9. Project closeout is much more difficult than securing the contract itself. It requires a sincere joint effort by the owner and the contractor. The cases studied in this work indicate that Saudis are not claim oriented. They prefer settling differences through direct negotiations.

10. There has been a noticeable improvement in the quality of construction. It is expected that the industry will even be more efficient in the future.

REFERENCE

1. M.I. Al-Jarallah. Construction Industry in Saudi Arabia. Journal of Construction Engineering and Management, Construction Division, ASCE, Vol. 109, No. 4, Dec. 1983, pp. 355-368.

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Use of Microwave Oven for Rapid Determination of Moisture Content of Highway Materials

MUMTAZ A. USMEN and HWEE YAN KHENG

ABSTRACT

An overview of research findings on the use of a microwave oven for the rapid determination of the moisture content of soils, aggregates, waste materials, and stabilized materials is presented in this paper. Principles of microwave heating and factors that affect the test results are briefly reviewed. Conventional and microwave oven moisture content test results are compared to assess the accuracy of the microwave drying technique. Regression analyses are performed to establish the statistical relationship between the two parameters. It is shown that granular materials produce more accurate results than do cohesive soils. It is also shown that although discrepancies exist between conventional and microwave oven moisture contents, the two measurements are quite strongly correlated, and one can be consistently predicted from the other. Conclusions and recommendations, including research needs, are provided at the end of the paper.

The engineering properties and service behavior of highway materials such as soils, aggregates, and stabilized materials are greatly affected by the presence of moisture. Moisture content, defined as the ratio (as a percentage) of the weight of water contained in the material to that of the solid particles, is therefore considered a key parameter that must be accurately determined in the testing phases of all highway construction projects.

The standard and most widely accepted procedure for establishing moisture content is based on oven drying wet samples to constant weight at a controlled temperature of 110°C ±5°C (see, for example, ASTM D 2216). Although this method is fairly simple and accurate, it is rather time consuming because of the slow nature of the drying process in the conventional oven. Depending on the soil type and sample size, a drying period of from 4 to 24 hr may be required in the conventional oven. To meet the needs of expeditious construction control, various rapid moisture measurement techniques based on nuclear, hygrometric, electrical resistance, capacitance, electromagnetic, thermal, and gravimetric principles have been developed. However, success in obtaining the desired accuracy by these techniques has been varied (1).

Recently, because of their increased popularity and availability in the consumer market at a low cost, microwave ovens have attracted considerable attention as rapid moisture measuring devices. Research (2-8) performed to assess the feasibility of using a microwave oven in measuring the moisture contents of various highway materials has generally produced favorable results in terms of time savings and accuracy. However, some limitations have also surfaced. The purpose of this paper is to present an overview of the findings of this research.

In the following sections, principles of microwave heating and factors that affect the test results are briefly reviewed. Data obtained by the authors and data published by others form the basis for a comparison of moisture contents determined by microwave and conventional ovens. Predictive regression equations relating the two parameters are presented. Finally, conclusions and recommendations, including research needs, are provided at the end of the paper.

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PRINCIPLES OF MICROWAVE HEATING

Microwaves are a part of the electromagnetic spectrum with wavelengths in the centimeter range, bounded by the longer radio waves and the shorter infrared light waves. The frequencies of microwaves range roughly between 10^3 and 10^6 MHz. The microwave oven is a device in which dielectric heating is effected by high-frequency electromagnetic waves. This type of heat forms as a result of dielectric losses that occur in a material that is located between the metal walls of the oven, which act as a capacitor connected to a high-frequency generator, the magnetron.

The effectiveness of dielectric heating in a microwave oven is strongly dependent on the polarity of the material exposed to the electromagnetic field. Polar molecules (called dipoles), in which the centers of positive and negative charge do not coincide, are in thermal equilibrium in the absence of an electromagnetic field. When an electromagnetic field in applied, the dipoles orient themselves quickly and repeatedly in the direction of the field. The continual molecular motion generated by the alternations of the field causes the material to heat by intermolecular friction. This type of heating is rapid because, unlike conventional heating, the heat does not need to be conducted through the material starting from the surface but is generated rather uniformly inside the material.

Microwaves are similar to lightwaves and can be absorbed, reflected, or transmitted by a given material. Only those materials capable of absorbing the microwaves can be effectively heated by them. The energy absorbed per unit volume of the material is directly proportional to the microwave frequency applied, the square of the field strength, and the dielectric constant of the material being heated (9). Water, having dipolar molecules, has a high dielectric constant (about 80 at room temperature) compared with most minerals found in soils (about 3 in the dry state and increasing with moisture) and will absorb the microwave energy readily. Thus it will heat at a much faster rate than will soil solids and will evaporate rapidly in a microwave oven. It has been found that the dielectric properties of a wide range of moist soils are completely dominated by the water phase (5,10).

FACTORS THAT AFFECT TEST RESULTS

Effective use of a microwave oven in drying or measuring the moisture content of highway materials depends on consideration of a number of factors, which are interrelated. These factors may be listed as (a) material type, (b) power setting, (c) exposure time and temperature, (d) sample size and use of multiple samples, (e) sample containers, and (f) alteration of material properties on exposure to microwaves.

Material Type

A wide variety of materials, including inorganic and organic clays, bentonite, diatomaceous earth, silt, sand, gravel, crushed stone, shale, coal-associated wastes, chalk, gypsum, and stabilized earth materials, has been tested in the microwave oven for moisture content. It has been found that, with the exception of organic soils, high-carbon-content waste materials, gypsum products, and metallic soils, most of the soils and aggregates commonly used in highway construction are suitable for microwave oven drying (2-8).

Materials such as bottom ash, fly ash, colliery shale, and fine coal refuse may contain appreciable quantities of unburnt carbon (coal). Such materials have been observed to smolder, smoke, or ignite on intensive exposure to microwaves, except when the coal content is quite low (i.e., below 1 or 2 percent) (4,8). According to Gilbert (5), organic materials such as peat also exhibit smoking and ignition problems when heated by microwaves and are thus not suitable for microwave oven drying. Ryley (4), however, has reported that a soil with high organic content could be successfully dried in the microwave oven (even at high power levels).

Complications exist with gypsum and gypsum-containing materials when dried in the microwave oven (2,4,8). In materials of this type, the loosely bound water of hydration can be driven off rapidly on exposure to microwaves at temperatures around 70°C, which are below the boiling point of free water. This causes inaccurate test results. Ryley (4) has shown that dehydration may occur even when gypsum is mixed with soil. Soils with high metal contents (iron ore, bauxite, etc.) apparently have a high affinity for microwave energy and overheat quickly when all the free water has been evaporated (5).

Stabilized materials, especially those treated with cement, are particularly suited for microwave oven drying because hydration is minimized during the rapid heating (2,4). The microwave oven has also been successfully used in determining the water content of plastic concrete mixtures (11,12).

Power Setting

Most of the microwave ovens presently available can be set to different power levels that vary from low to high. The amount of useful power absorbed affects the heating rate. Faster rates of heating and water evaporation can be achieved at the higher power settings of the microwave oven (7,8).

Ryley (4) studied the effect of power setting on the moisture content of various materials. Slight increases in moisture content were observed with increased power setting in soils and aggregates, and the problem of ignition was eliminated in some coal wastes at the lowest power setting. One soil exhibited a tendency to "jump off" the container at the highest power setting. A similar problem was noted by Kheng (8) with materials that are either too wet or too dry. It was observed that if the sample had excess moisture, splashing would occur, particularly at the high power setting. If the material was powdery and relatively dry, particles began to spread in the microwave oven after it was turned on. Air circulation in the oven appeared to play a role in this latter behavior. Both splashing and spreading in the microwave oven cause inaccurate moisture content results.

Exposure Time and Temperature

It is important to recognize that the time required to dry a wet sample at a particular power setting of the microwave oven depends on the amount of water present in that sample. Because temperature is normally not controlled in the microwave oven during heating (in contrast to the conventional oven), some adsorbed water may be driven off in addition to the free water if the samples are dried to constant weight. This phenomenon is more significant in plastic clays than in granular materials because of the presence of adsorbed as well as interlayer (hydroxyl) water (6,7). Figures 1 and 2 show, respectively, the relationships between microwave exposure time and temperature and exposure time and

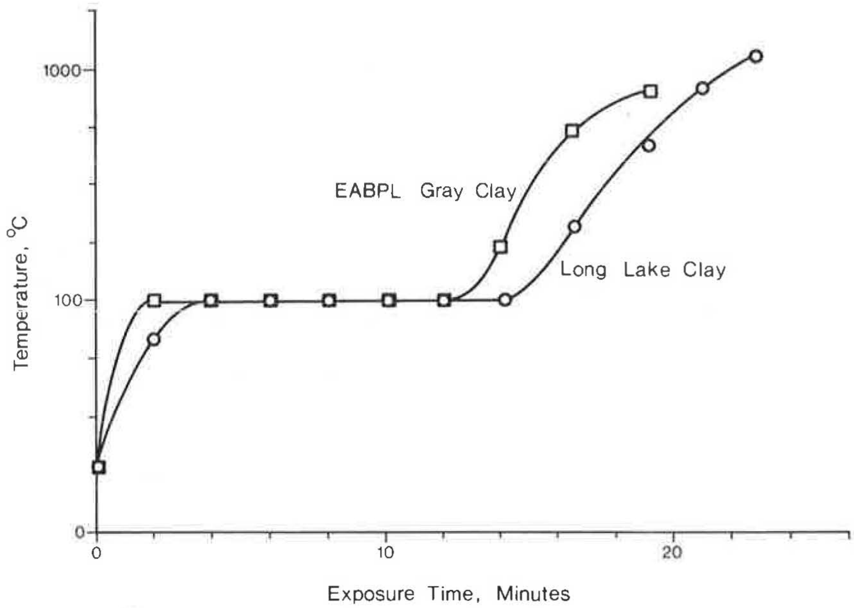

FIGURE 1 Temperature versus exposure time for two clays.

moisture loss for some clays. The temperature curves shown in Figure 1 indicate a plateau around 100°C after which a rapid heating of the sample occurs. This is typical of many soils heated by microwaves. The moisture loss curves shown in Figure 2, based on Ryley (4), are also quite typical of the drying behavior of soils in a microwave oven and a conventional oven until a constant weight is attained.

On the basis of a water evaporation temperature of 100°C and assuming a soil specific heat of 0.2 cal/g°C, Gilbert (5) derived an equation for the microwave exposure time needed to produce moisture contents comparable to those obtained by the conventional oven:

$$T = \{M [(0.2/W + 1)(100 - t) + 539] (4.18896)\}/P \quad (1)$$

where

- T = time in microwave oven (sec),
- M = mass of water present in the sample (g),
- W = moisture content of the sample in decimal form,
- t = ambient temperature (degrees Celsius), and
- P = power output of the oven (watts).

A power-load calibration curve and a preestimate of the moisture content are required before this equation is used.

Studies have shown that in most practical situations an average period of from 5 to 30 min is sufficient for drying samples to constant weight in the microwave oven, which indicates a substantial time savings over the conventional oven drying process. However, the actual exposure times to obtain a constant weight in the microwave oven have been found to usually be longer than those predicted by Equation 1 (6,8). This is as expected because there is moisture loss beyond the 100°C plateau observed in

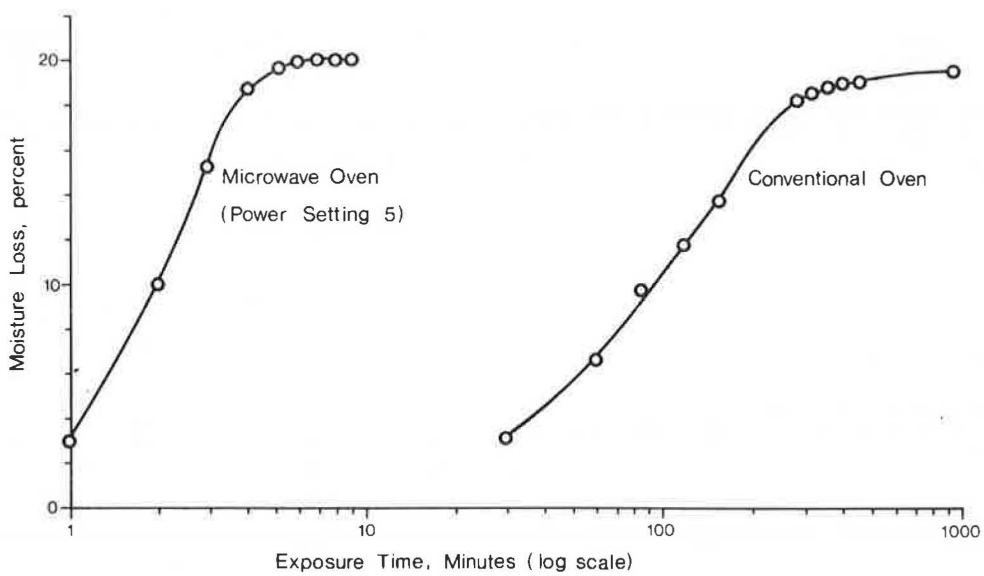

FIGURE 2 Moisture loss versus exposure time for London clay.

exposure time-temperature curves, and a constant weight is not necessarily attained on that plateau.

Because of the extended heating, moisture contents determined by the microwave oven are generally higher than those obtained by the conventional oven. This will be discussed in greater detail later. However, according to Charlie et al. (7), this problem can be alleviated for the most part if a temperature-controlled microwave oven is used.

Sample Size and Use of Multiple Samples

Studies by Lade and Nejadi-Babadai (6) and Charlie et al. (7) on different sized samples of homogenized cohesive soils indicate that increased sample size generally results in a reduction of the microwave oven moisture content. However, on the basis of comparisons of microwave and conventional oven test results for samples of different sizes, Charlie et al. (7) have also reported that sample size does not influence the accuracy of moisture content determinations, provided the sample is large enough to be accurately weighed. Sample weights in the range of from 10 to 500 g have been successfully used, with a 100- to 200-g range being the most common.

Drying multiple samples simultaneously in the microwave oven is not feasible, particularly if the samples belong to different materials or contain different amounts of water, or both (4,5). Not only would it take much longer for the specimens to dry together, but also a different exposure time would be required to dry each specimen, which renders this procedure highly impractical.

Sample Containers

It is essential that the sample containers used for drying materials in a microwave oven do not impede the microwaves, do not burn or deform, and do not experience any weight loss. Metal containers are not suitable because they reflect microwaves and spark when in contact with the shelf of the oven (4,5). Containers made of porcelain, borosilicate glass (Pyrex), polypropylene, and silica are preferable because of the favorable microwave transmission properties of these materials. Plastic and paper are also good microwave transmitters but they may be deformed and burned by the heat from the glass plate in the microwave oven (6).

Sample containers made of materials that heat by microwaves appear particularly suitable because water condensation on the cool container walls during heating will be minimized (4). Porcelain and borosilicate glass heat under microwave influence, whereas polypropylene and silica do not.

Alteration of Material Properties

Clays and clayey soils are known to experience changes in plasticity, shrinkage, and swelling characteristics when heated to temperatures above 100°C (13). Depending on the temperature, both adsorbed and interlayer water may be lost resulting in reduced plasticity and reduced swelling potential.

Lade and Nejadi-Babadai (6) studied the effects of microwave oven heating on the Atterberg limits of some clays. The liquid limit, the plastic limit, and the plasticity index were found to decrease for all soils when they had been preheated in the microwave oven. The largest reductions in these limits occurred for the highly plastic clays, and the smallest reductions were observed for the low-plasticity soils. The shrinkage limits tended to increase indicating a reduction in swelling potential. These effects are similar to those caused by drying soils in a conventional oven at high temperatures.

CONVENTIONAL VERSUS MICROWAVE OVEN MOISTURE CONTENTS

The accuracy and reliability of the moisture content test results determined by a microwave oven can be best evaluated by comparing these results with moisture content test results obtained on identical samples using a conventional oven. A good agreement or a good correlation between the two measurements would attest to the feasibility of using the microwave oven as a rapid moisture content measuring device. A modest amount of research data is available from studies conducted by the authors (8) and by other investigators (2,4,6,7) for such comparisons. A tabulation, analysis, and discussion of these data are presented herein.

Conventional versus microwave oven moisture contents for various highway materials, categorized as cohesive soils, granular soils and aggregates, special materials (wastes, shale, chalk, and bentonite), and stabilized materials, are given in Tables 1-4. The microwave oven moisture contents (W_m) shown in these tables are based on drying the materials to constant weight at the highest power setting of the oven, except for two samples as noted

TABLE 1 Conventional Versus Microwave Oven Moisture Contents for Cohesive Soils

W_c (%)	W_m (%)	ΔW ($W_m - W_c$) (%)	Material: Description	Material: Class	Reference
13.46	13.80	+0.34		CH	(8)
19.52	19.72	+0.20			
24.75	24.64	−0.11			
44.07	44.33	+0.26			
67.31	67.52	+0.21			
14.20	14.70	+0.50		CL	(8)
19.42	19.57	+0.15			
23.81	24.33	+0.52			
34.26	34.67	+0.41			
64.83	65.45	+0.62			
11.45	11.65	+0.20		ML	(8)
16.73	16.94	+0.21			
21.78	21.87	+0.09			
30.45	30.82	+0.37			
40.69	40.97	+0.28			
85.39	85.60	+0.21	Wyoming brown clay	CH	(7)
100.38	103.28	+2.90	Black cotton soil	CH	
27.76	27.60	−0.16	Red brown clay	CL	(2)
30.65	30.42	−0.23	Quartzite silt		
147.3	148.6	+1.3	Haley clay	CH	(6)
119.8	121.2	+1.4			
86.1	88.3	+2.2			
60.9	63.3	+2.4			
96.3	97.8	+1.5	Grundite clay	CH	(6)
59.8	61.5	+1.7			
52.2	54.1	+1.9			
38.4	40.8	+2.4			
55.1	56.2	+1.1	H-soil	CL	(6)
49.0	50.4	+1.4			
40.1	41.6	+1.5			
42.7	43.0	+0.3	M-soil	CL	(6)
30.5	31.2	+0.7			
29.3	30.4	+1.1			
40.7	41.6	+0.9	L-soil	ML	(6)
32.4	33.5	+1.1			
26.5	27.9	+1.4			
20.1	20.5	+0.4	Gault clay		(4)
19.7	20.8	+1.1	London clay		
20.5	20.7	+0.2	Organic soil		
20.0	20.7	+0.7	Brick earth (A)		
21.4	22.3	+0.9	Brick earth (B)		

TABLE 2 Conventional Versus Microwave Oven Moisture Contents for Granular Soils and Aggregates

W_c (%)	W_m (%)	ΔW (W_m - W_c) (%)	Soil Description	Class	Reference
2.19	2.28	+0.09	No. 57 limestone	GP	(8)
4.24	4.41	+0.17			
5.23	5.40	+0.17			
6.22	6.39	+0.17			
8.24	8.33	+0.09			
7.57	7.49	-0.08	Limestone sand	SM	(8)
10.55	10.70	+0.15			
13.39	13.74	+0.35			
16.49	16.78	+0.29			
26.54	26.76	+0.22			
3.33	3.31	-0.02	Ohio River sand	SP	(8)
6.35	6.41	+0.06			
9.36	9.41	+0.05			
12.43	12.47	+0.04			
20.37	20.44	+0.07			
19.44	19.69	+0.25	Medium-graded sand		(2)
22.55	22.60	+0.05	Coarse sand		
3.68	3.68	0.00	Gravel 3/8 in.-No. 4		
1.15	1.19	+0.04	Gravel 3/4-3/8 in.		
11.1	11.6	+0.05	Antelope Valley sand		(6)
15.1	15.3	+0.02	Silty sand		
8.0	8.0	0.00	Ottawa sand		
9.4	9.3	-0.1	Sulehay sand		(4)
9.3	9.1	-0.2	Wheatley gravel		
1.4	1.1	-0.3	Limestone (passing 20 mm)		

TABLE 3 Conventional Versus Microwave Oven Moisture Contents for Some Special Materials

W_c (%)	W_m (%)	ΔW (W_m - W_c) (%)	Material Description	Class	Reference
Waste Materials					
12.70	13.99	+1.29	Bottom ash	GW-GM	(8)
16.73	18.21	+1.48			
20.65	21.74	+1.09			
24.70	25.57	+0.87			
13.42	13.70	+0.28	Low-carbon fly ash	ML	(8)
17.47	17.91	+0.44			
21.69	21.86	+0.17			
25.82	25.88	+0.06			
56.53	57.36	+0.83			
29.45	30.07	+0.62	Waste calcium sulfate	SM-SM	(8)
36.19	37.10	+0.91			
43.62	44.48	+0.86			
50.22	51.24	+1.02			
57.49	58.75	+1.26			
22.90[a]	25.00	+2.10	Weald clay + 20% calcium sulphate		(4)
10.2	10.4[b]	+0.2	Homs Hall pulverized fuel ash		
26.9	27.0	+0.1	Chalk (passing 5 mm)		
Shale					
133.70	134.47	+0.77	Bear Paw shale	CH	(7)
5.2	5.4[c]	+0.2	Colliery shale (unburnt, passing 20 mm)		(4)
Bentonite					
846.67	854.10	+7.43	Wyoming bentonite		(7)
906.5	926.1	+19.6	Black Hills bentonite		(6)
660.8	692.7	+31.9			
603.0	659.0	+56.0			
127.3	138.4	+11.1	Dixie Bond bentonite		(6)
116.6	130.3	+13.7			
70.1	84.1	+14.0			

[a]Dried at 80°C.
[b]Medium power setting.
[c]Low power setting.

TABLE 4 Conventional Versus Microwave Oven Moisture Contents for Stabilized Materials

W_c (%)	W_m (%)	ΔW (W_m - W_c) (%)	Material Description	Reference
37.95	37.88	-0.07	Clay with 3% lime	(2)
11.94	11.90	-0.04	Soil cement	
19.4	20.3	+0.9	Brick earth + 10% cement	(4)
20.2	21.7	+1.5	London clay + 10% cement	
9.6	9.9	+0.3	Sulehay sand + 10% cement	
8.7	9.2	+0.5	Wheatley gravel + 10% cement	

in Table 3. Except for the results obtained by Charlie et al. (7), no temperature control has been imposed on the samples in the microwave oven drying process. The conventional oven moisture contents (W_c) are based on drying the materials to constant weight at a controlled temperature of 110°C ±5°C, in line with the standard procedure, with one exception as noted in Table 3. To facilitate comparisons, the discrepancies between the two measurements ($\Delta W = W_m - W_c$) are provided in the tables. Material descriptions or unified soil classifications, or both, are also listed along with the original sources of data.

An examination of the ΔW values in Tables 1-4 reveals that a positive discrepancy exists between W_m and W_c in a great majority of cases. This clearly demonstrates the previously described observation that microwave oven moisture contents are predominantly higher than conventional oven moisture contents. It can also be easily seen from the same data that the discrepancies between the two measurements are greater for cohesive soils (Table 1), in most cases, than for granular materials (Table 2), with extremes being observed with bentonite (Table 3). Among the special materials listed in Table 3, the relatively large discrepancy noted for bottom ash is attributed to the high percentage of combustibles (a loss on ignition of 15 percent) in that material. The waste calcium sulfate materials (gypsum) also show large discrepancies, as would be expected. The results shown for stabilized materials in Table 4 show negative ΔW values in one case and positive ΔW values in the other. It is the authors' belief that the latter case would prevail most of the time if moisture losses due to hydration were eliminated by rapid drying in the microwave oven.

Quantitatively, the discrepancy between microwave and conventional oven moisture contents for granular materials appears to be generally within 0.25 percent, indicating an excellent agreement between the two measurements. The discrepancies between the two measurements in cohesive soils vary over a much wider range, exceeding 0.5 percent in many cases. The discrepancies for bentonite are enormously high, mostly above 10 percent. The agreement between microwave and conventional oven moisture content results is obviously not very good for cohesive soils in general and is particularly poor for highly plastic clayey materials.

The conventional versus microwave oven moisture content data provided in Tables 1-4 are presented graphically in Figures 3-6 for further analysis. Only the data on cohesive soils (Figure 3), granular soils and aggregates (Figure 4), bentonite (Figure 5), and stabilized materials (Figure 6) are included. Because of the potential unreliability of test results, or insufficiency of data, no attempt is made to further analyze the waste materials, chalk, and shale. The dashed diagonal lines shown in Figures 3-6 depict the case of perfect agreement between the

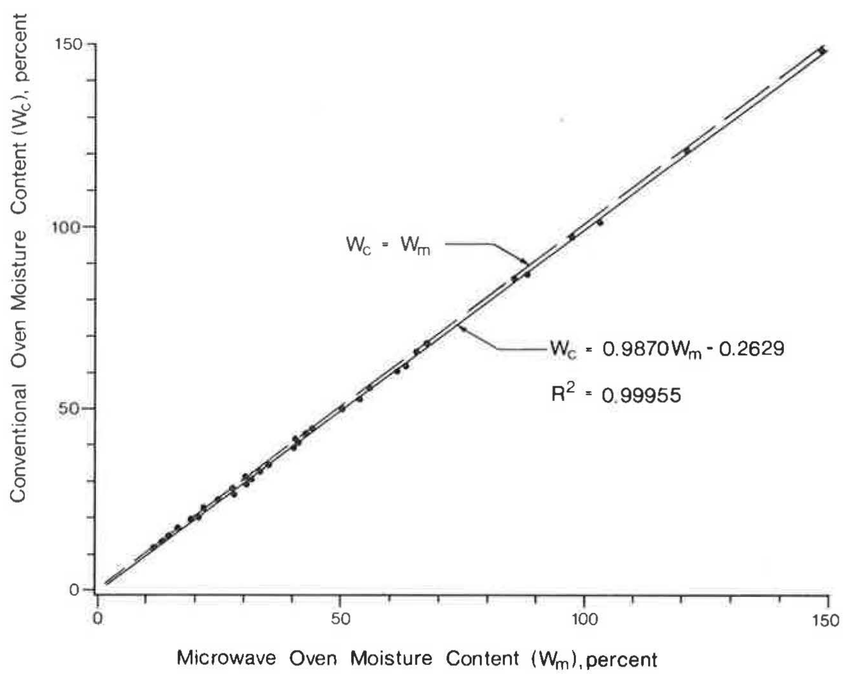

FIGURE 3 Conventional versus microwave oven moisture contents for cohesive soils.

two test results ($W_c = W_m$), around which the scatter of the data points (W_m, W_c) can be observed. The solid lines are obtained by linear regression analyses, and the appropriate regression equations and the corresponding R^2 (square of the coefficient of correlation between W_m and W_c) values are also shown in the figures.

It can be readily seen in Figures 3-6 that, in all cases, a great majority of the data points and their regression lines fall below the $W_c = W_m$ line, reinforcing the predominant positive discrepancy between W_m and W_c. The exceedingly high R^2 values suggest that the variables W_m and W_c are strongly correlated, and one (W_c) can be con-

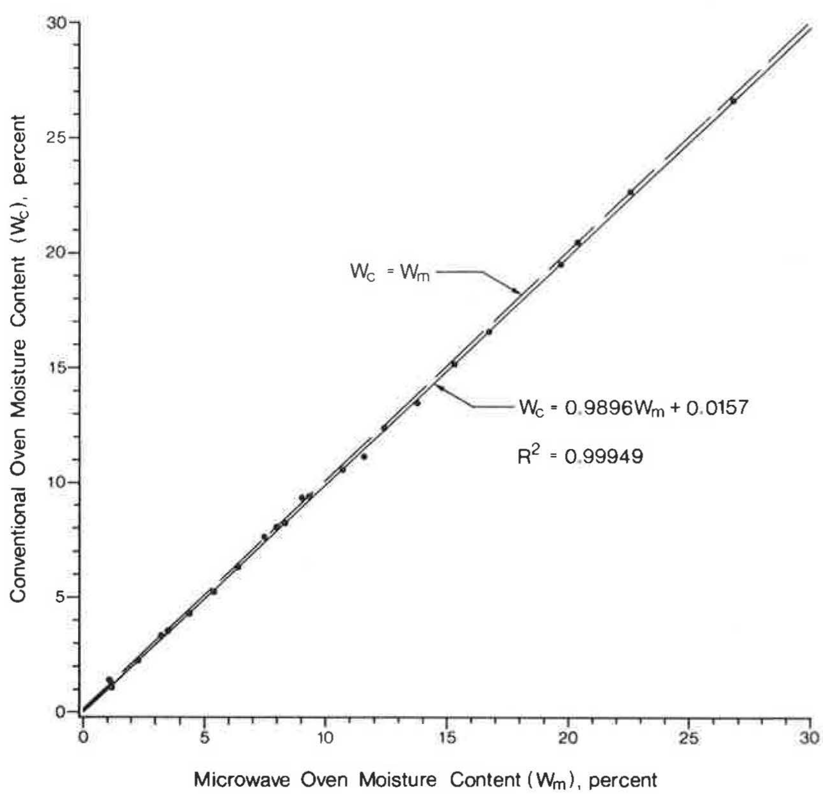

FIGURE 4 Conventional versus microwave oven moisture contents for granular soils and aggregates.

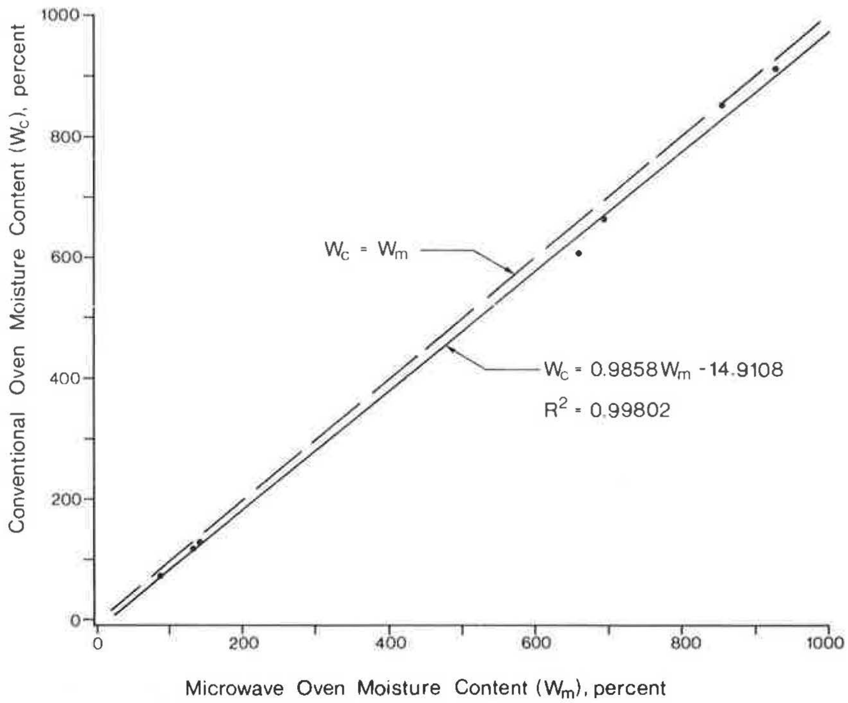

FIGURE 5 Conventional versus microwave oven moisture contents for bentonite.

sistently predicted from the other (W_m). Although the data base used in this analysis is not extensive, the regression equations provided can serve as predictive models for estimating the standard conventional oven moisture contents from microwave oven test results for materials that are similar to the ones used in this analysis.

CONCLUSIONS AND RECOMMENDATIONS

On the basis of the review and analysis of research results presented in this paper, the following conclusions and recommendations are warranted:

1. The microwave oven shows good potential as a

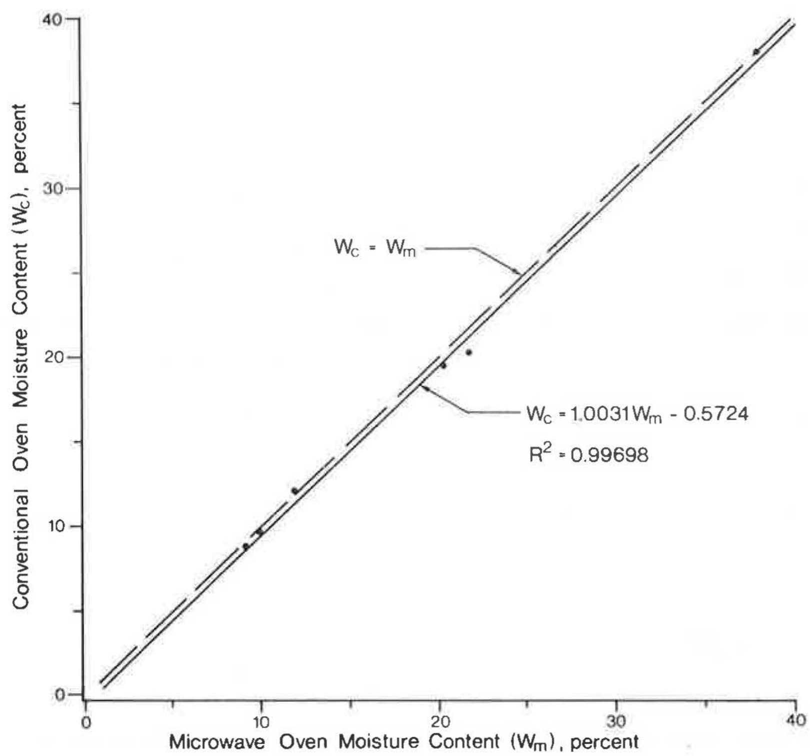

FIGURE 6 Conventional versus microwave oven moisture contents for stabilized materials.

practical and inexpensive device that can be used for rapid determination of the moisture content of many soils and aggregates used in highway construction. Because of practical constraints, the microwave oven is not recommended at this time for drying organic soils, metallic soils, coal-associated wastes, and gypsum-containing materials. It is, however, applicable to stabilized materials such as soil-cement.

2. Granular materials produce the most accurate microwave oven moisture content test results. The accuracy of the method is relatively poorer for cohesive soils, and the accuracy decreases with increasing plasticity. Microwave oven moisture contents are mostly higher than conventional oven moisture contents for all materials because of the lack of temperature control in microwave drying. It appears that temperature control may improve accuracy.

3. The time required to dry soil samples in the microwave oven at a given power setting will depend on the amount of moisture present. However, in most practical cases, materials can be dried to a constant weight at the high power setting within less than 30 min. This is a substantial time saving over the standard procedure using the conventional oven.

4. Simultaneous drying of multiple samples in the microwave oven and use of metal, plastic, and paper sample containers are not recommended. Porcelain and borosilicate glass containers are the most appropriate.

5. Soils (especially clays) dried by microwaves experience changes in plasticity, shrinkage, and swelling characteristics. Thus it is not advisable to use the microwave oven for preparing (drying) soils for other tests in which these factors may be significant.

6. Although discrepancies exist between microwave and conventional oven moisture contents, the two variables are strongly correlated. Hence, regression equations, such as the ones provided in this paper, can be used to predict the standard conventional oven moisture contents from rapid test results obtained by the microwave oven, when experience indicates that such a procedure is warranted.

7. There is an apparent need for further research aimed at the standardization of the microwave oven drying process for moisture content determination. The effects of factors discussed in this paper on the accuracy of the test results must be fully studied as part of this research. Basic research is also needed to further understand the mechanisms involved in the drying of various soils and other highway materials with particular focus on the physicochemical and dielectric properties of the materials.

8. Finally, users of microwave ovens should be cautioned against the potential hazards of the microwaves. Besides presenting radiation hazards if proper safety precautions are not observed, microwaves affect heart pacers at substantial distances.

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REFERENCES

1. L.F. Ballard. Instrumentation for Measurement of Moisture: Literature Review and Recommended Research. NCHRP Report 138. HRB, National Research Council, Washington, D.C., 1973.
2. A.E. Creelman and V.E. Vaughan. Determination of Moisture Contents of Soil Samples by Microwave Heating. Proc., 1966 Convention of the Canadian Good Roads Association, Halifax, Nova Scotia, Sept. 1966, pp. 459-464.
3. B.B. Algee, J.C. Callaghan, and A.E. Creelman. Rapid Determination of Moisture Content in Soil Samples Using High Power Microwaves. IEEE Transactions on Geoscience Electronics, GE-7, No. 1, Jan. 1969, pp. 41-43.
4. M.C. Ryley. The Use of a Microwave Oven for the Rapid Determination of Moisture Content of Soils. RRL Report LR 280. Road Research Laboratory, Ministry of Transport, Crowthorne, Berkshire, England, 1969.
5. P.A. Gilbert. Feasibility Study--Microwave Oven Used for Rapid Determination of Soil Water Contents. Evaluation of Soil Mechanics Laboratory Equipment, Report 13. U.S. Army Engineer Waterways Experiment Station, Vicksburg, Miss., Aug. 1974.
6. P.V. Lade and H. Nejadi-Babadai. Soil Drying by Microwave Oven. ASTM STP 599: Soil Specimen Preparation for Laboratory Testing. ASTM, Philadelphia, Pa., 1976, pp. 320-340.
7. W.A. Charlie, M.W. Von Gunten, and D.O. Doehring. Temperature Controlled Microwave Drying of Soils. Geotechnical Testing Journal, Vol. 5, Nos. 3/4, Sept./Dec. 1982, pp. 68-75.
8. H.Y. Kheng. Use of the Microwave Oven for the Rapid Determination of Soil Moisture Content. Master's thesis. West Virginia University, Morgantown, Dec. 1984.
9. H. Puschner. Heating with Microwaves. Phillips Technical Library, Springler-Verlag, Inc., New York, 1966.
10. J.R. Lundien. Terrain Analysis by Electromagnetic Means: Laboratory Measurement of Electromagnetic Propagation in the 1.0 to 1.5 GHz Microwave Spectral Region. Technical Report 3-693, Report 5. U.S. Army Engineer Waterways Experiment Station, Vicksburg, Miss., 1971.
11. R.T. Peterson and D. Leftwich. Determination of Water Content of Plastic Concrete Using a Microwave Oven. Final Report, FCP 44F3-313. North Dakota State Highway Department, Bismarck; FHWA, U.S. Department of Transportation, Sept. 1978.
12. D.E. Beecroft and R.L. Dominick. Rapid Test Methods for the Evaluation of Concrete Properties. Final Report, DOT-FH-11-8876. Oregon State Highway Division, Salem; FHWA, U.S. Department of Transportation, Jan. 1982.
13. R.E. Grim. Applied Clay Mineralogy. McGraw-Hill Book Co., New York, 1962.

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