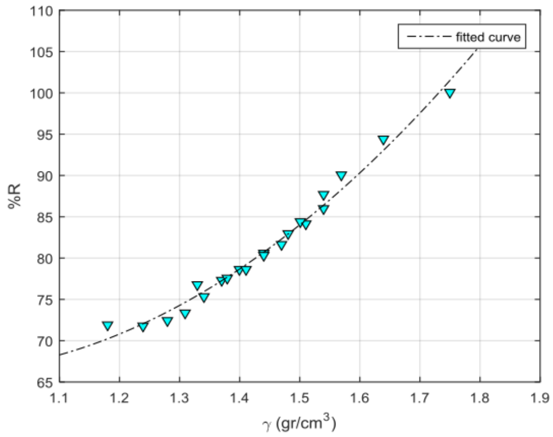

Figure 9: Compaction as a function of special weight

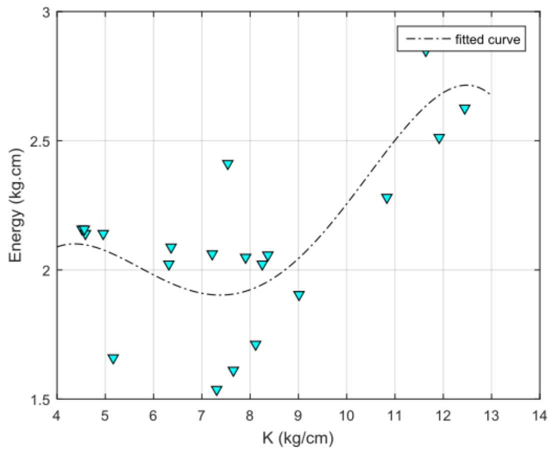

Figure 10: Energy as a function of hardness

By maintaining surface conditions and similar materials, values of the hammer in the horizontal and vertical states, special weight and the humidity content can be estimated through mathematical calculation and correlation by RH impact hammer having only one of the following data such as compaction.

It is possible to measure soil compaction in the field without sampling and using old procedures just with one impact on the soil in the shortest time.

The compaction behavior of soils in laboratory mode is the same in specific weights above 1,6 g/cm^3 and density percentages above 90 %.

Numbers bigger than 3 in laboratory mode show great density in soils in moist percentages of 0 to 15%.

Soils in density less than 70 % and specific weights less than 1,2 g/cm^3, will lead to invalid evaluation. Therefore, this range is out of serviceability of the device.

It is possible to control the density conditions provided by this hammer in this research, with moisture percentages of less than 15 % and the maximum depth of 6 cm from the soil surface.

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