Scientia Iranica A (2014) 21(6), 1762–1772

Sharif University of Technology
Scientia Iranica
Transactions A: Civil Engineering
www.scientiairanica.com

Reliability of soil water content measurements by the calcium carbide gas pressure method for small specimens

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Received 18 December 2012; received in revised form 23 August 2013; accepted 8 April 2014

KEYWORDS
Soil water content;
Calcium carbide;
Oven-drying;
Speedy;
Moisture.

Abstract. The Calcium Carbide Gas Pressure (CCGP) method is a rapid measurement procedure for obtaining Soil Water Content (SWC), which relies on the chemical reaction of the calcium carbide reagent with water in soil pores. Currently, the method is limited to soil samples of 20 g or larger. However, test equipment for much smaller sample sizes does exist, and there is a need for quantifying the reliability of SWC measurements of small samples. The research involved a total of 232 tests carried out on 22 different soil types containing particles no larger than No. 4 sieve size. The water content of soil specimens with varying wetness was measured using both conventional oven-drying and CCGP methods. The error distribution analysis indicated that the CCGP method, as used in this study, estimates the SWC for all soil types with a mean absolute discrepancy of around 0.3% and 0.2%, with general and soil specific calibrations, respectively. It was found that the CCGP method is reliable for SWC determination of small specimens up to 20% of SWC if the manufacturer's instructions are followed.

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1. Introduction

Determining Soil Water Content (SWC) has been a basic and major interest for geotechnical engineers for many years. It is essential to know SWC in many geotechnical engineering applications, such as in early detection of landslide risk and compaction quality control in earthwork and highway projects. Determination of SWC is also a fundamental need in soil physics and hydrology, for defining optimal times for irrigation, estimating infiltration rate and evaluating potential leakage from a waste site [1,2].

Several methods are currently being used for determination of SWC. Although the oven-drying method is the most accurate and is the standard approach, it is time consuming and labor-intensive. Radioactive methods, such as neutron scattering and gamma ray attenuation, are widely accepted non-destructive methods, but they require special caution and licensing to operate in order to avoid possible health hazards [3]. Relatively new dielectric based methods, such as time and amplitude domain reflectometry methods, are significantly affected by soil electrical properties, compaction characteristics and texture, requiring soil-specific calibrations for accurate measurements. These methods also require expensive and complex electronic equipment and the obtained data must be properly interpreted.

Calcium Carbide Gas Pressure (CCGP) is a rapid method, often referred to as the "speedy method". In addition to measuring SWC, the CCGP method can also be used for measurement of water content

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in a wide range of materials, including aggregates, dust and powders. The method was evaluated to be applicable for most soils and recognized as a standard test method [4,5]. CCGP consists of measuring the amount of acetylene gas formed in a steel vessel, as a product of the chemical reaction between calcium carbide and pore water. The pressure reading on the calibrated gauge of the device is in direct correlation to the amount of gas, and it relates to the gravimetric SWC if all the pore water is assumed to react with the calcium carbide. The device is portable and self functioning (i.e., electricity-free), making the method very practical to use.

Calcium carbide moisture testers are usually presented with their specimen weight capacity. ASTM 4944 [4] does not recognize the results of testers with specimen weight capacity under 20 g. However, test equipment for much smaller sample sizes does exist, and there is a need for quantifying the reliability of SWC measurements of small samples.

This study is primarily concerned with evaluation of the reliability of the CCGP method using a test apparatus with a specimen weight capacity of less than 20 g, in contrast to the ASTM 4944 [4] protocol for quantification of SWC over a wide range of soil types. The performance and reliability of the method were evaluated extensively in comparison to the standard oven-drying method [6].

2. Materials and methods

2.1. Tested soil types and specimen preparation

Within this study, experimental studies were carried out on all soil types defined in the Turkish Standard TS1500 [7], similar to AASHTO T88 [8], including soil with dual symbols. Soil types can be placed into four major categories: a) clayey soil (CL, CI and CH), b) silty soil (ML, MI and MH), c) sandy soil (SP, SP-SM, SP-SC, SW, SW-SM, SW-SC, SM and SC), and d) gravelly soil (GP, GP-GM, GP-GC, GW, GW-GM, GW-GC, GM and GC). Some soil types were obtained from the field and some were prepared in the laboratory as a mixture. The index properties of the tested soil types are tabulated in Table 1 for fine grained soils (Group 1), coarse grained soils with little or no fines

Table 1. Index properties of all soil types.

Group 1	**CL**	**CI**	**CH**	**ML**	**MI**	**MH**
Specific gravity	2.63	2.6	2.56	2.55	2.6	2.58
Fines content (%)	85	90	80	90	95	90
Liquid limit	33.8	39	53	30	40	65
Plasticity index	13.8	15	33	8	12	30
Organic matter (%)	1.29	2.11	1.43	1.87	1.98	2.14
Group 2	**GP[1]**	**GW[2]**	**SP**	**SW**		
Specific gravity	2.65	2.66	2.44	2.64		
Fines content (%)	0.1	0.1	2.3	0.1		
Coefficient of uniformity, C_u	3.53	4.57	3.06	6.5		
Coefficient of gradation, C_c	0.88	1.44	1.1	1.04		
Group 3	**GM[3]**	**GC[4]**	**SM**	**SC**	**GP-GM[5]**	**GP-GC[6]**
Specific gravity	2.65	2.63	2.67	2.62	2.66	2.68
Fines content (%)	15	15	15	15	7	10
Liquid limit	30	33.8	30	33.8	30	33.8
Plasticity index	8	13.8	8	13.8	8	13.8
Coefficient of uniformity, C_u	N.A.[9]	N.A.	N.A.	N.A.	3.57	3.57
Coefficient of gradation, C_c	N.A.	N.A.	N.A.	N.A.	0.89	0.57
Group 3 (cont.)	**GW-GM[7]**	**GW-GC[8]**	**SP-SM**	**SP-SC**	**SW-SM**	**SW-SC**
Specific gravity	2.68	2.68	2.59	2.62	2.62	2.67
Fines content (%)	7	10	5,7	7	10	7
Liquid limit	30	33.8	30	33.8	30	33.8
Plasticity index	8	13.8	8	13.8	8	13.8
Coefficient of uniformity, C_u	4.81	5.5	5.33	3.82	6.25	6.13
Coefficient of gradation, C_c	1.4	2.23	1.02	0.81	2.25	1.72

[1]SP; [2]SW; [3]SM; [4]SC; [5]SP-SM; [6]SP-SC; [7]SW-SM; [8]SW-SC according to USCS (Unified Soil Classification System) [13].

[9]N.A.: Not Applicable.

(Group 2), and coarse grained soils with fines and soils with dual symbols (Group 3).

Specimens with varying target gravimetric water content were prepared by adding water, and mixing the soil and the water uniformly. For each soil type, 10 to 11 specimens with varying nominal water content were prepared, resulting in 232 specimens (soil-water mixture). Oven-dried specimens were selected to be representative of the water condition of the entire amount of soil. Drying a specimen for around 12 to 16 hours at a temperature of 110 ± 5°C is sufficient in most cases, but in the present study, the specimens were dried for 24 hours. A balance with 0.01 g readability was used but the calculated average SWC was rounded to the nearest 0.1%.

2.2. Calcium carbide gas pressure method

Calcium Carbide (CaC_2) is manufactured by heating a lime (CaO) and carbon (C) mixture to 2000 to 2100°C (3632 to 3812°F) in an electric arc furnace. At those temperatures, the lime is reduced by carbon to calcium carbide and carbon monoxide (CO), according to the following reaction [9]:

$$\mathrm{CaO} + 3\mathrm{C} \xrightarrow{2000\text{-}2100^\circ\mathrm{C}} \mathrm{CaC_2} + \mathrm{CO}. \tag{1}$$

Partial oxidation of methane is also used for calcium carbide production in which calcium carbide acts as a rich source of acetylene (C_2H_2). The reaction between the calcium carbide and the water (H_2O) releases acetylene gas [10]. Decomposition of 1 kg of calcium carbide, with 0.562 kg of water, results in 260-300 liters of acetylene gas, according to the exothermal reaction given by Eq. (2).

$$\mathrm{CaC_2} + 2\mathrm{H_2O} \rightarrow \mathrm{C_2H_2} + \mathrm{Ca(OH)_2}. \tag{2}$$

The volume of released acetylene varies according to the particle size of the calcium carbide reacted with water. The duration for acetylene formation also depends on the particle size of the calcium carbide [11,12]. The particle size based classification of calcium carbide, reaction duration, and the volume of the released acetylene gas due to reaction, are tabulated in Table 2.

It is critical that all soil water reacts with the calcium carbide for accurate results. However considerable amounts of soil water can be adsorbed by solid particles of soils, like clays, with high plasticity. It is clear that adsorbed water cannot react with calcium carbide, which leads to measurement errors. Additionally, soil having temperature dependent water releasing chemicals should be tested under temperature controlled conditions. Users need to pay careful attention to testing constraints and should follow the instructions of the manufacturer.

Within this study, a standard vessel size test apparatus, S2000D, was used (Figure 1). This size of tester is suitable for 0 to 20% soil water content range for soil specimens of 6 g in nominal weight. The maximum particle size of the specimens was smaller than the standard No. 4 sieve size. Existence of the proper amount of calcium carbide enclosed in the vessel plays a significant role in the accuracy of the test. According to Eq. (2), 12 g of calcium carbide is needed for a 6 g specimen if the specimen is assumed to consist of pure water. However, a more conservative amount was adopted by the manufacturer of the CCGP device, and all tests were performed with 20 g of calcium carbide.

The measurements were performed by placing the

Figure 1. Picture of CCGP test apparatus.

Table 2. Classification of calcium carbide (compiled from [11,12]).

Class	Particle size	Acetylene volume due to reaction	Reaction duration of 1 kg of calcium carbide (minutes)
Fine grained	2-4 mm	260 lt	3
	4-7 mm		10
Medium grained	7-15 mm	280 lt	13
	15-25 mm		14
Coarse grained	25-50 mm	300 lt	15
	50-80 mm		24

representative soil specimen and the calcium carbide in the pressure vessel. The vessel was shaken vigorously and continuously in a rotating motion to generate adequate contact between the specimen particles and the calcium carbide. Shaking duration was different for each specimen, so the progress of the needle on the pressure gauge, which correlated to water content, was periodically monitored. When the reaction ends, the pressure in the vessel becomes constant and the needle becomes stabilized. The final gauge reading was made while holding the vessel in a horizontal position at eye level. The recorded reading (w_{wet}) was the moisture content based on the specimen's wet weight in percent. This value is used to find out the gravimetric SWC (w_{ccgp}) by a simple conversion in Eq. (3). The vessel was cleaned and dried carefully between consecutive tests.

$$w_{\text{ccgp}} = \frac{100 \times w_{\text{wet}}}{100 - w_{\text{wet}}}. \qquad (3)$$

3. Experimental findings

Two SWC values were obtained for each specimen, one is the average value of the two oven-drying results (Tests 1 and 2) and the other is from the CCGP method (Test 3). The experimental data is tabulated in Table 3.

The results of the oven-drying method are often taken as the reference for SWC measurements with the CCGP method. However, there is no unanimously accepted method for defining the accuracy of the oven-drying approach. Variations mostly follow the normal distribution curve statistically, which is a sign of the validity of the methodology adopted.

3.1. General calibration measurement approach

A general calibration curve was developed for the equipment set used in the study, as can be seen in Figure 2 and Eq. (4). All specimens were included in the production of the calibration curve to obtain full representation of the soil specimens. The average results of the oven-drying method (w_{od}) were plotted against the results of the CCGP method (w_{ccgp}), and a best fit curve was plotted through the points of the calibration curve to check the level of scattering. Deviation lines of ±1% around the calibration curve are added in Figure 2, in order to help visualize the data scatter.

$$w_{\text{od}} = 0.16 + 1.04 w_{\text{ccgp}}. \qquad (4)$$

Discrepancies between oven-drying and generally calibrated CCGP values are given in Figure 3, where tested soil groups can also be identified. The discrepancy is defined as the difference between the oven-drying and the CCGP values ($w_{\text{od}} - w_{\text{ccgp}}$). Water content values of samples from the calibration curve were rounded to the nearest 0.1%, not to the nearest 1%, as ASTM 4944 [4] suggested, in order to avoid the lack of fairness when comparing oven-drying and CCGP measurements.

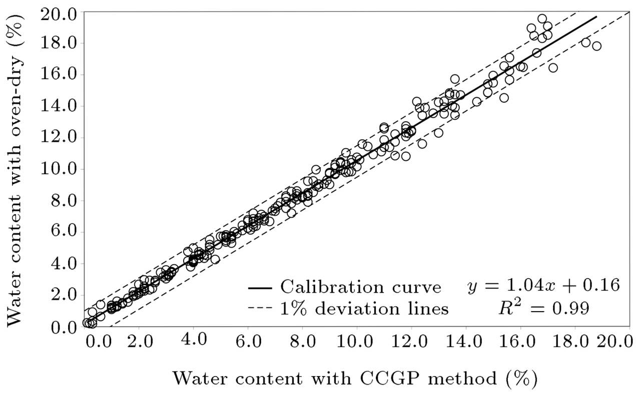

Figure 2. General calibration curve of the CCGP device used in this study.

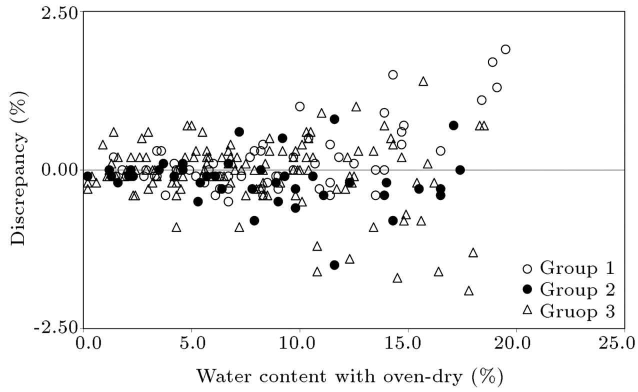

Figure 3. Discrepancies of the CCGP method for all groups with general calibration.

The mean discrepancy of the CGGP method was found to be around 0.3% when all specimens were considered. However, the CCGP method performed with the highest accuracy for Group 2 soil (coarse grained soil with little or no fines) if the discrepancy between the oven-drying value and the CCGP value was taken as a measure. The mean discrepancies were 0.3%, 0.3% and 0.4% for Group 1, Group 2 and Group 3 soils, respectively. Most samples having 1.0% or larger discrepancy belong to the set of specimens having SWC near or over 10.0%.

The maximum error was the highest for the clayey soil, with a maximum discrepancy of 1.9%, and the lowest was for gravelly soils around 1.0%. The highest degree of overestimation occurred in sandy soil, with a minimum discrepancy of -1.9%, and the lowest for clayey soils, around -0.4%. The high clay content results in underestimation of the SWC because of the limited reaction of calcium carbide with pore water,

Table 3. SWC values obtained with oven-drying and CCGP methods.

Soil			w_{od}^1 (%)	w_{ccgp}^2 (%)	Soil			w_{od} (%)	w_{ccgp} (%)
class	**Test 1**	**Test 2**	**Average**	**Test 3**	**class**	**Test 1**	**Test 2**	**Average**	**Test 3**
CH	1.39	1.32	1.4	1.0	MH	1.35	1.31	1.3	1.2
	3.04	2.80	2.9	2.6		2.07	1.93	2.0	1.9
	4.21	4.34	4.3	4.0		3.70	3.90	3.8	3.9
	5.77	5.41	5.6	5.4		4.21	4.11	4.2	4.0
	6.61	6.04	6.3	6.2		6.20	6.07	6.1	6.1
	7.74	8.01	7.9	7.2		6.78	6.66	6.7	6.6
	9.03	7.53	8.3	7.4		8.12	8.24	8.2	8.0
	10.20	9.20	9.7	9.0		10.22	9.10	9.7	9.2
	13.34	13.66	13.5	13.2		11.34	11.41	11.4	11.2
	17.81	15.25	16.5	15.4		13.22	13.84	13.5	12.8
						15.86	13.77	14.8	13.4
CI	1.82	1.78	1.8	1.6	MI	1.52	1.51	1.5	1.4
	3.61	3.58	3.6	3.0		2.70	2.91	2.8	2.6
	4.75	4.96	4.9	4.6		3.17	3.44	3.3	3.1
	5.89	5.61	5.8	5.4		5.23	5.16	5.2	4.9
	7.74	6.91	7.3	7.0		6.81	6.64	6.7	6.4
	8.95	9.12	9.0	8.6		7.71	7.61	7.7	7.1
	10.39	9.52	10.0	8.5		8.21	8.44	8.3	8.2
	14.35	13.48	13.9	13.2		10.61	10.19	10.4	9.4
	19.08	17.82	18.5	16.5		11.34	11.41	11.4	11.0
	20.00	19.07	19.5	16.8		12.91	12.17	12.5	11.8
						13.03	14.71	13.9	12.3
CL	3.90	2.97	3.4	2.8	ML	1.22	1.31	1.3	1.2
	4.67	4.39	4.5	4.2		3.65	3.25	3.5	3.2
	6.52	5.52	6.0	5.5		4.21	4.13	4.2	3.8
	8.56	7.79	8.2	7.4		6.18	6.32	6.3	6.0
	8.81	9.01	8.9	8.5		7.12	6.22	6.7	6.8
	10.53	10.95	10.7	10.0		8.64	8.34	8.5	8.2
	12.24	10.62	11.4	10.4		9.51	8.57	9.0	8.8
	14.33	15.12	14.7	13.6		11.01	10.82	10.9	10.6
	15.21	14.16	14.7	13.4		12.57	11.11	11.8	11.0
	18.58	19.53	19.1	17.0		14.15	14.40	14.3	12.2
						19.53	18.33	18.9	16.4
GP[3]	1.26	1.27	1.3	1.2	GW[4]	1.21	1.13	1.2	1.0
	2.22	2.25	2.2	2.1		2.11	2.42	2.3	2.2
	3.44	3.89	3.7	3.3		3.67	3.31	3.5	3.2
	5.56	5.82	5.7	5.4		4.72	4.54	4.6	4.3
	8.33	7.98	8.2	7.7		5.18	5.41	5.3	5.4
	9.12	9.45	9.3	8.9		6.21	6.56	6.4	6.3
	10.33	10.85	10.6	10.1		7.75	7.89	7.8	7.6
	12.07	12.45	12.3	11.9		8.92	9.12	9.0	9.0
	14.71	13.29	14.0	13.5		9.91	9.65	9.8	9.6
	16.01	16.89	16.5	16.1		11.21	10.99	11.1	10.9
	18.13	16.58	17.4	16.6		13.66	14.12	13.9	13.6
SP	1.53	1.60	1.6	1.6	SW	0.23	0.27	0.3	0.1
	2.24	2.13	2.2	2.0		2.03	2.15	2.1	2.0
	3.34	3.58	3.5	3.2		4.45	3.94	4.2	4.0
	4.69	4.49	4.6	4.2		6.07	6.12	6.1	5.8
	5.38	5.35	5.4	5.2		7.67	8.14	7.9	8.2
	6.44	6.88	6.7	6.2		9.67	10.00	9.8	9.8
	7.43	6.97	7.2	6.2		11.52	11.65	11.6	12.4
	8.75	8.97	8.9	8.6		14.07	14.46	14.3	14.4
	9.33	9.13	9.2	8.2		15.21	15.73	15.5	15.0
	12.23	10.93	11.6	10.2		16.07	16.94	16.5	16.0
	17.55	16.58	17.1	15.6					

Table 3. SWC values obtained with oven-drying and CCGP methods (continued).

Soil class	**Test 1**	**Test 2**	w^1_{od} (%) **Average**	w^2_{ccgp} (%) **Test 3**	**Soil class**	**Test 1**	**Test 2**	w_{od} (%) **Average**	w_{ccgp} (%) **Test 3**
GM[5]	1.08	1.10	1.1	1.0	GC[6]	0.18	0.21	0.2	0.2
	2.87	2.99	2.9	2.4		1.70	1.52	1.6	1.2
	4.73	4.81	4.8	3.8		1.63	2.23	1.9	1.8
	6.87	6.50	6.7	6.0		2.84	2.95	2.9	2.6
	7.88	7.97	7.9	7.4		3.18	3.37	3.3	3.0
	10.49	9.70	10.1	9.2		4.02	4.31	4.2	4.0
	10.18	10.97	10.6	9.8		5.58	5.45	5.5	4.6
	12.33	12.78	12.6	11.0		5.80	5.65	5.7	5.0
	13.47	13.33	13.4	12.4		7.29	7.74	7.5	7.4
	14.81	14.56	14.7	13.8		9.75	9.87	9.8	9.7
SM	0.43	0.29	0.4	0.3	SC	1.11	0.74	0.9	0.3
	2.23	2.19	2.2	1.8		2.43	2.93	2.7	2.0
	5.40	5.00	5.2	4.6		4.95	4.55	4.8	4.2
	6.66	6.90	6.8	6.0		6.56	6.81	6.7	6.2
	8.22	8.26	8.2	8.0		8.81	8.32	8.6	7.6
	10.50	10.05	10.3	9.6		10.89	11.16	11.0	9.6
	12.87	12.41	12.6	11.0		11.92	12.68	12.3	11.8
	14.11	13.67	13.9	12.5		14.09	14.36	14.2	13.0
	15.98	15.43	15.7	13.6		16.36	16.08	16.2	15.6
	18.04	18.55	18.3	16.8		17.73	17.85	17.8	18.8
GP-GM[7]	1.19	1.23	1.2	1.1	SP-SM	1.41	1.49	1.5	1.4
	2.60	2.27	2.4	2.2		2.40	2.45	2.4	2.5
	3.21	3.11	3.2	2.9		3.31	3.14	3.2	3.1
	4.17	3.97	4.1	4.0		4.13	4.39	4.3	4.8
	5.72	5.91	5.8	5.2		4.67	4.44	4.6	4.4
	6.58	5.95	6.3	6.0		5.44	5.51	5.5	5.2
	7.18	7.51	7.3	6.9		7.37	6.85	7.1	6.5
	8.81	7.75	8.3	7.8		8.89	9.21	9.1	8.8
	9.92	9.52	9.7	9.0		10.21	9.33	9.8	9.0
	10.23	10.55	10.4	9.8		12.24	12.66	12.5	12.0
	15.90	14.87	15.4	14.8		14.58	15.10	14.8	14.8
GP-GC[8]	1.12	1.31	1.2	1.0	SP-SC	1.51	1.29	1.4	0.6
	2.27	2.41	2.3	2.4		2.98	2.95	3.0	2.2
	3.09	2.99	3.0	3.0		5.14	4.84	5.0	4.0
	4.57	4.45	4.5	4.5		7.01	6.95	7.0	6.6
	5.51	5.96	5.7	5.1		8.38	8.17	8.3	8.2
	6.46	7.21	6.8	6.2		10.78	10.81	10.8	11.8
	8.67	8.38	8.5	8.4		12.51	12.06	12.3	13.0
	9.27	7.94	8.6	7.8		14.45	14.56	14.5	15.4
	9.52	9.91	9.7	9.2		16.12	16.71	16.4	17.2
	10.37	9.92	10.1	10.0		18.16	17.88	18.0	18.4
	11.42	9.29	10.4	9.4					
GW-GM[9]	1.23	1.44	1.3	1.0	SW-SM	2.18	1.83	2.0	1.8
	2.68	2.10	2.4	2.2		3.32	3.51	3.4	3.2
	3.28	3.14	3.2	3.1		4.29	4.37	4.3	4.2
	4.43	4.08	4.3	4.0		5.08	5.03	5.1	4.6
	5.54	5.75	5.6	5.2		6.66	6.35	6.5	6.2
	6.88	6.91	6.9	6.4		8.18	8.67	8.4	7.8
	7.81	7.20	7.5	7.0		9.94	10.56	10.3	9.2
	8.28	7.81	8.0	7.8		12.22	12.54	12.4	12.0
	9.81	10.11	10.0	9.5		12.29	13.16	12.7	11.8
	10.30	9.53	9.9	9.4		16.06	15.79	15.9	15.0
	12.40	11.04	11.7	11.4		18.97	18.02	18.5	17.0

Table 3. SWC values obtained with oven-drying and CCGP methods (continued).

Soil class	Test 1	Test 2	w_{od} (%) Average	w_{ccgp} (%) Test 3	Soil class	Test 1	Test 2	w_{od} (%) Average	w_{ccgp} (%) Test 3
GW-GC[10]	0.00	0.36	0.2	0.3	SW-SC	0.65	0.64	0.6	0.6
	2.18	1.82	2.0	1.8		2.69	2.43	2.6	2.2
	4.31	4.38	4.2	4.4		4.00	4.24	4.1	4.0
	5.85	5.95	5.9	5.6		5.88	5.54	5.7	5.2
	6.76	6.88	6.8	6.6		6.14	6.72	6.4	5.8
	7.09	7.30	7.2	7.6		9.00	7.54	8.3	8.0
	8.84	9.63	9.2	8.4		10.15	10.76	10.5	9.4
	11.35	10.34	10.8	11.4		11.48	12.95	12.2	11.4
	11.95	12.17	12.1	11.8		13.76	14.83	14.3	13.2
	13.53	13.30	13.4	13.6		15.05	16.25	15.6	15.6
	14.29	15.42	14.9	14.9					

[1]w_{od}: Soil water content with oven-drying;

[2]w_{ccgp}: Soil water content with CCGP method;

[3]SP; [4]SW, [5]SM; [6]SC; [7]SP-SM; [8]SP-SC; [9]SW-SM; [10]SW-SC according to USCS (Unified Soil Classification System) [13].

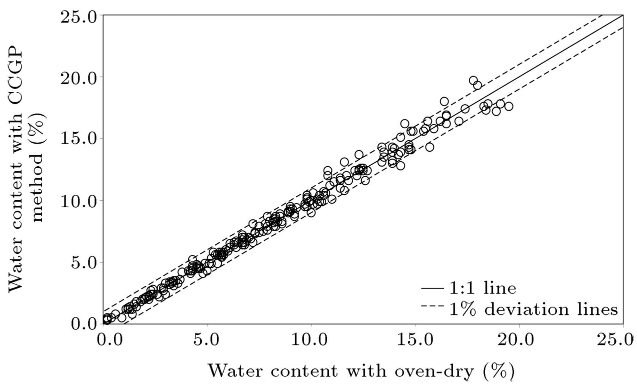

Figure 4. Deviation of generally calibrated CCGP results from 1:1 line.

due to the strong affinity towards the water molecules, especially for clay with a high specific surface. Another reason for this underestimation would be the existence of possible clod and clump formations of soil in the vessel during measurements, especially for highly plastic clay, which is not friable enough to break up during the shaking of the test vessel. The trapped water in these clod or clump formations might not have been allowed to come in full contact with the calcium carbide, resulting in an incomplete reaction, producing a lower amount of acetylene gas, and resulting in under representative results.

Comparison of oven-drying and generally calibrated CCGP methods for all specimens can also be seen in Figure 4. Points clustered evenly around the 1:1 line until a water content of 10.0%, and the limits of the agreement were acceptably narrow, indicating adequate reliability of the CCGP method in the SWC range of 0 to 10%. Slight misalignment from the 1:1 line occurred at higher SWC levels. For this reason, the performance of the method was further investigated for 0 to 10% range of SWC. The mean discrepancy was recalculated for samples having SWC of less than 10.0%, and was found to be around 0.2% when all soil groups were considered together. Maximum and minimum discrepancies were 1.0% and -0.9%, respectively.

An error distribution analysis was performed in order to achieve better understanding of the reliability of the CCGP method with respect to oven-drying, by constructing unit error histograms. The difference between values obtained with CCGP and the average of the two oven-drying measurements, all taken simultaneously from the same sample, was defined as the error for the CCGP measurements, and the findings are shown in Figure 5 for all soil groups. In Figure 5, the horizontal axis is the error of the CCGP results, and the vertical axis of the unit histogram is defined as the ratio of the number of observations with error to the number of all observations (frequency).

As can be seen in Figure 5, the distribution of the errors seems to be confined to an error value on the right of zero for Group 1 (underestimation) and on the left for the rest of the groups (overestimation). On the other hand, the error distribution of all specimens can be interpreted as nearly centered around zero. Errors of the method fell within the range of -1.9% and +1.9%, as can be seen in Figure 5(d), when all soil specimens were considered together. Most errors (90 percent of the specimens) took place between 0.6% and -0.4%.

3.2. Soil specific calibration measurement approach

In addition to general calibration, a linear soil specific calibration was also performed for each of the soil types. A general form of the soil specific calibration curve is

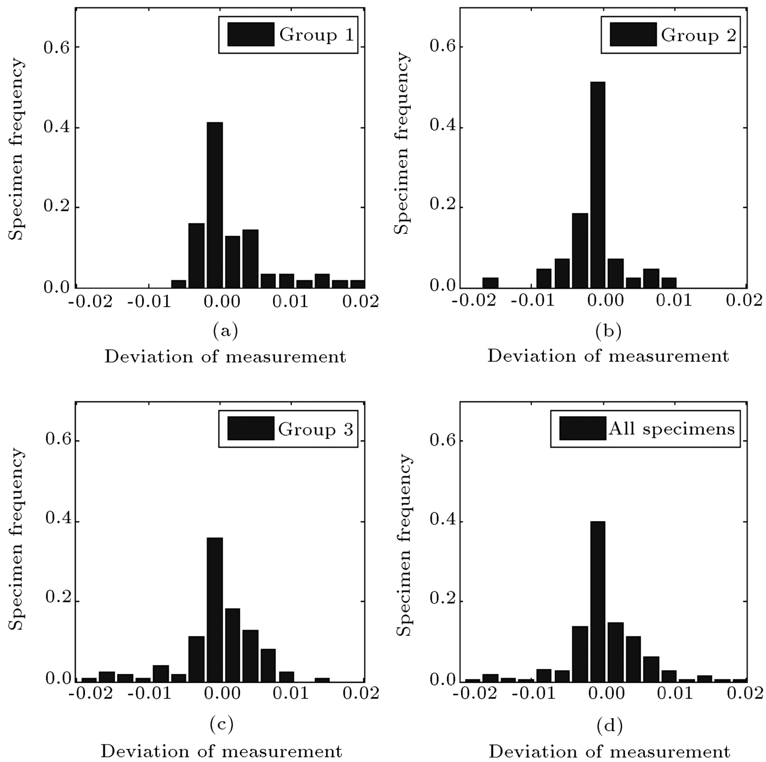

Figure 5. Error of CCGP method with general calibration for a) Group 1 specimens, b) Group 2 specimens, c) Group 3 specimens, and d) all specimens up to 20% of SWC.

given in Eq. (5). The calibration constants, a and b, are obtained by plotting SWC values obtained from calibration samples and fitting a linear equation, as in Eq. (5), as suggested by ASTM D4944 [4]. The values of a and b, and the coefficient of determination, R^2, obtained for the soil types considered in this study are tabulated in Table 4. Readers should note that the values given in Table 4 are only valid for the soil types and device used in this study, and should be determined separately for other soil types and devices, according to ASTM D4944 [4], as part of the soil-specific calibration approach.

$$w_{\mathrm{od}} = a w_{\mathrm{ccgp}} + b. \tag{5}$$

Discrepancies between the oven-drying and the soil specific calibrated CCGP methods are given in Figure 6, where tested soil groups can be investigated individually. The mean discrepancy of the CGGP method was found to be around 0.2% when all specimens were considered. The maximum error was 0.7% for clayey soil, and 0.8% for the rest of the major soil types. The highest degree of overestimation occurred in sandy soil, with a discrepancy of -1.2%, and the lowest for gravelly soil of -0.6%.

Comparison of the oven-drying and the soil specific calibrated CCGP methods for all specimens can be seen in Figure 7. Points clustered evenly around the 1:1 line up to the water content of 20.0%, and the limits

Table 4. Calibration constants and coefficient of determination of soil specific calibration curves of this study.

Soil type	a	b	R^2
CH	1.04	0.21	0.996
CI	1.13	-0.19	0.993
CL	1.10	-0.07	0.997
MH	1.08	-0.22	0.996
MI	1.08	-0.11	0.994
ML	1.15	-0.54	0.989
GP[1]	1.03	0.15	0.999
GW[2]	1.00	0.14	0.998
SP	1.11	-0.08	0.996
SW	1.00	0.05	0.995
GP-GC[3]	1.06	-0.01	0.991
GP-GM[4]	1.04	0.13	0.999
GW-GC[5]	0.99	0.11	0.993
GW-GM[6]	1.02	0.22	0.999
SP-SC	0.89	0.99	0.996
SP-SM	1.03	0.03	0.994
SW-SM	1.03	0.25	0.994
SW-SC	1.07	-0.01	0.998
SM	1.10	0.06	0.996
SC	0.96	0.98	0.989
GC[7]	1.00	0.30	0.990
GM[8]	1.06	0.34	0.996

[1]SP; [2]SW; [3]SP-SC; [4]SP-SM; [5]SW-SC; [6]SW-SM; [7]SC; [8]SM according to USCS (Unified Soil Classification System) [13].

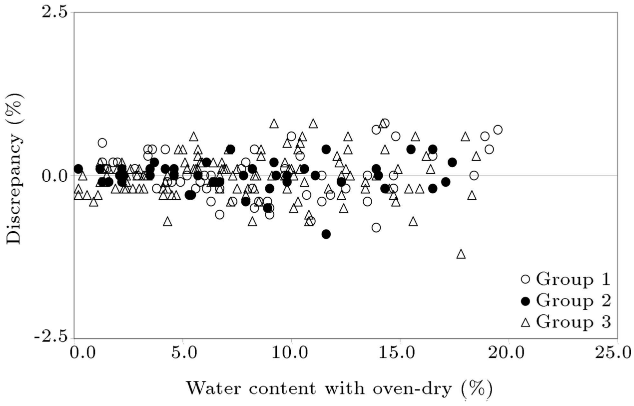

Figure 6. Discrepancies of the CCGP method for all groups with soil specific calibration.

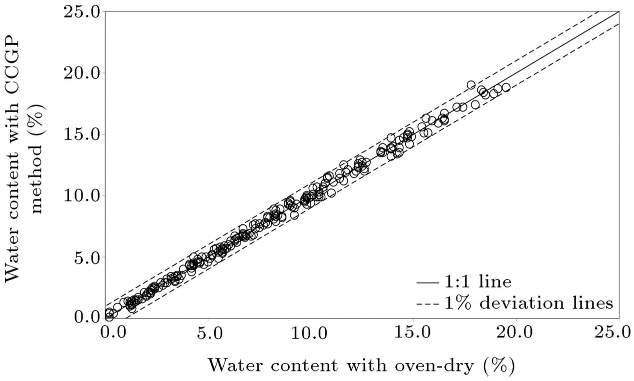

Figure 7. Deviation of soil specific calibrated CCGP results from 1:1 line.

of the agreement, were acceptably narrow, indicating the adequate reliability of the CCGP method. Slight misalignment from the 1:1 line occurred at higher SWC values, but the error of the CCGP method did not exceed $\pm 1\%$ deviation, except at a point, which can be regarded as an outlier.

In Figure 8, the unit error histograms of the results of the soil specific calibrated CCGP method obtained with an error distribution analysis can be seen. When compared with general calibration, soil specific calibration makes the unit error histograms clearly narrower and more nearly centered around zero. Additionally, the error distribution of Groups 1 and 3 becomes more compliant with normal distribution.

4. Conclusions and recommendations

The discrepancy between oven-drying results and CCGP results are mostly less than about $\pm 1\%$, and not exceeding $\pm 2\%$ for any specimens with a general calibration, which compares well to oven-drying variations. Soil specific calibration makes the error distribution significantly narrower, and the discrepancies become mostly less than about $\pm 0.5\%$ and not exceeding $\pm 1\%$. The highest degree of underestimation occurred for the clayey soil, probably due to the strong affinity of water molecules and trapped water in the clay clumps formed during the shaking of the vessel, resulting in an incomplete reaction.

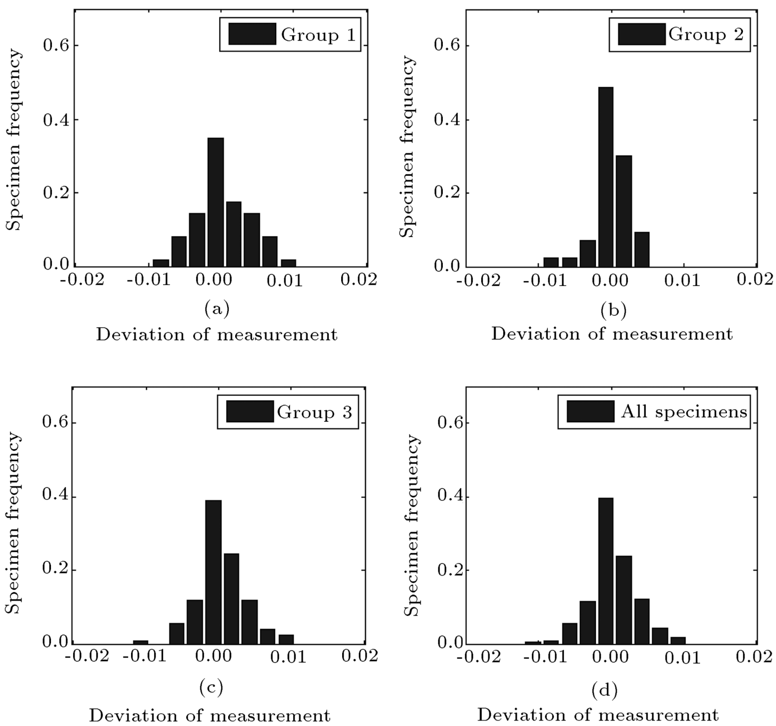

Figure 8. Error of CCGP method with soil specific calibration for a) Group 1 specimens, b) Group 2 specimens, c) Group 3 specimens, and d) all specimens up to 20% of SWC.

The error distribution analysis indicated that the CCGP method reliably estimates the SWC for small specimens, compared to the oven-drying method, for all soil types with a mean absolute discrepancy of around 0.3%, with a general calibration, and 0.2% with a soil specific calibration. Although it is not a method intended as a replacement for the standard oven-drying method, the CCGP method, even for small samples, proves to be valid and reliable for determination of soil water content when fast results are needed.

It is concluded that using a test apparatus with a specimen weight capacity under 20 g, in contrast to ASTM 4944 [4], and using a soil specific calibration instead of general calibration does not change the reliability of the method. CCGP testers for small specimens, as small as 6 g, containing particles no larger than No. 4 sieve size, can be used for SWC determination without lack of accuracy up to a water content of 20%.

Reliable readings with CCGP can be obtained after waiting at least 3 minutes and up to 10 minutes with increasing water content. The method is convenient when rapid results are required. Testing is done under field conditions, requiring no other device or power. It is also critical to limit the specimen mass, as specified by the manufacturer of the CCGP apparatus.

Acknowledgement

The authors acknowledge and appreciate the funding of the 106M231 project by The Scientific and Technological Research Council of Turkey (TUBITAK).

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