Final Report 2001-21

Research

Measurement of Moisture in Aggregate Stockpiles

Technical Report Documentation Page

1. Report No.	2.	3. Recipients Accession No.
MN/RC – 2001-21		

4. Title and Subtitle	5. Report Date
MEASUREMENT OF MOISTURE IN AGGREGATE STOCKPILES	March 2001
	6.

7. Author(s)	8. Performing Organization Report No.
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9. Performing Organization Name and Address	10. Project/Task/Work Unit No.
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12. Sponsoring Organization Name and Address	13. Type of Report and Period Covered
Minnesota Department of Transportation 395 John Ireland Boulevard Mail Stop 330 St. Paul, Minnesota 55155	Final Report 1997-2001
	14. Sponsoring Agency Code

15. Supplementary Notes

16. Abstract (Limit: 200 words)

Asphalt mixture variations that result from moisture fluctuations in aggregate stockpiles pose a serious problem at dryer-drum plants. The moisture content of a stockpile is infrequently measured, if at all. If the proportion of aggregate is not adjusted to account for its moisture content, an improper mix will result.

This project looked at identifying a practical and accurate field method or probe for measuring the moisture content of aggregates, testing the probe in a hot-mix plant, and developing a control strategy for asphalt oil addition to the mix.

Researchers identified a suitable commercial probe by reviewing past research and conducting laboratory studies. Testing in the plant showed that this probe could rapidly measure aggregate moisture in plant conditions at the same level of accuracy as gravimetric measurements. Researchers also developed a control strategy for the asphalt oil addition. Testing showed the effectiveness of this control, in conjunction with commercial probe moisture measurements in the feed bin. A problem with probe operations robustness was identified.

17. Document Analysis/Descriptors	18. Availability Statement
Moisture Measurement in Aggregates Control of Hot Mix Plant	No restrictions. Document available from: National Technical Information Services, Springfield, Virginia 22161

19. Security Class (this report)	20. Security Class (this page)	21. No. of Pages	22. Price
Unclassified	Unclassified	72	

MEASUREMENT OF MOISTURE IN AGGREGATE STOCKPILES

Final Report

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March 2001

Published by:

Minnesota Department of Transportation
Office of Research Services
Mail Stop 330
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St. Paul, MN 55155

ACKNOWLEDGEMENTS

The authors would like to thank Tom Hunt at the Minnesota Department of Transportation for valuable input. Personnel at Commercial and Midwest Asphalt, in particular Mourad Bouhajja, for access to aggregates and plant, and Troxler for the loan of the capacitance probe.

EXECUTIVE SUMMARY

Asphalt mixture variations resulting from moisture fluctuations in aggregate stockpiles are a serious problem at dryer-drum plants. The moisture content of a stockpile is infrequently measured, if at all. If the proportion of aggregate is not adjusted to account for its moisture content, an improper mix will result. The aim of this project was to identify a practical and accurate field method/probe for measuring the moisture content of aggregates, test the probe in a hot mix plant and develop a control strategy for asphalt oil addition to the mix. Through a literature review and laboratory studies a suitable commercial moisture probe was identified. Testing in the plant showed that this probe could rapidly measure aggregate moisture in plant conditions at the same level of accuracy as gravimetric measurements. A control strategy for the asphalt oil addition was developed. Testing showed that, in conjunction with commercial probe moisture measurements in the feed bin, this control would be effective. A problem with probe operation robustness was identified.

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CHAPTER 1

INTRODUCTION

Background

With current technology, determinations of the moisture level in the aggregates of a hot mix plant are infrequent. Over a given production cycle—due to changing weather conditions or the source of the aggregate—the moisture levels in the aggregate will experience fluctuations from the initial measured value. Unknown moisture levels in the aggregate feed to a hot mix plant can lead to two major problems in the quality of the final pavement mix:

1. If the drying of the aggregate is incomplete, the residual moisture will remain in the asphalt mix.
2. The amount of the aggregate in the mix is determined on a weight basis. The moisture level needs to be considered in this calculation. Clearly if the exact moisture level is unknown, the mix proportions will not match the required specification.

If practical, frequent field measurements of the moisture in aggregate can be combined with an understanding of the fluctuations in aggregate moisture levels then plant adjustments can be made to ensure consistency of the mix. The analysis of data from the Office of the Minnesota Road Research Project (Mn/ROAD) clearly illustrated a reduction in hot-mix asphalt variability when aggregate moisture content was measured and appropriate plant adjustments made [1].

Objective

The aim of this project was to

1. Identify at a practical and accurate field method/probe for measuring the moisture content of aggregate stockpiles,
2. test the use of the probe in measuring the moisture in the aggregate feed to the mix drum, and
3. suggest and test how such measurements can be used to control the proportions of aggregate and asphalt in the mix.

Scope

The development of moisture measuring technologies for aggregates involved a combination of laboratory, field and computational studies. Specifically the following were accomplished.

1. An extensive literature review and initial testing identified the Trxoler CP 200 capacitance probe [2] as worthy of further detailed study.
2. The development and implementation of a laboratory procedure to calibrate aggregate moisture measurement technologies for field use.
3. A field study aimed at determining typical moisture fluctuations in aggregate stockpiles.
4. Field studies aimed at determining the moisture fluctuations in the fine aggregate feed bin during a hot mix production run.
5. The development of possible plant control strategies and guidelines.

Details of the above studies are provided in following chapters of this report.

CHAPTER 2

WHY IS MOISTURE IMPORTANT?

Introduction

The aim in this chapter is to provide an illustration as to why a correct moisture determination is important in ensuring that asphalt oil additions to the mix are in the correct portions.

The Perfect World

First consider the ideal case of a hot mix plant using three aggregates, Fine, Medium, and Coarse. Further let us assume that the mix design, on a dry weight biases, is

$$\begin{aligned} W_{FDRY} &= 60\% \\ W_{MRDY} &= 25\% \\ W_{CDRY} &= 15\% \end{aligned} \tag{2.1}$$

where the subscripts are F = Fine, M = Medium, and C = Coarse. Let the asphalt oil addition be 5% be weight, i.e.,

$$\frac{100 * W_{OIL}}{W_{FDRY} + W_{MDRY} + W_{CDRY}} = \theta_{OIL}^{DES.} = 5\% \tag{2.2}$$

In achieving this mix it needs to be recognized that the moisture content in the aggregates needs to be accounted for. If W_{agg} is the desired weight of a given aggregate type (F, M or C) to be added to the mix then the actual weight added needs to be

$$W_{aggWET} = (1 + \frac{\theta_{agg}}{100}) W_{aggDRY} \tag{2.3}$$

where

$$\theta_{agg} = 100\frac{W_{aggWET} - W_{aggDRY}}{W_{aggDRY}} \tag{2.4}$$

is the moisture fraction (wt%) in the given aggregate type.

The Real World

If the correction in Eq. (2.3) is made to the wet aggregate addition to the mix the correct portion of asphalt oil for the design will be maintained. In a practical case we will not know, at each point in time, the exact value of the moisture fraction in an aggregate bin. Further, the best measured value available θ_{agg}, may be out of date and be far removed from the actual value θ^{A}_{agg}. The consequence is, that if Eq. (2.3) is used to calculate the weight that must be added to the mix, the actual dry weight added, in terms of the required dry weight, will be

$$W^{A}_{aggDry} = \frac{100 + \theta_{agg}}{100 + \theta^{A}_{agg}} W_{aggDRY} \tag{2.5}$$

and the actual asphalt oil content, in terms if the designed content, in the mix will be

$$\theta^{A}_{OIL} = \text{factor} * \theta^{DES.}_{OIL} \tag{2.6}$$

where the factor of excess or deficiency of the asphalt oil addition is given by

$$\text{factor} = \frac{W_{FDRY} + W_{MDRY} + W_{CDRY}}{W^{A}_{FDRY} + W^{A}_{MDRY} + W^{A}_{CDRY}} \tag{2.7}$$

If the asphalt falls too far below the design value then the final aggregate mix will fail to bond. If too much asphalt is added the asphalt concrete will be too soft and expensive in terms of the unnecessary oil addition. There is also evidence that the binder content and void ratio in the pavement is closely related to the asphalt oil content (see page 36 in Stoup-Garndiner and Newcomb [1]).

A Spreadsheet Simulation

The Basic Set Up

A spreadsheet model is developed to assess the impact of moisture variations in the fine aggregate of the weight fraction of the asphalt addition to the mix. In setting up this spreadsheet the following assumptions are used.

1. A mix ratio of fine, medium and coarse is assumed. In this work the mix portions given in Eq. (2.1) are used.
2. An initial measure of moisture is imposed θ^m for each fraction, F(ine), M(edium), C(oarse). In normal operation of the model, this measured value is fixed throughout each simulation.
3. Variations, in time and space, of the moisture content in the fine aggregates are obtained from plant gravimetric measurements. These measurements are designated as actual moisture measurements θ^A_F. For convenience of the analysis variations in the medium and coarse grades are neglected throughout the simulation, i.e.,

$$\theta^A_M = \theta_M, \theta^A_C = \theta_C \tag{2.8}$$

With these settings each line in the spreadsheet corresponds to a change in the actual moisture. In this way, at each line, Eq. (2.5) (applied to the fine aggregate) will predict a value for the actual weight portion of fine aggregate in the mix and Eq. (2.6) will give the weight fraction of asphalt oil in the mix. A specific example of the spreadsheet layout is given in Fig. 2.1; the data in this spreadsheet is taken from one of the data sets discussed in more detail below.

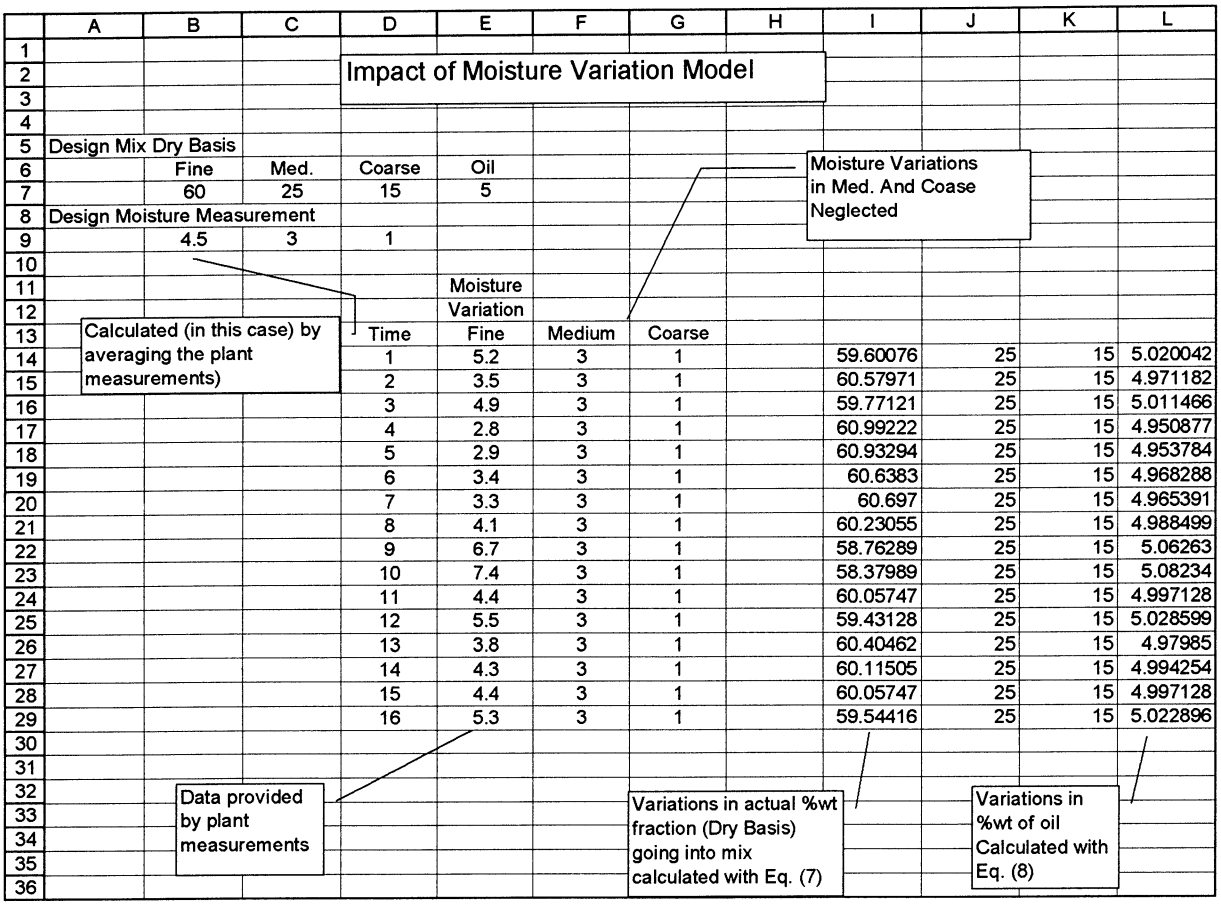

Figure 2.1: The spreadsheet model for assessment of moisture variations.

Field and Plant Measurements

Two sets of plant moisture measurements are used to investigate the impact of moisture variations. The first set is taken from field measurements made during Mn/ROAD construction [1]. The second set of measurements consisted of a sampling of various locations in the fine aggregate stockpile at the Maple Grove plant of Commercial Asphalt. The sampling of the fine aggregates stockpile was performed using a shovel. The shovel was used to dig 2 foot deep holes at eight evenly spaced locations around the base of the stockpile. The holes were dug approximately 3 feet above ground level, and were oriented parallel to the ground. The shovel

was then used to scoop aggregate material from the end of the hole. The extracted aggregate was then immediately placed in a sealed, plastic bag for storage. Following completion of the stockpile sampling, the sealed bags were brought back to the laboratory, where the moisture content was measured using the standard gravimetric method. Stockpile samples were taken on two occasions. The first sampling occurred on July 2, 1998, during a dry period. The second set of samples was taken on August 24, 1998, following a few days in which rain had fallen. The spatial moisture measurements from Commercial are given in Table 2.1 for the stockpile locations (1-8). In the spreadsheet model this data is treated as 16 separate entries, see Fig. 2.1. Further the data set can be extended by generating pseudo measured data based on a normal distribution with the mean = 4.5 and standard deviation 1.26 of the measured data, see Table 2.2.

The moisture measurements from the Mn/ROAD project are given in Table 2.3. The sample numbers (1-28) correspond to the time intervals at which samples were taken during the Mn/ROAD paving operation. These measurements are used directly in the spreadsheet model.

Table 2.1 Moisture measurements from commercial

Stockpile Location	Moisture Content (% weight)	
	July 2, 1998	August 24, 1998
1	5.2	6.7
2	3.5	7.4
3	4.9	4.4
4	2.8	5.5
5	2.9	3.8
6	3.4	4.3
7	3.3	4.4
8	4.1	5.3
Mean (all 16) = 4.5, std = 1.26		

Table 2.2 Pseudo moisture data generated from Table 2.1

Mean = 4.5, std =1.26	
Sample	Moisture Content %(wt)
17	4.2
18	2.6
19	8.3
20	4.3
21	5.6
22	4.5
23	3.2
24	4.9
25	3.6
26	4.5
27	5.8
28	4.0
29	3.8
30	4.2
31	3.1
32	6.1
33	3.9
34	4.9
35	5.4
36	2.7
37	3.9
38	3.3
39	4.4
40	4.7
41	3.9
42	3.7
43	3.0
44	5.4
45	4.9
46	5.8
47	5.0
48	4.6
49	6.4
50	2.0

The Effect of Moisture Fluctuations

The data in Tables 2.1 and 2.2 is used in the spreadsheet model, Fig. 2.1, to assess the effect of moisture fluctuations in the fine aggregate on the actual weight fraction of asphalt added to the asphalt mix.

Table 2.3 Moisture measurements from Mn/ROAD [1]

Time	%Moisture in fines
1	6.38
2	6.22
3	5.80
4	6.04
5	6.07
6	5.93
7	6.18
8	5.66
9	5.71
10	5.55
11	5.42
12	6.32
13	6.06
14	5.93
15	5.91
16	5.95
17	6.68
18	6.20
19	5.96
20	6.38
21	6.40
22	6.38
23	6.60
24	6.25
25	6.00
26	6.60
27	6.52
28	6.72
	Mean = 6.14, std = 0.335

Figure 2.2. shows the moisture variations in the fine aggregate stockpile. The first 16 points are measured the later points are generated. Figure 2.3 shows the resulting variations in the oil content calculated with the spreadsheet in Figure 2.1. Figure 2.4 shows the variations in the asphalt oil content for the Mn\ROAD Data in Table 2.

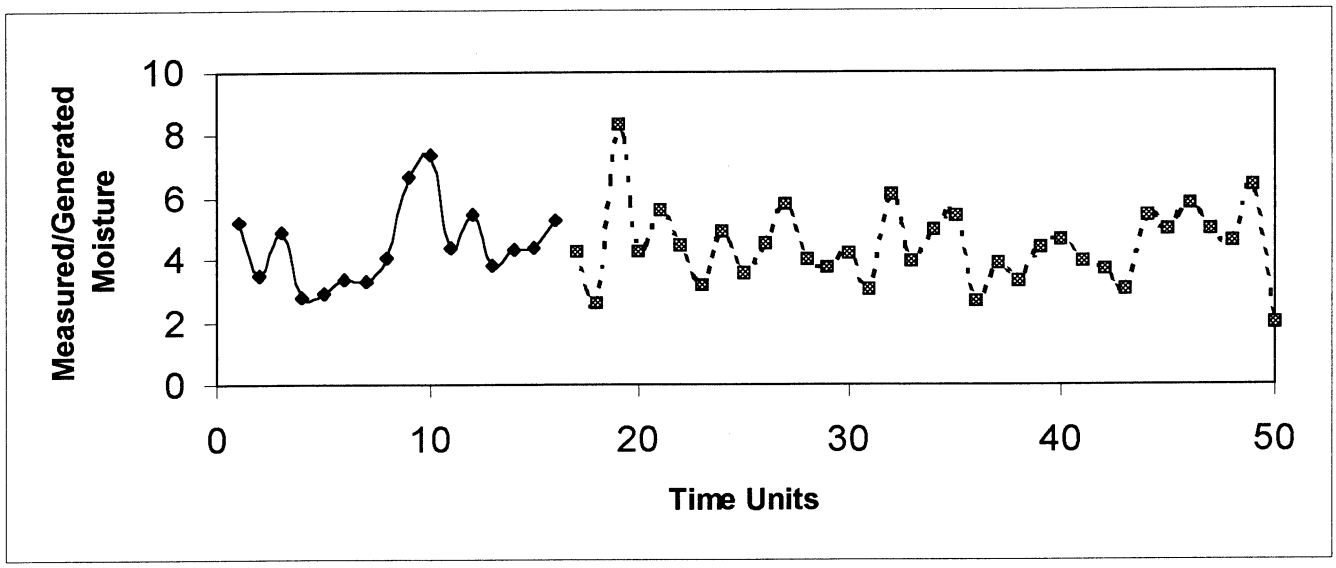

Figure 2.2: Fine aggregate moisture data from the Commercial plant.
(The first 16 points are measured the later points are generated)

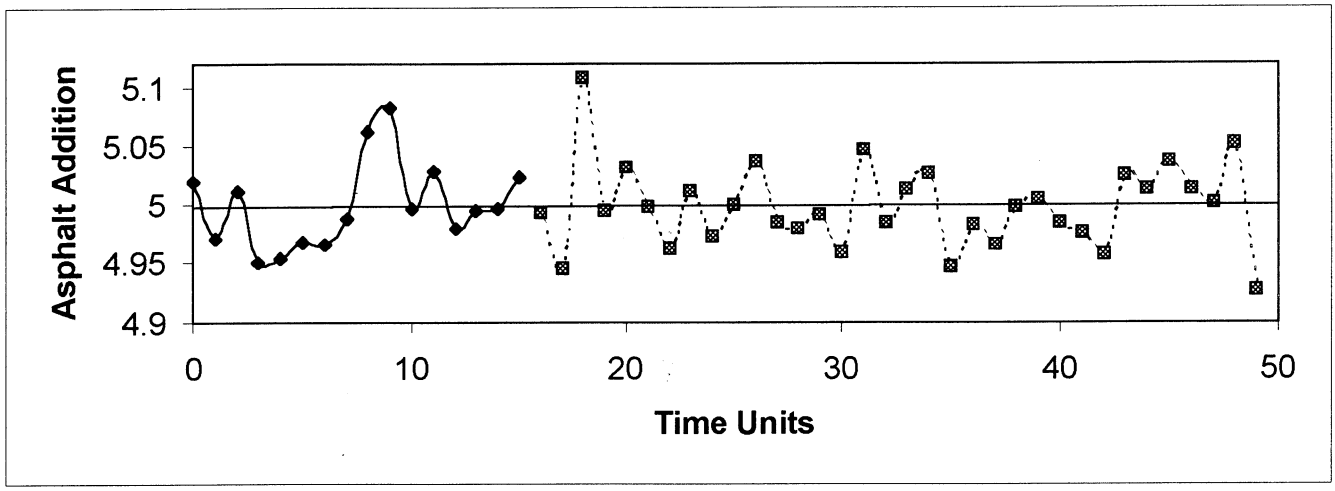

Figure 2.3: Changes in asphalt oil additions based on moisture measurements in Fig. 2.2

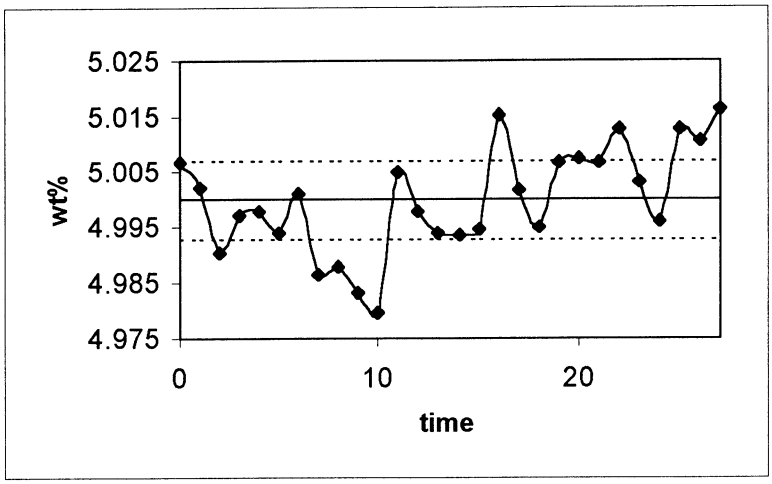

Figure 2.4: Asphalt wt% variations from spreadsheet model for Mn/ROAD data.

Discussion

The ideal plant performance would be a constant value of asphalt oil addition of 5 wt%. Asphalt Variations for the Commercial are larger. It is stressed in this case, however, that this is an imaginary paving operation in which the mix design is based on a single averaged moisture measurement of the stockpile. Thus this represents a worse case scenario. In practice it would be expected that a stockpile moisture measurement would be made on a daily basis, especially after heavy rain. In the case of the Mn/ROAD data, Figure 2.4, wt% variations in the asphalt oil added to the mix can be considered small. It has been observed, however, that quality factors such as void ratio were influenced by the amount of asphalt in the mix [1].

Summary

The effect of moisture on the proportions in an aggregate mix design has been quantified. A spread sheet simulation, based on measured data, indicates that typical moisture fluctuations in a plant can lead to a poor proportion of asphalt oil in the mix which in turn can lead to poor

pavement performance. The intent of this work is to show that if the moisture in the aggregate feed can be rapidly and accurately measured at regular intervals an improved mix performance in terms of oil addition can be achieved.

In the next chapter potential means of measuring the moisture in aggregate materials are reviewed and a commercial capacitance probe that can work in the conditions of a hot mix plant is highlighted. Subsequent chapters will examine the laboratory and plant use of this probe leading the way towards a potential control strategy for the asphalt oil additions.

CHAPTER 3

METHODS FOR MEASURING MOISTURE IN GRANULAR MATERIALS

Introduction

The determination of the moisture content of granular materials is necessary for many applications. These applications include but are not limited to soil moisture measurements, profiling of seawater intrusion into groundwater, as well as many process control designs. The focus of this work will be moisture measurement techniques that can be used in asphalt mixing plants. In first place the direct gravimetric measurement approach will be described. Subsequently indirect methods based on the electromagnetic properties media will be discussed in detail.

Direct Method—Gravimetric Measurement

The gravimetric method of moisture measurement consists of directly weighing the dry mass and water mass present in a sample of material. Mass of water present in a sample is determined through evaporation upon heating, either in a conventional oven or in a microwave oven. ASTM standardized techniques for these measurements have been established [3,4]. Both methods involve the heating of the sample to approximately 105° C until the measured mass of the "dry" sample is nearly constant. Moisture content is defined as the mass of evaporated water (and other volatiles) divided by the mass of the oven-dried sample. This definition may be expressed as

$$\theta = [(M_{cws} - M_{cs}) / (M_{cs} - M_c)] * 100 = M_w / M_s * 100$$

where θ = water content, %

M_{cws} = mass of container and wet specimen, g

M_{cs} = mass of container and oven dry specimen, g

M_c = mass of container, g

M_w = mass of water, g

and M_s = mass of solid particles, g

Although water content is represented by w in the above equation, the symbol θ is most often used for this purpose, and will have the same meaning throughout this report. In this chapter the symbols θ_g and θ_v are representative of the weight and volume basis water contents, respectively.

The gravimetric method is inexpensive and fairly simple to perform. In addition, it is the most accurate method of soil (and other porous media) water content measurement. However, it is destructive to the material being sampled, and may not be well suited for continuous monitoring of moisture content. Therefore, its usefulness is usually limited to the calibration and validation of indirect methods.

Indirect Methods—Electromagnetic Techniques

Introduction

The majority of field techniques that are used today rely on the electromagnetic properties of the medium in the determination of moisture measurements. Because the electromagnetic properties of water are very different from those of its porous matrix (usually soil or other non-magnetic

solids), the electromagnetic properties of the medium as a whole depend primarily on the moisture content. Methods of these types may utilize transmission of electromagnetic waves, such as in the case of time domain reflectometry (TDR), capacitance probes, active microwave scattering methods, and ground-penetrating radar (GPR). Other apparatus consist of probes or arrays of probes, such as resistivity measurement systems.

Theory

Determination of moisture content through electromagnetic measurements almost always relies, either directly or indirectly, on the relative electric permittivity, given by the dielectric constant ε, of the material. The dielectric constant of a material arises from its polarization or electric dipole moment per unit volume. This property is frequency dependent and takes on complex values. Common notation for ε is

$$\varepsilon(\omega) = \varepsilon_r(\omega) \pm j\varepsilon_i(\omega) \tag{3.1}$$

where ε_r and ε_i refer to the real (polarization or capacitance) and imaginary (resistivity) parts of the dielectric constant, respectively, ω is the angular frequency of electromagnetic radiation, and j is the square root of -1. For most materials, $\varepsilon \approx \varepsilon_r$ [5]. However, an apparent dielectric constant (ε_a) is measured by most moisture measurement techniques; in such cases, $\varepsilon_a = \varepsilon \approx \varepsilon_r$. Furthermore, ε_r provides a measure of the energy stored by the dipoles aligned in an applied electromagnetic field. It is also proportional to the square of the index of refraction of the material, the polarization of the material, as well as its capacitance. The complex dielectric component ε_i is related to the energy dissipation rate in the medium, as well as the resistivity of the material. It is also more dependent on and sensitive to parameters such as ion concentrations. In fact, the conductivity is related to imaginary component ε_i by the equation

$$\sigma = \varepsilon_o \varepsilon_i \omega \tag{3.2}$$

where ε_o is the permittivity of free space [6]. However, contributions of ionic conductivity (including salinity) are minimized at higher frequencies.

The frequency dependence of the dielectric constant of a material is related to the relaxation frequency, ω_r, of the medium. This characteristic frequency usually lies somewhere in the microwave range [7]. In addition, ω_r^{-1} is the time constant for decay of polarization upon the removal of an electric field. The real part of the dielectric constant, ε_r, is approximately constant at frequencies ranging from 0 to ω_r, above which it decreases in magnitude until it becomes constant again in the visible region of the electromagnetic spectrum. It is also equivalent to the index of refraction of the medium squared [7]. The decrease in the magnitude of ε_r occurs because, at frequencies surpassing ω_r, dipoles present in the material cannot follow the electric field, resulting in a decreased ability of the medium to store electric field energy. The imaginary part, ε_i, peaks in magnitude at ω_r, decreasing at higher frequencies due to permanent dipoles present in the medium [7].

The dielectric constant is also dependent on the moisture content of the material. For example, typical values for ω_r are approximately 18 GHz for pure water and 1 GHz for soils. The lower relaxation frequency in soils is due to the binding of water molecules to soil particles. However, as the moisture content rises to and exceeds a transition point θ_τ, the binding of water molecules to soil particles decreases enough so that the entrapped water behaves like a free liquid. This phenomenon results in a higher slope in the ε vs. θ curve.

Several researchers have studied the relationship between ε and θ in moist porous media. Their research has yielded more than a few relationships between relative permittivity (dielectric constant) and moisture content (θ). Perhaps the most popular of these empirical relationships is the one developed by Topp et al. [8,9] for use with their time-domain reflectometry (TDR) measurements, which is

$$\theta_v = -5.3 \times 10^{-2} + 2.92 \times 10^{-2} \varepsilon_a - 5.5 \times 10^{-4} \varepsilon_a^2 + 4.3 \times 10^{-6} \varepsilon_a^3 \qquad (3.3)$$

where θ_v is the volumetric water content and ε_a is the apparent dielectric constant.

Written in another form, this relationship is [10]

$$\varepsilon_r = 3.03 + 9.3\,\theta + 146\,\theta^2 - 76.7\,\theta^3 \qquad (3.4)$$

where ε_r is the real part of the complex dielectric constant. These expressions have been found to be in good agreement for a water content range of $\theta = 0.02 \sim 0.4$ [11]

The relative permittivity or dielectric constant is related to the capacitance of the material through the relation [12]

$$C = g\varepsilon \qquad (3.5)$$

where g is a geometrical constant, which is determined by the form of the capacitor. For the case of a parallel-plate capacitor,

$$g = \varepsilon_o a/d \qquad (3.6)$$

while for a coaxial capacitor,

$$g = (2\pi\varepsilon_o L) / \ln(b/a) \qquad (3.7)$$

where a, b, and L are dimensional constants related to the geometry of the capacitor.

Microwave Absorption

Microwave radiation lies in the region of the electromagnetic spectrum with wavelengths ranging from 1 mm to 1 m (300 MHz to 300 GHz). Water absorbs this type of electromagnetic wave to a much greater extent than most materials [13]. The optimum wavelength for absorption is 1.3 cm, but the two common wavelengths utilized at this time are 3 cm and 10 cm. These are also effective because of the large absorption band of water in the microwave region.

Microwave energy is commonly transmitted through the sample material while the absorption or attenuation of the energy is measured. Electrolytes cause little inaccuracy with wavelengths of 3 cm or less [13], but their conductivity may affect the derived moisture measurement with longer wavelengths. Such measurement systems have been used on many types of granular solids, although continuous in-line measurements are only accurate up to 45% moisture [13].

Near Infra-Red (NIR) Absorption

This technique is very similar in principle to the microwave absorption method just described. In this case, near infra-red radiation is applied to the sample, and the attenuation of the energy at wavelengths of 1.2, 1.43, 1.94, and/or 2.95 μm is compared to a reference wavelength (one not absorbed by water) such as 1.7 μm [13]. The relative attenuation of such energy at the absorption band frequencies of water provides an indication of the moisture content of the sample.

The NIR radiation may be transmitted through or reflected from the material sample. However, penetration is limited to short distances because of the high attenuation of infrared energy (the

magnitude of which depends on the material). Therefore, it is only practical to use NIR transmission when a thin sample of moist material is present.

Ground Penetrating Radar (GPR)

Ground-penetrating radar methods utilize the transmission or reflection of electromagnetic waves in a studied medium to determine the moisture content of that medium. This method of moisture measurement is approximately 30 years old [14].

Depth of penetration, as well as resolution, is determined by the conductivity of the medium. In a material such as peat, the attenuation of a GPR signal occurs as

$$A = A_o e^{-\alpha z} \tag{3.8}$$

$$\alpha = (\sigma/2)*\sqrt{(\mu/\varepsilon)} \tag{3.9}$$

where z is the distance traveled, σ is the conductivity of the medium, μ is the magnetic permeability, ε is the relative permittivity (apparent dielectric constant), and A is the amplitude of the signal [14]. The attenuation of the GPR signal also increases with increasing antenna frequency [15].

The velocity of the propagating GPR transmission is

$$v = 1 / \sqrt{(\mu\varepsilon)} \tag{3.10}$$

A typical velocity assumption for water-saturated sediments is 0.07 m/s [15]. However, this is a fairly low value in practice, and calibration may be needed. The velocity of the GPR signal is needed in order to calculate the transmission depth or distance when these conditions are important.

Resistance Probes

Resistance or resistivity probes usually consist of an array of electrodes, which are inserted into the sample medium. A current (either AC or DC) is applied to one or more of the electrodes and, after equilibrium occurs, the voltage or potential between each of the other electrodes is calculated. This potential is a function of the resistance of the material between the electrodes, which in turn is a function of the water content of the medium. In fact, this resistance is a function of porosity, pore water saturation, and the electrical resistivity of the pore water, which is itself dependent on the presence of dissolved free ions [16]. Because it has been established that there is an inverse relationship between resistivity (and therefore resistance) and water content [17] the moisture content of the medium may thus be determined.

Another type of resistance measurement method is the electrical resistance block. In this scenario, a "block" containing a fabricated porous material (gypsum and/or nylon), several electrodes, and a chemical buffer is inserted into the sampled material. Such a device [18] allows the matric potential of the surrounding material to come to equilibrium with the internal porous material through perforated plastic tubes. The chemical buffer offsets the effects of salinity on the resistance reading.

The major drawback to the probe/array resistance method is the fact that aggregate properties such as resistivity and resistance are not well understood, and their relationship to moisture content is empirical and uncertain [17], especially for unsaturated conditions. In fact, the only porous media for which a good relationship has been established between resistivity and moisture content is clean sand [19]. Also, calibration is required to determine quantitatively the

moisture content of a sample material. Finally, because the resistance of ice is very large, the resistance method measures only the liquid phase moisture content of a material.

Time Domain Reflectometry (TDR)

Time domain reflectometry (TDR) was first studied around 1980 [5]. It usually involves the transmission of electromagnetic waves along a shielded coaxial cable that acts as a wave-guide. Changes in the dielectric constant of the surrounding material create reflections or loss points of the transmitted wave. These effects on the TDR signal are then recorded by a readout unit, which receives the returning wave. Loss points register as a slope change in the pulse wave [16]. The velocity of the wave through the cable is a function of the dielectric property of the surrounding material. Because the phase velocity of the wave(s) may be known through the TDR readout instrumentation, the dielectric constant of the probed material may be determined through analysis of a graphical readout [16]. However, an even simpler determination of the dielectric constant is possible due to the following relationship between dielectric and travel time:

$$\varepsilon_a = \sqrt{(ct/L)} \qquad (3.10)$$

where c is the speed of light, t is the observed travel time of the signal, and L is the path length of the TDR probe [20].

As is the case with all moisture measurement methods, TDR techniques have some drawbacks. One of these is a tendency towards an overestimation error when iron minerals such as magnetite, hematite, or goethite are present [21].

Capacitance Probes

Because the (apparent) dielectric constant of dry aggregate (or other dry materials) ranges from 2 to 5 while that of water is approximately 80, the presence of water in a material will greatly influence the bulk relative permittivity of that material. Therefore, capacitance meters have been developed which measure the capacitance of the surrounding material. Furthermore, the fact that the capacitance of the medium is directly proportional to its measured (real) dielectric constant results in a linear relationship between observed values of C and ε_a. Because of the relationship between capacitance and dielectric constant, the moisture content may be determined indirectly through this method.

Most capacitance meters consist of two electrodes housed within an access tube or probe which act as two sides of a capacitor across which is applied an electric (usually alternating) field. Often, a capacitance probe will also house a circuit board. The electronic system is designed such that the resulting frequency of the output is a function of the capacitance of the unknown medium (aggregate, soil, etc.). Therefore, observation of the output frequency allows the experimenter to calculate the capacitance of the measured sample volume [12]. However, the output frequency is a function of the molecules' freedom to respond to the electromagnetic input. This freedom of response is a function of not only the complex relative permittivity of the molecules but also of local molecular binding forces, molecular inertia, other binding forces, as well as the frequency of the applied electric field [12]. Furthermore, it has been found that frequencies above 30 MHz are better suited to this application. This is because the relaxation frequency, ω_r, of the macroscopic dipoles associated with interfacial polarization in heterogeneous materials is approximately 27 MHz [12]. The use of frequencies above this level

prevents those dipoles from responding significantly to the applied field and contributing to the measured apparent dielectric constant.

A calibration procedure is also needed for capacitance methods. A standardized field and laboratory calibration procedure has been established for the Sentry 200-AP device [2,22]. In this case the laboratory calibration is required when samples do not have at least a 15 % variation in moisture content.

There are a few sources of error that must be accounted for when applying capacitance techniques to a sample material. For instance, the conductivity of the test material is important for frequencies below 10 GHz [13]. At these frequencies, increased conductivity of the material limits the range and upper moisture limit of the measurement. Therefore, the presence of electrolytes within the material will influence the measurement. Furthermore, the presence of iron minerals such as magnetite, as in the case of TDR, will cause an overestimation of the real dielectric constant ε_a [21]. Also, because the dielectric constant is also a function of temperature, some compensation for the material temperature must be made. Finally, the packing density of granular materials such as aggregate, especially around instrument electrodes, is very important. The presence of air gaps near a capacitance probe may greatly affect the measured value of the capacitance [12].

Summary

In this chapter a range of moisture measurement techniques and the associated theory have been reviewed. In the remaining part of this work a capacitance probe, the Troxler Sentry 200-AP

device will be calibrated and tested extensively for use in measuring moisture in aggregate stockpiles and bins. This probe is chosen because

1. It was readily available through a loan from the Troxler company [2].
2. It has been used with success, in previous road construction projects, by other researchers [22].
3. It is used in plant environments, e.g., Portland concrete plants, where environmental conditions match those found in an asphalt concrete plant.

Throughout the testing with this probe benchmarking and calibration will be achieved by using ASTM gravimetric techniques [3,4]. The laboratory calibration and laboratory testing of the probe is reported in the nest chapter.

CHAPTER 4

LABOATORY TESTING

Introduction

The objective in this chapter is to report on laboratory tests that were performed to investigate and calibrate the performance of the Troxler Sentry 200-CP Probe in predicting the moisture contents of fine aggregates. There are three main parts

1. A description of the approach used to obtain a baseline gravimetric measurement.
2. A calibration of the Troxler probe for a range of aggregates at different levels of moisture.
3. An assessment of the use of the possible use of the probe in the field via a simulation.

Sample Handling

Two main sample sources for fine aggregates were used.

Commercial (June-September 1998)

Samples of fine aggregate were obtained from Commercial Asphalt (Maple Grove plant) and placed in 35-gallon plastic barrels for storage. The material for all samples was taken from a point approximately 5 feet above ground on the eastern side of Commercial Asphalt's fine aggregate stockpile. The containers of aggregate were covered when not in use, and mixed by hand, in a wheelbarrow within, 24 hours of any measurements. After the entire contents of the barrel had been placed and mixed in the wheelbarrow, the aggregate was returned to the barrel again. Dry aggregate was also recycled after each gravitational measurement. This fine aggregate was emptied onto the material surfaces of the barrels after any set of measurements.

When mixing of the samples was performed, the dried material was then mixed into the moist aggregate. In some instances distilled water was added to maintain the moisture level of the sample.

Midwest (June-Sep 1999)

Samples from Midwest asphalt's New Brighton plant were collected and stored in a similar manner. Samples were taken from the fine aggregate stockpile had the designator 5/16" Sand Elk River, the gradation is given in Table 4.1.

Table 4.1 Gradation of 5/16" sand Elk River from Midwest

Mesh	Passing
1 1/2"	100
1"	100
3/4"	100
5/8"	100
1/2"	100
3/8"	100
#4	94.1
#8	85.7
#10	81.2
#16	76.4
#30	58.9
#40	42
#50	28.9
#100	9.6
#200	5.3

In comparison to the Commercial samples there were some important differences in storage and handling for the Midwest samples, in particular

1. Samples were conditioned with distilled water throughout the process so that a range of moisture levels (~2% to ~10%) was maintained.
2. Before each measurement the barrel sample was mixed in a cement mixer. Two mix times of 1.5 and 10 minutes were used.

Measurement And Calibration

Probe Measurements

Each Troxler probe measurement followed a standard procedure. A scoop was used to dig a hole approximately 1 m deep in the subject aggregate barrel. The Sentry probe was then placed in the hole such that the bottom tip of the probe was firmly contacting the bottom of the hole. The probe was adjusted until it was oriented vertically. The scoop was then used to back-fill the hole surrounding the probe. Aggregate material from the wall of the hole was used as filler first, in order to maintain a homogeneous radial moisture profile and to preserve the accuracy of the measurement. Back filling continued, working away from the probe as little as possible, until aggregate material reached the bottom of the narrowed metallic probe head. Once this was accomplished, gentle packing of the backfill material was performed using the scoop. The Troxler measurements in terms of counts, D, read from directly from the print out are given in Table 4.2. The method for converting these count values to %wt moisture values is discussed in detail below.

Baseline Gravimetric Measurements

A baseline measurement was obtained for each Troxler probe measurement. Material for providing baseline gravimetric measurements were obtained in the following fashion: Most of the material removed from the probe sample holes (all but the first 2 or 3 scoops) was used.

Table 4.2 Raw count data from Troxler probe

Commercial Hand Mix	Midwest 1.5 min. Mix	Midwest 10 min. Mix
4971	5172	5256
4979	5258	5257
5004	5299	5308
5024	5303	5362
5033	5310	5387
5039	5349	5451
5259	5375	5507
5359	5407	5508
5365		5550
5534		5556
		5573
		5575
		5576
		5579
		5613
		5664

The gravimetric measurement procedure commenced following the probe reading, never more than 5 minutes later. Metallic trays were used to hold all gravimetric measurement samples. Before use these trays were cleaned with tap water and dried in the oven. In preparation for sampling, the trays were removed from the oven and allowed to cool until they could be handled with bare hands. A dry paper towel was used to remove any remaining dry material from the trays. Following cleaning, the trays were weighed on a scale in the lab. The weights and descriptions of each tray were recorded. Immediately following the probe sample, the aggregate was placed into the trays and weighed again. The weights of the trays and material were recorded, and the trays were placed in the laboratory oven. The laboratory procedure follows the steps described by ASTM Standard D 2216 – 92 where applicable. However, for practicality smaller ample sizes of 0.8 kg to 2.2 kg were used. When complete drying occurred the water content (% wt) of the sample material was calculated as follows:

$$\theta = [(M_{cws} - M_{cs})/(M_{cs} - M_c)] \times 100 = (M_w/M_s) \times 100$$

where:

M_{cws} = mass of container and wet specimen, g,

M_{cs} = mass of container and oven dry specimen, g,

M_c = mass of container, g,

M_w = mass of water, g, and

M_s = mass of solid particles, g.

Gravimetric moisture values corresponding to each of the data points in Table 4.2 are given in Table 4.3.

Table 4.3 Base-line gravimetric moisture measurements

Commercial Hand Mix	Midwest 1.5 min. Mix	Midwest 10 min. Mix
2.10	7.08	6.83
2.60	7.41	6.42
3.03	9.25	6.86
3.39	7.31	6.88
3.11	7.34	8.51
2.99	9.03	7.29
5.28	9.03	8.73
5.86	8.92	9.12
6.41		8.84
4.97		8.73
		8.84
		9.12
		8.63
		9.06
		9.80
		9.01

Calibration Of The Troxler Probe

The Troxler probe measures the frequency difference for a given moisture count D. Before shipping this measurement has been calibrated against %wt moisture, M, in the factory using the following curve fit

$$D = C_0 e^{C_1 M} + C_2 \tag{4.1}$$

or its inverse

$$M = \frac{\ln\left[\frac{D - C_2}{C_0}\right]}{C_1} \tag{4.2}$$

The calibration for the probe used in this study is given in Table 4.4.

Table 4.4: Troxler calibration constants see Eq. (4.1)

	C_o	C_1	C_2
Factory	-4251.5506	-0.04250	8641.0356
Commercial	-4251.5506	-0.05145	8641.0356
Midwest	-4251.5506	-0.03610	8641.0356

The factory calibration is carried out with sand and goes up to moisture contents of 15 %wt. A re-calibration can be readily achieved on setting up the appropriate Trxoler software and carrying out a minimum of three measurements, using gravimetric measurements as a base line. The alternative, used in this work, is to adjust the constants, C_0, C_1 and C_2, until, for all the available data, a "best" fit between the Probe measurements, calculated using Eq. (4.2) from the count data in Table 4.2, and the base line gravimetric measurements (Table 4.3) is achieved. A study of Eq. (4.1) or Eq. (4.2) indicates that values are most sensitive to the value of the C_1 constant. As a result a good calibration can be achieved by only changing this number and keeping the other

values fixed at the factory settings, see Table 4.4. In this way a calibration for each data sets in Table 4.2 and 4.3 is stated as

Find C_1 such that

$$\sum_{\text{measurements}} \left| M_{\text{Table 4.3}} - M_{\text{Eq.4.2,Table 4.2}} \right| = \text{minium} \qquad (4.3)$$

where the L1 norm (absolute difference) is used to down play the influence of outliers. In words change the value of C_1 in Table 4.4 until the sum of the absolute differences between the measured gravimetric moisture (Table 4.3) and the moisture calculated with the D count (Table 4.2) in Eq. (4.2) is a minimum.

Since two sources of aggregate are used in the study—Commercial and Midwest—two separate calibrations are carried out. The calibration for commercial uses the data in the first columns of Table 4.2 and Table 4.3. The calibration for the Midwest only uses the 10-minute mix data in column 3 of Table 4.2 and 4.3. The resulting calibrations are given in Table 4.4

Results

The results, probe moisture measurements (%wt) compared with the gravimetric measurements, are given in Table 4.5. The population standard deviations and means of the differences between the oven and probe measurements are given in Table 4.6. A scatter plot, of all the data, is given in Figure 4.1. The Midwest results for the 1.5-minute mix time are skewed due to the fact that the calibration use in the probe is based on the 10 minute mix time. These results clearly show that, if a well-mixed sample is used, the Troxler probe will match oven measurements of moisture to within 0.5 wt%.

Table 4.5 Gravity vs. probe moisture measurements

Grav.	Probe	Error
Commercial		
2.10	2.86	-0.76
2.60	2.90	-0.30
3.03	3.03	0.00
3.39	3.14	0.24
3.11	3.19	-0.08
2.99	3.22	-0.23
5.28	4.45	0.83
5.86	5.03	0.83
6.41	5.07	1.34
4.97	6.10	-1.12
Midwest 1.5 min. mix		
7.08	5.64	1.44
7.41	6.33	1.07
9.25	6.67	2.58
7.31	6.71	0.60
7.34	6.76	0.57
9.03	7.09	1.94
9.03	7.31	1.72
8.92	7.58	1.33
Midwest 10 min. mix		
6.83	6.32	0.51
6.42	6.33	0.09
6.86	6.75	0.11
6.88	7.20	-0.32
8.51	7.41	1.09
7.29	7.96	-0.67
8.73	8.45	0.28
9.12	8.46	0.65
8.84	8.84	0.00
8.73	8.89	-0.16
8.84	9.04	-0.21
9.12	9.06	0.06
8.63	9.07	-0.44
9.06	9.10	-0.04
9.80	9.41	0.39
9.01	9.88	-0.87

Table 4.6. Standard deviation and mean of differences between oven and probe measurement

Aggregate	STD	Mean
Commercial	0.63	0.2078
MW 1.5 Mix	0.68	1.407
MW 10 Mix	0.48	0.03

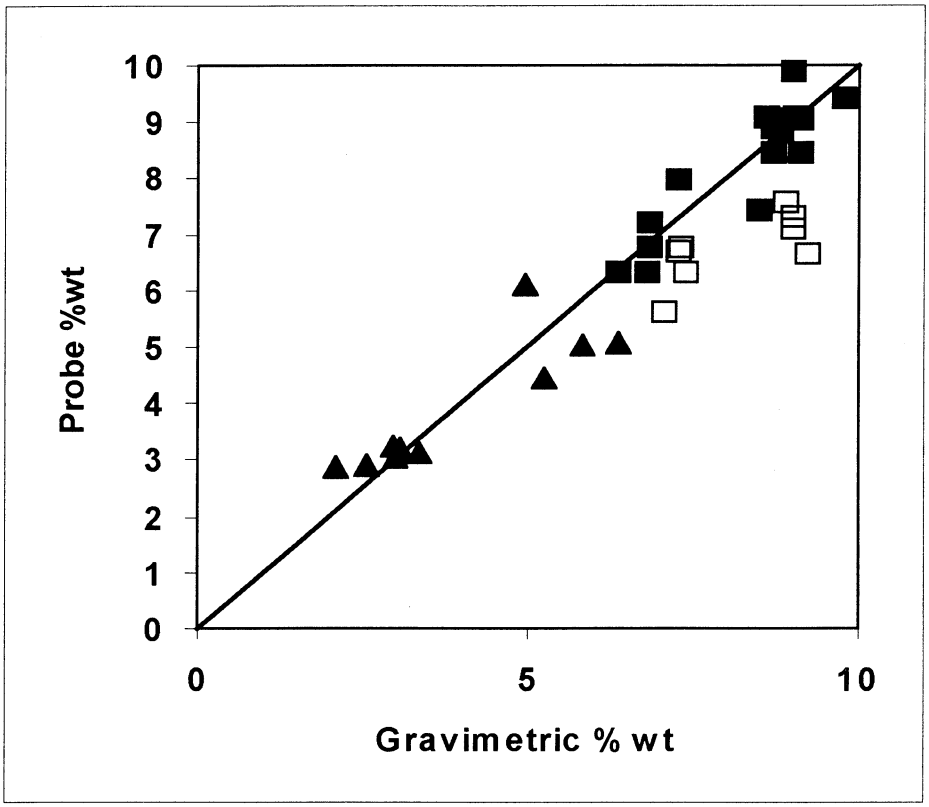

Figure 4.1: Scatter plot of probe vs. gravimetric.

The solid triangles are commercial; the solid squares are the 10 min. mix Midwest samples the open squares the 1.5 min. mix samples

Plant Simulation

If the previous section it was shown that, in the libratory, the Troxler probe can predict to within 0.5 wt% of the moisture predicted with the oven measurement. The question that follows from this is. If this level of accuracy can be archived in the field what advantage would this have? This question can be answered using simulation.

Assume a mix design of 60% fine, 25 % medium and 15% coarse aggregates, with a 5% by dry weight of aggregate asphalt oil addition. At the start of a given pavement operation the moisture levels (%wt) in the aggregates are 4.5%, 3% and 1% respectively. Further assume as the paving operation continues the moisture in the medium and coarse aggregates remains fixed but the moisture in the fine aggregate fluctuates with time. A sin wave with "jumps"—to simulate rapid drying and wetting events is chosen as an appropriate test signal for the moisture fluctuations, see Figure 4.2.

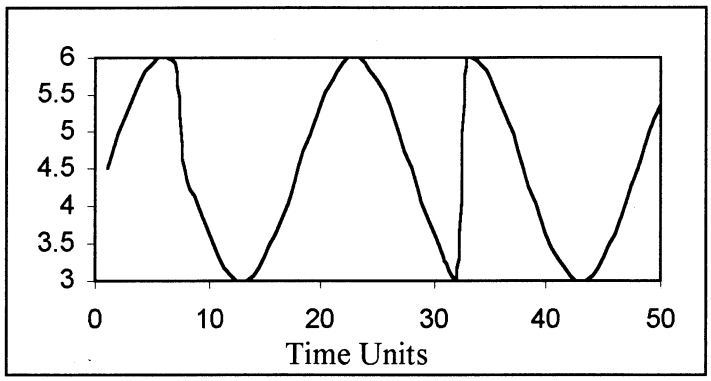

Figure 4.2: Test signal for moisture fluctuations in the fine aggregate.

With this moisture signal, retrieving equations from chapter 2, and the actual asphalt oil content, in terms of the designed content, in the mix will be

$$\theta_{OIL}^{A} = \text{factor} * \theta_{OIL}^{DES.} \tag{4.4}$$

The factor of excess or deficiency of the asphalt oil addition is given by

$$\text{factor} = \frac{W_{FDRY} + W_{MDRY} + W_{CDRY}}{W_{FDRY}^{A} + W_{MDRY} + W_{CDRY}} \tag{4.5}$$

where W_{FDRY} is the designed weight fine weight fraction and W^{A}_{FDRY} is the actual dry weight fraction. If no correction, based on a moisture measurement, is made then fluctuations in the asphalt oil addition will trace the fluctuations in the moisture content of the fine aggregate (Fig. 4.2), see the continuous line in Figure 4.3. If on the other hand the Troxler probe is used to continually measure the moisture fraction θ_F^M (wt%) and corrective action is taken by resetting the fine aggregate feed rate to

$$W_F = (1 + \frac{\theta_F^M}{100}) W_{FDRY} \tag{4.6}$$

the fluctuations in the asphalt oil additions are reduced; see the dashed lines in Figure 4.3. Fluctuations still occur when the Troxler probe is used because in our simulation a normally distributed measurement error (difference between probe and actual) with standard deviation 0.48 has been used. The choice of $\sigma = 0.48$ is based on the laboratory results, see Table 4.6., during the simulation the error is assigned by randomly selecting from the normal population of mean zero and standard deviation $\sigma = 0.48$. The appropriate Excel equation is

$$\theta^M = \theta^A + \text{NORMINV(RAND(),0,0.48)} \tag{4.7}$$

where θ^A is the actual moisture obtained from the assumed moisture variation (Fig. 4.2) and NORMINV and RAND() are standard Microsoft Excel functions. In this way a repeat of the simulation across the 50-time unit domain will result in a different prediction for the asphalt oil.

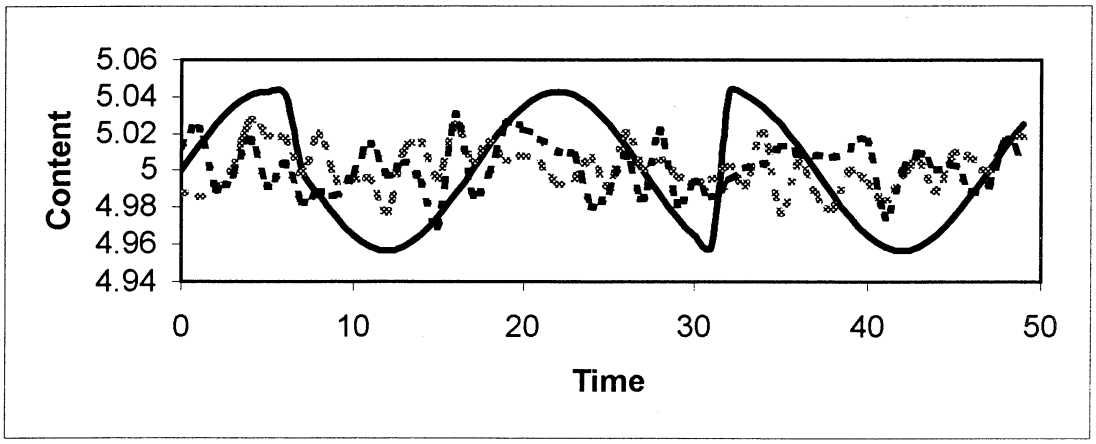

Figure 4.3: Simulation of asphalt oil fluctuations.
The continuous line is when no moisture correction is made. The dashed lines are simulations where a correction is made.

fluctuations based on probe moisture measurements. This is illustrated in Figure 4.3 by showing two realizations (runs) of the simulation.

The plot in Fig. 4.3 provides a qualitative indication as to how the Troxler probe can limit the flu cautions of asphalt oil addition. A quantitative measure is obtained on calculating the integral (a trapezoidal numerical scheme at each time unit works well)

$$E = \int_0^{t_{final}} \left| 5 - \theta^A \right| dt \qquad (4.8)$$

This measure has a value of E = 1.32 when no moisture correction is made and a value of E ~ 0.5 (100 realizations). Hence there is clear evidence that if the Probe can perform in the field at the level seen in the laboratory it could prove to be an effective device for controlling the asphalt oil addition to the mix.

Summary

This chapter has presented results that establish that the Troxler CP 200 probe can be used to measure moisture content of fine aggregates within a degree of accuracy that will allow for in plant applications. The next chapter presents results of plant trials.

CHAPTER 5

PLANT TESTING

Introduction

Previous parts of the study have identified the Troxler CP200 probe as the best candidate for tracking the moisture variations in aggregate stockpiles in an asphalt concrete plant. The final phase of the project is the field-testing of this probe. Extensive field-testing over the 1999 and 2000 construction season was undertaken at Midwest asphalt's New Brighton facility. This involved three main study areas

1. Testing of the probe in determining the moisture in the fine sand aggregate stockpile.
2. Development of a plant testing strategy.
3. Development of plant control guidelines.

Measurement of Moisture in the Stock Pile

Sampling Method

Over a number of weeks the probe was tested in the fine sand stockpile at Midwest. Probe measurement were taken by first creating a sufficiently large and horizontal area in the stockpile. An in-place probe D count measurement was then made following, as closely as possible the laboratory procedure outlined in Chapter 4. Probe measurements were compared with a gravimetric measurement of the material taken from the base of the test hole; which had a typical depth of 0.3 to 0.5 m. The gravimetric testing was also done in the plant. The typical plant practice of drying the sample for one hour was followed. It was found that, due to local

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Center measurement: a single measurement at the center of the triangle.

Vertex Average: measurements at the vertices of the triangle averaged, into a single measurement.

Measurements

The raw data obtained with probe, in terms of counts, is given in Table 5.1. The corresponding moisture contents, obtained by using the data in Table 5.1 in the conversion equation

$$M = \frac{\ln\left[\frac{D - C_2}{C_0}\right]}{C_1} \qquad (5.1)$$

are given in Table 5.2 (Note the calibration constants used). The moisture contents obtained from the oven and gravimetric method using samples taken from the probe measurement holes are given in Table 5.3.

Table 5.1 Raw probe counts from fine stockpile

Vertex 1	Vertex 2	Vertex 3	Center
5174	5261	5155	5214
5138	5300	5263	5306
5402	5289	5279	5213
5210	5304	5296	5252
5152	5203	5275	5297
5335	5213	5221	5279
5224	5239	5136	5250
5203	5214	5256	5223
5238	5241	5146	5167
5371	5220	5284	5340
5332	5235	5271	5227
5216	5364	5141	5220
5156	5202	5156	5250
5168	5180	5121	5128
5213	5109	5269	5250
5248	5173	5159	5084
5124	5099	5057	5174
5077	5161	5079	5237

Table 5.2 Probe measured moisture contents (%wt) calculated with data in Table 5.1

Calibration values C_0 = -4251.551, C_1= -0.03379, C3 = 8641.036

Vertex1	Vertex2	Vertex3	Center
6.0	6.8	5.9	6.4
5.7	7.1	6.8	7.2
8.1	7.0	6.9	6.4
6.3	7.2	7.1	6.7
5.9	6.3	6.9	7.1
7.4	6.4	6.4	6.9
6.5	6.6	5.7	6.7
6.3	6.4	6.7	6.5
6.6	6.6	5.8	6.0
7.8	6.4	7.0	7.5
7.4	6.6	6.9	6.5
6.4	7.7	5.8	6.4
5.9	6.3	5.9	6.7
6.0	6.1	5.6	5.6
6.4	5.5	6.9	6.7
6.7	6.0	5.9	5.3
5.6	5.4	5.1	6.0
5.2	5.9	5.2	6.6

Table 5.3 Oven measured moisture contents (%wt)

Vertex1	Vertex2	Vertex3	Center
6.0	7.0	6.2	6.8
6.1	6.0	7.3	6.9
7.2	6.9	7.3	6.5
7.1	7.7	6.4	6.4
5.0	6.4	6.7	5.8
6.5	6.7	7.1	7.5
7.7	7.6	7.6	7.5
6.4	6.2	6.2	6.1
6.2	6.2	6.2	6.1
6.7	6.4	6.9	6.5
6.7	6.8	6.4	6.3
6.0	5.8	5.7	6.2
6.3	6.3	5.7	6.1
5.9	6.0	6.1	5.9
5.2	6.4	5.8	5.9
5.7	5.8	6.1	5.6
5.5	5.5	5.7	5.7
5.8	5.7	5.6	5.7

In Table 5.4 The average vertex moistures measurements, from the oven and the probe, are recorded along with the center measurements.

Comparisons

Figure 5.1 compares the oven center measurement against the oven-averaged measurements. This plot provides an indication of the natural level of variation in the stockpile over the triangular sampling region; the standard deviation (SD = 0.35%) of the difference between the

center and averaged measurements is recorded in the plot. Figure 5.2 compares the probe center measurement against the oven-averaged measurements; there is a reasonable high degree of

Table 5.4 Average and center moisture measurements for the probe and oven

Probe		Oven	
Average	Center	Average	Center
6.2	6.4	6.4	6.8
6.6	7.2	6.5	6.9
7.3	6.4	7.1	6.5
6.9	6.7	7.1	6.4
6.3	7.1	6.0	5.8
6.8	6.9	6.8	7.5
6.3	6.7	7.6	7.5
6.5	6.5	6.3	6.1
6.3	6.0	6.2	6.1
7.1	7.5	6.7	6.5
7.0	6.5	6.6	6.3
6.6	6.4	5.8	6.2
6.0	6.7	6.1	6.1
5.9	5.6	6.0	5.9
6.2	6.7	5.8	5.9
6.2	5.3	5.9	5.6
5.4	6.0	5.6	5.7
5.5	6.6	5.7	5.7

Scatter (SD = 0.6%) in this data. Figure 5.3 compares the probe-averaged measurements with the oven-averaged measurements. This plot indicates a reasonably close fit between the probe and oven measurements (SD = 0.44%). When seen in the light of the natural variation of stock pile moisture, see Fig 5.1, this comparison is excellent, clearly indicating that, if an appropriate averaging measurement strategy is employed and calibration is made, the Troxler probe is very effective at rapidly (~2 minute) determining accurate moisture contents (%wt) of aggregate stock piles.

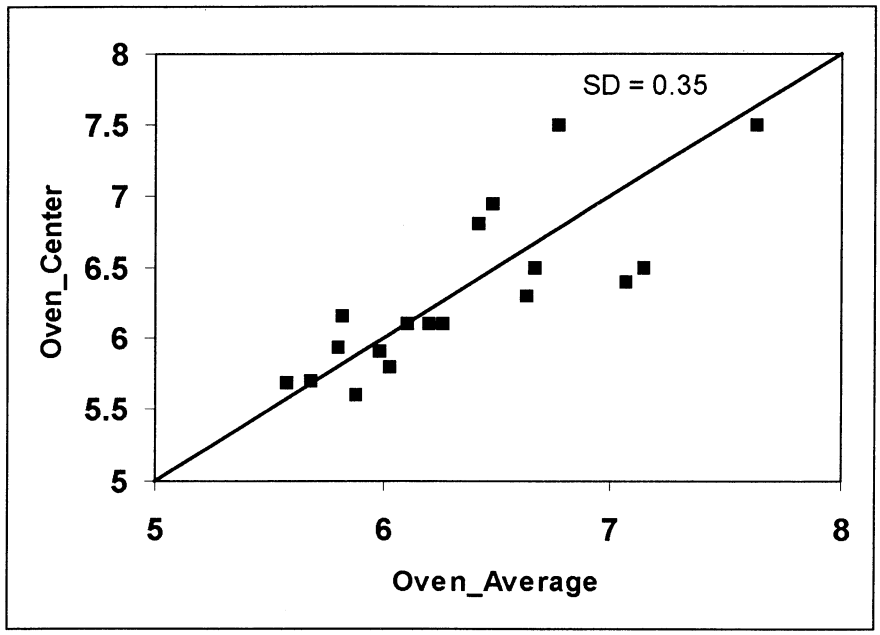

Figure 5.1: Oven moisture measurements: Center vs. Vertex average

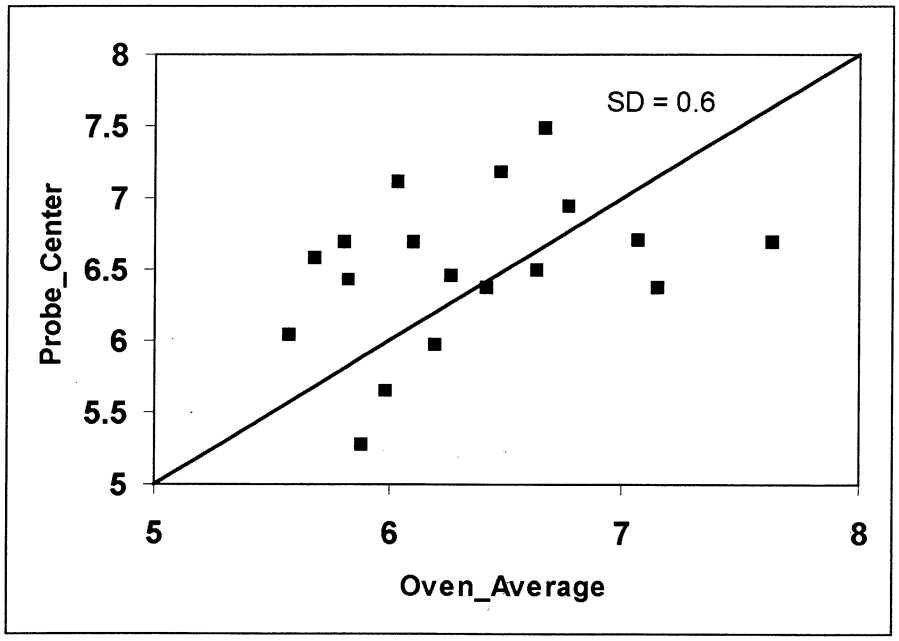

Figure 5.2: Probe center moisture measurements vs. oven average

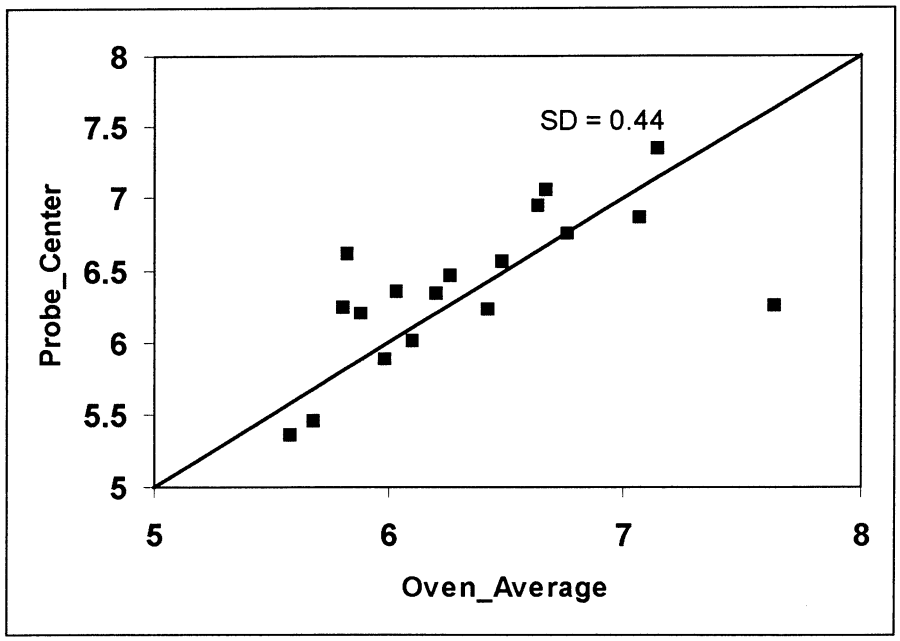

Figure 5.3: Probe average moisture measurements vs. oven average

Measurement of Moisture in the Feed Bin

To conclude the project we were able to place the probe into the fine sand bin at Midwest and measure the moisture in a continuous flow environment.

The probe was placed in the bin following Troxler guidelines that allowed the probe to angle with the flow. The probe was placed in the converging part of the bin. Measurements—probe readings and one-hour oven samples—were taken every 5 minutes. 250 minutes of data were taken (48 measurement points). Data was taken in batches over two days and the bin flow rate was ~ 15-30 tons per hour (~0.25 capacity). The raw data in terms of probe count, probe moisture value and one hour oven measurements, taken from the bin output at the time the probe measurement was made, is given in Table 5.5; the probe value is obtained by using Eq. (5.1) with the following settings C_0 = -4251.551, C_1= -0.0568, C_2 = 8641.036.

Table 5.5 Raw data from bin test

Time (m)	Count	Probe	Oven	Time (m)	Count	Probe	Oven
0	5260	4.0	4.61	120	5350	4.5	4.64
5	5278	4.1	4.26	125	5333	4.4	4.46
10	5307	4.3	4.33	130	5356	4.5	4.68
15	5324	4.4	4.19	135	5343	4.5	4.44
20	5328	4.4	4.22	140	5337	4.4	4.44
25	5330	4.4	4.36	145	5320	4.4	4.57
30	5328	4.4	4.09	150	5311	4.3	4.20
35	5328	4.4	4.79	155	5300	4.2	4.64
40	5338	4.4	4.29	160	5289	4.2	4.20
45	5350	4.5	4.45	165	5326	4.4	3.79
50	5351	4.5	4.24	170	5312	4.3	4.86
55	5370	4.6	4.34	175	5299	4.2	4.42
60	5378	4.7	4.78	180	5312	4.3	4.71
65	5378	4.7	4.73	185	5377	4.7	4.50
70	5379	4.7	4.52	190	5350	4.5	4.69
75	5381	4.7	4.21	195	5316	4.3	4.76
80	5395	4.8	4.72	200	5342	4.5	4.80
85	5404	4.8	4.46	205	5346	4.5	4.72
90	5406	4.8	4.5	210	5325	4.4	4.55
95	5414	4.9	4.61	215	5366	4.6	4.78
100	5402	4.8	5.01	220	5349	4.5	4.52
105	5396	4.8	4.76	225	5390	4.7	4.22
110	5402	4.8	4.57	230	5306	4.3	4.55
115	5390	4.7	4.62	235	5393	4.7	4.67

In Figure 5.4 the moving average (3 point) probe measurements are compared with moving average (3 point) gravimetric measurements (the moving average taken to smooth out temporal fluctuations).

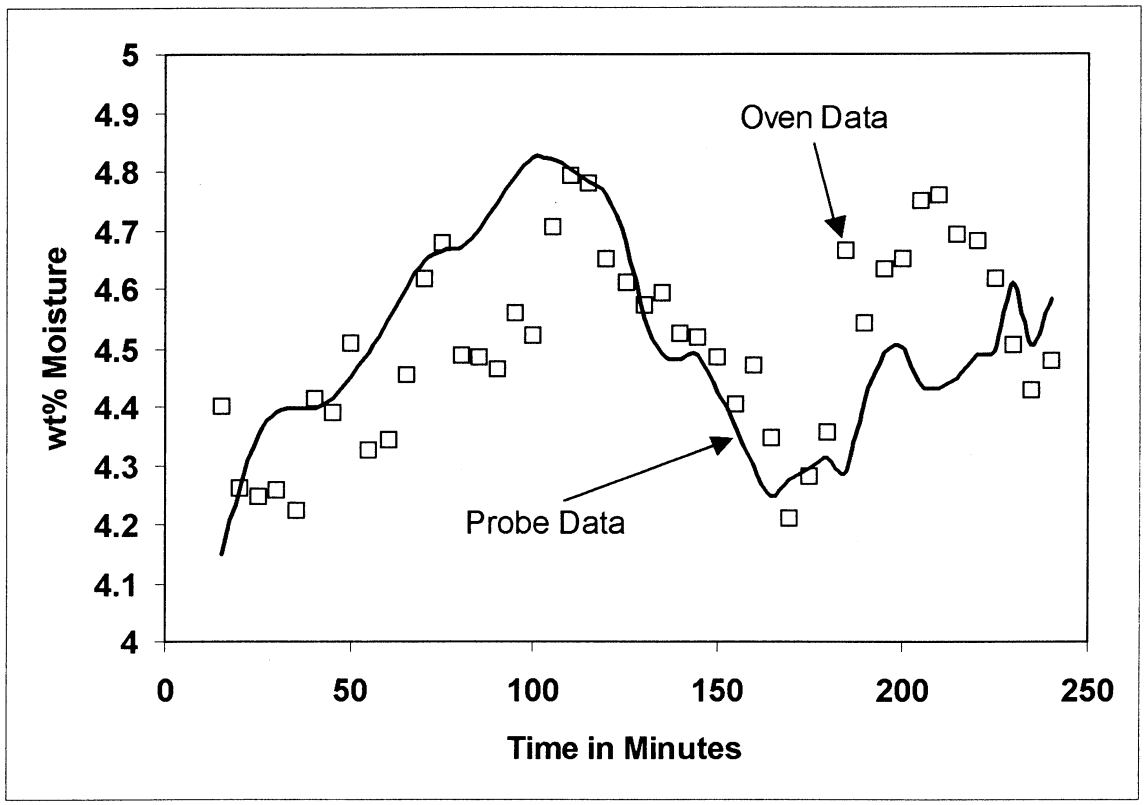

Figure 5.4 Comparison of probe and oven in tracking the moisture in the feed bin

Note:

1. The close tracking between the oven and probe measurements. The maximum difference is only ~0.2 wt%; the standard deviation of the difference is 0.16 wt%.
2. The much smoother plot for the probe data.

Plant Control

A Control Strategy

Although the test run reported in Figure 5.4 is limited it strongly indicates that the probe has the potential of doing an excellent job in tacking the bin moisture level. Further it also suggests that the probe could be used to control the asphalt oil addition to maintain the design mix portions.

Consider the test case previously introduced in chapters 2 and 4. In this test case the design mass flow rates, on a dry weight bases, into the drum are

$$\begin{aligned} W_{FDRY} &= 60 \text{ units / time} \\ W_{MRDY} &= 25 \text{ units / time} \\ W_{CDRY} &= 15 \text{ units / time} \end{aligned} \tag{5.2}$$

where the subscripts are F = Fine, M = Medium, and C = Coarse and the asphalt oil addition is 5 units/time to maintain θ_{OIL} = 5%wt (dry basis) of asphalt oil in the mix. As noted throughout this report to account for moisture variation the flow rate of the aggregates or the asphalt oil needs to be controlled to maintain the 5%wt portion in the mix. If the asphalt oil addition is controlled then the moisture corrected flow of asphalt oil is given by

$$W_{OIL} = \theta_{OIL}\left(\frac{W_{FDRY}}{100+\theta_F^M} + \frac{W_{MDRY}}{100+\theta_M^M} + \frac{W_{CDRY}}{100+\theta_C^M}\right) \tag{5.3}$$

where θ^M is the measured (wt%) of the moisture in the aggregate. Equation (5.3) can be used as a control strategy for the asphalt oil addition, where the moisture measurements can be taken to be three point moving averages of the measurements taken from probes inserted in the fine, medium and coarse aggregate feed bins.

Assessment of Strategy

Observation of the plant trial data in Fig. 5.3 indicates that the moisture variation in the fine aggregate bin is cyclic. With this in mind an appropriate "test signal" for the moisture variation in the fine aggregate is

$$\theta_F^A = 4.5 + 1.5\,\mathrm{Sin}(\frac{t}{25}\pi) \tag{5.4}$$

where $0 < t < 50$ is a measure of time. This function will match the behavior in Fig. 5.3 and exhibit moisture limits (3% and 6%) observed in the plant. Moisture fluctuations in the medium and coarse bins will be ignored, i.e., fixed moisture levels of 3 wt% and 1 wt% will be assumed. Errors in the fine bin probe measurements are assumed to be normally distributed with, based on the laboratory study in Chapter 4, a mean of 0 and a standard deviation of 0.48. In this way, considering the values from Eq. (5.4) as actual moisture, a set of moisture probe measurements can be generated from

$$\theta^M = \theta^A + \mathrm{NORMINV(RAND(),0,0.48)} \tag{5.5}$$

where NORMINV and RAND() are standard Microsoft Excel functions. Values obtained in Eq. (5.5) are used in a three point moving average before application in Eq. (5.3). When this control strategy is used the resulting fluctuations in the oil fraction (wt%) is given by

$$\theta_{OIL}^A = \frac{W_{OIL}}{\frac{W_{FDRY}}{100+\theta_F^A} + \frac{W_{FDRY}}{100+\theta_M^A} + \frac{W_{FDRY}}{100+\theta_C^A}} \tag{5.6}$$

The effectiveness of the strategy can then be checked by

1. visually comparing the oil fractions obtained with Eq. (5.6) when a probe measurement is made through the 50 time steps of the production cycle with the oil fraction obtained when a single moisture measurement ($\theta_F = 4.5$, $\theta_M = 3$, $\theta_C = 1$) is made,

2. calculating the sum

$$\text{Performance} = \sum_{\text{test}} \left| \theta_{\text{OIL}}^{\text{A}} - 5 \right| \tag{5.7}$$

A number of realizations (tests) can be made each test initiated by generating a set of measured moisture measurements using Eq. (5.5). Figure 5.5 compares the performance of 3 realizations of the controlled oil flow with the case where no correction is made; a noticeable difference in performance can be seen.

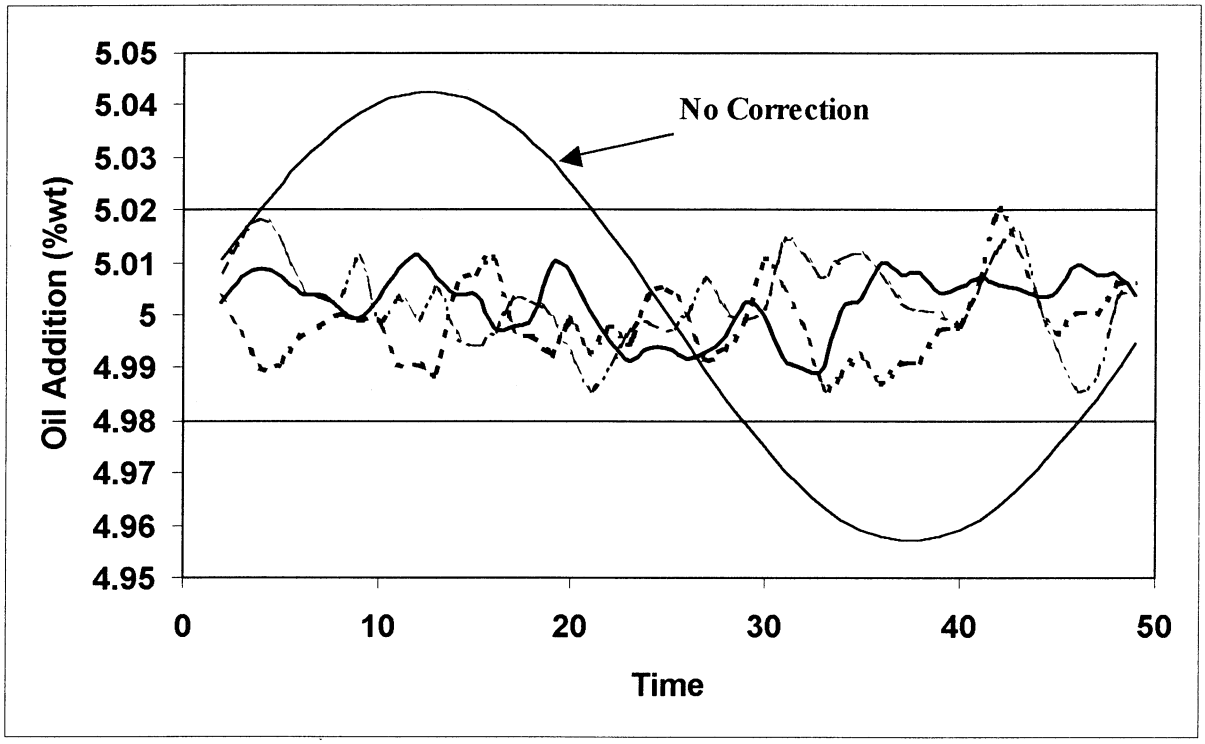

Figure 5.5: Oil addition (%wt) with and without control.

The performance measure, obtained by averaging values from Eq. (5.7) over 100 realizations is 0.33 which is about a factor of 4 less than the performance obtained when no control is applied (1.35). This indicates a very strong cost saving if the proposed control strategy is used. Recognize, however, that the performance of the control strategy depends on (1) the accuracy of

the probe, (2) the range of fluctuations in the plant moisture. In the test case shown here the probe accuracy was characterized by a standard deviation of 0.48. This value was obtained form the laboratory calibration study in Chapter 4. The filed testing, however, indicates that a lower standard deviation can be used. The fine bin trials showed a standard deviation of 0.16 between the probe and oven measurements. When this value is used in Eq. (5.5) the performance drops to 0.183, approaching 8 times smaller that the case where no control is used.

Robustness of Probe

The reason for the relatively short plant fine bin trial was due to the fact that, due to the conditions in the bin, the probe cable snapped. This made the probe inoperable and required its return to the manufacturer for a replacement probe. The replacement probe did not arrive until the end of the 1999 construction season. As such a follow up campaigned was initiated for the 2000 construction season. In this campaign a more robust fixture for the probe was designed.

Report of the 2000 Campaign

The Troxler probe was installed at Midwest Asphalt Corporation's New Brighton plant in Minnesota. As the probe was not meant to be permanently installed, the system shown in Figures 5.6 and 5.7 was developed and implemented by a Midwest Asphalt employee.

Two pipefittings were attached to the top of the probe and mounting holes were machined so that the probe could be suspended inside of the protective circular steel casing as shown in Figure 5.6. Note that the bottom portion of the probe hung free from the casing as shown in Figure 5.7. The probe cable was threaded through the pipefittings shown in Figure 5.6 and the extension

cable was connected inside the heavy gage rubber hose. The hose served to protect the cable and connection from wearing under the aggregate flow. The probe and casing were suspended inside the symmetric bin by three steel cables as shown in Figure 5.7. Finally, the protective hose was attached by cable ties to the steel support cable.

Due to a number of testing problems (see discussion below) only a small number of static probe bin readings and associated gravimetric measurements were taken. These are reported in Table 5.6. These measurements indicate, once again, a close comparison between the probe and oven measurements. Note, however, the measurements were taken in early October 2000 after an extended dry period; this explains the low and close to constant moisture values.

Table 5.6 Static fine bin data from 2000

The probe measurements are obtained using the count value in Eq. (5.1) with C_0 = -4251.551, C_1= -0.0456, C_2 = 8641.036.

Count	Probe	Oven
5021	3.5	3.6
5062	3.8	3.8
5027	3.6	3.5
4995	3.4	3.8
5028	3.6	3.9
5041	3.7	3.3
5029	3.6	3.5
5049	3.7	3.9
5012	3.5	3.6
5028	3.6	3.5
5038	3.6	3.5
5051	3.7	3.8
5031	3.6	3.6
5046	3.7	3.7
5005	3.4	3.5

During the tests conducted in the fall of 1999, it was reported that the probe cable broke five times. Repairs were made by removing the damaged portion of the cable and splicing it back together. At one point, the probe itself became damaged and was returned to the manufacturer. It is presumed that the probe was beyond repair as an entirely new probe was received and used in the more recent testing.

After receiving the new probe from the manufacturer, a brief laboratory study was conducted to ensure that the new probe was working properly. During the study, error messages were received from the software reading, "Error in Received Transmission." The error message disappeared after several days of testing and the cause of the problem was never determined and it was concluded that the probe was working properly.

After the lab study, the probe was installed in the aggregate bin at Midwest Asphalt. On the first day of testing, flowing readings were unavailable and the static readings did not make sense. The software was reporting a static D reading of 0000. After draining the aggregate bin, the probe was extracted and it was found that the connection between the probe cable and extension cable had broken. A new connection was installed and the two cables were taped together to add strength to the connection. During the remainder of the first day of testing, only static readings were taken, as there was still a problem in measuring the flowing material. The cause of this problem was never determined conclusively.

On the second day of testing, the "Error in Received Transmission" message reappeared and no readings were taken. The probe was again extracted and the previously repaired connection was

intact. After checking all the connections and testing the extension cable with a voltmeter, it was decided to remove the probe entirely from the bin and end the study. In subsequent days, in the laboratory, the system was tested and the "Error in Received Transmission" message appeared intermittently. The cause of the problem has yet to be determined. It is presumed that there is again damage inside of the probe as all external connections have been tested.

Discussion

Clearly the field experiences with the two probes indicate a lack of robustness for use in the dynamic part of the asphalt mix plant. This is a disappointment since the results that were obtained show a great potential of the probe to control the plant. A more permanent fixture would help but may be difficult to justify in terms of production down time and interference.

Summary

The conclusions from this field study are

Static Measurements

1. To obtain accurate moisture measurements from an area of the stockpile average measurements have to be taken. This is true for both oven and probe measurements.
2. An appropriate sample grid is an equilateral triangular side ~0.5 m with sample points at the vertex to a depth of ~0.3 - ~0.5 m.
3. Averaged vertex moisture measurements provide a sound moisture measurement for stockpile moisture.

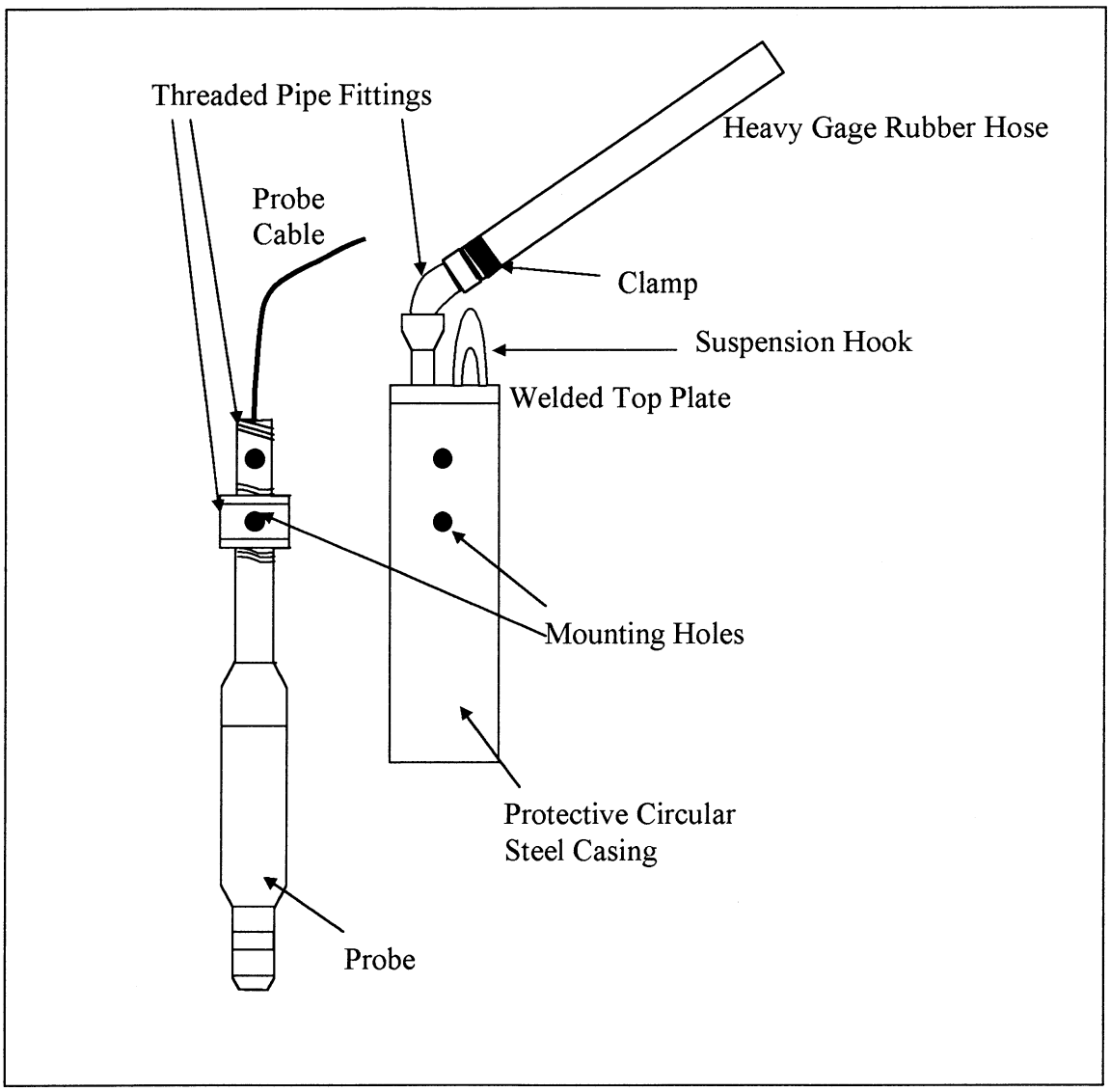

Figure 5.6: Schematic of Troxler probe and protective casing.

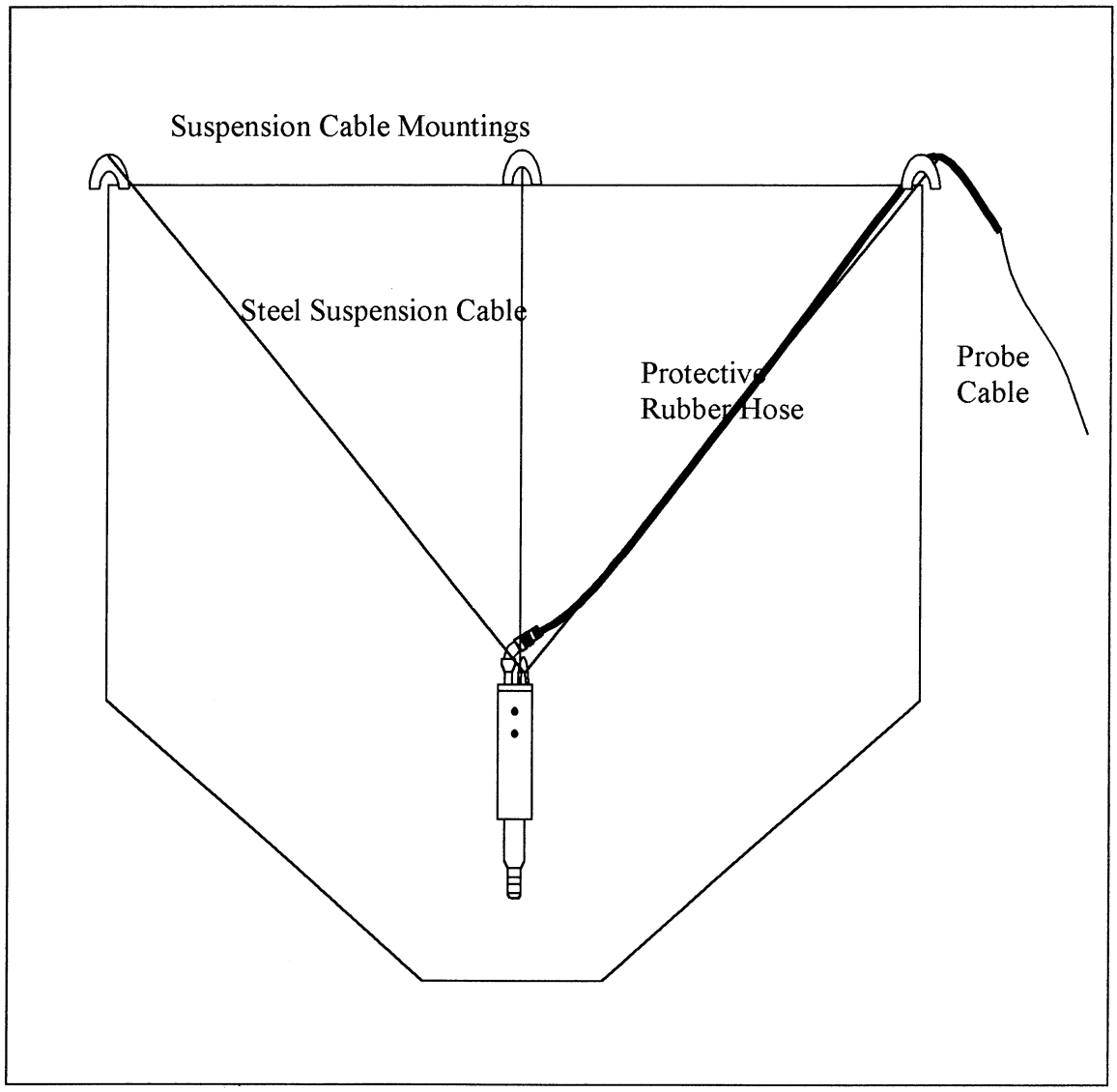

Figure 5.7: Bin setup.

4. In using the above sampling strategy calibrated values obtained with the probe are very close to values obtained with a one-hour oven measurement, the standard deviation of the difference ~ 0.4 wt%.
5. The time required to take a probe reading is much less than that required for a gravimetric reading based on a 1 hour oven drying.

Dynamic Measurements

6. The probe can be mounted in the fine aggregate feed bin.
7. Over a production cycle three point moving temporal averages of probe readings closely track the three point temporal average moistures obtained from a gravimetric measurement; the standard deviation of the difference ~ 0.16 %wt.
8. A numerical simulation with an assumed sin test signal for actual moisture shows that the control of the oil asphalt addition based on a probe moisture reading, Eq. (5.3), can have a significant beneficial impact on the oil addition, see Fig. 5.5.
9. The robustness of the probe for long-term dynamic measurement in the bin is a major concern.

CHAPTER 6

CONCLUSIONS AND RECOMMENDATIONS

Objective

The aim of this project was to

1. Identify at a practical and accurate field method/probe for measuring the moisture content of aggregate stockpiles,
2. test the use of the probe in measuring the moisture in the aggregate feed to the mix drum, and
3. suggest and test how such measurements can be used to control the proportions of aggregate and asphalt in the mix.

Main Findings

There are a number of key findings in this study

1. A simulation with a combined measured and constructed moisture distribution has quantified how moisture fluctuations in the aggregate feed effect the portion of asphalt oil in the mix (see Chapter 2).
2. A literature review indicated that a capacitance probe is a sound and robust method for obtaining moisture measurements in granular media. A commercial probe, Troxler Sentry CP 200, was obtained for specific testing of aggregates used in asphalt concrete processing (see Chapter 3).
3. Laboratory measurement and calibration, with gravimetric measurements, indicate that the commercial probe can predict moisture content (measured as wt%) in asphalt

aggregates at the accuracy level (~0.5 wt%) required to control asphalt oil addition to the mix (see Chapter 4).

4. A stockpile sampling strategy for stockpile moisture based on averaging the three measurements taken at the vertex of an equilateral triangle of side ~0.5m was developed. Probe and gravimetric measurements made in this way are in close agreement; observed measurement differences had a standard deviation of ~0.4 wt% (see Fig. 5.3).
5. When the commercial probe was used in the feed bin it was shown that, when a moving three point average is used, the probe moisture measurements tracked gravimetric measurements, see Figure 5.4; observed measurement differences had a standard deviation of ~0.16 wt%.
6. A control strategy for asphalt oil addition, Eq. (5.3), based on timely moisture measurements was developed. Testing of this control strategy gave a very strong indication that the commercial moisture probes would be successful in controlling asphalt mix portions.
7. It was observed that both probes tested did not survive long term use in the aggregate feed bins. This lack of robustness is a roadblock toward the wide scale acceptance of probes measurements in dynamic plant measurements.

Recommendations

The work in this study as shown that

1. If appropriate calibration is made and an appropriate sampling strategy is employed commercial capacitance probes (e.g., the Troxler sentry 200 CP) provide a rapid means of assessing the moisture (wt%) in aggregate stockpiles. In is recommended that the

Minnesota Department of Transportation (Mn/DOT) encourage the use of this device among contractors as a replacement/backup to gravimetric measurements.

2. The concept of controlling the asphalt oil addition from commercial probe bin moisture measurements is possible and has great potential. There is however, a question mark over the robustness of commercial probes to consistently work through multiple production runs. It is recommended that Mn/DOT explore ways of working with the industry and the equipment manufactures to improve the robustness of the probes for plant control.

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