Methods, Instrumentation and Standards for Measuring Thermal Properties in Soil, Rock and Concrete

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Introduction

Today we'll talk about measurement methods, we have been called on to make measurements of thermal resistivity are called to be in a number of different places but the one that has been most unusual was the experiment that we did on the Phoenix scout mission to Mars several years ago, that flew in 2007, landed in 2008, was intended to run for, I think, three months. I was highly skeptical of whatever, if it did get there, that whatever lands safely. I had designed the electronics that went into that, that you can imagine I was a little bit worried that if those failed, and failed in the right way, that it could short out the whole thing and bring down the whole mission, so I guess in a way I was kind of hoping that it wouldn't get there safely.

It did, it worked perfectly, you can see the lander here and this was just a soil science mission, essentially. These are the solar panels, this is the platform of the lander and a number of instruments were on that platform for doing soil analysis, there's a scoop here that goes out and takes soil samples and brings them back and puts them into the analyzers that are on the platform of the lander. And on the scoop is mounted this device and it might look a little bit familiar to you, it's the thermal and electrical conductivity probe. So in addition to making the measurements we'll talk about, today, the thermal conductivity, heat capacity measurements that also measured water content, with those same probes, and also electrical conductivity. And in addition to that, they could put it up in the air like that and it measure wind speed so it was kind of a multifunction probe, it had a humidity sensor, as well. You might be able to see the little patch on the side here, the semipermeable membrane and so it would measure the humidity on Mars.

TECP Purpose

The idea was to measure the thermal and electrical properties of the Martian regolith, and from that, try to infer some things about possible liquid water content, ice content, and maybe even pore size distribution. Now the interesting thing about this is that the thing was intended to run for three months, it ran for five, we got a lot of data. Those data were analyzed in a kind of a cursory way, we now know what the thermal properties are for the Martian soil or regolith. But, NASA does a good job of funding the actual mission to get the thing off of there and get some data back and don't do such a great job of funding the analysis of that and so if any of you have a burning desire to analyze thermal properties data from Mars or even wind data, the data are all there or you can spend your evenings and weekends working on it if you want and you probably could publish some papers out of that.

Interesting Direct Applications

This thermal properties area is one that the folks at Decagon who work on that really enjoy because there's just such a wide range of applications that people come up. Somebody called up one day and wanted to measure the thermal properties of a cornea, not sure why, unless it's for that LASIK surgery or those kind of things that they need to know, and we said, "Well, no the probe is 6 cm long, you can't measure a cornea with that," and they said, "Oh its okay I can get a whole bunch of them and just poke them all on the needle," and so that's what they did, and made measurements that way. And you wouldn't have thought that thermal properties of artificial skin, I didn't even know there was such a thing as artificial skin, but apparently there is and somebody wants to know what the thermal properties of it, and so we've provided equipment for that. For nanofluids there's

been a lot of interest in that. We've provided a lot of the equipment for measuring that, the thing that we're all here for, the buried cables, of course you understand well, but the thing that started this, even though I'm a soil scientist, about half of our company is devoted to moisture in foods and it really was the food of thermal properties measurement that motivated the first device that we made for measuring thermal properties.

Now you would think that since, essentially, all food is cooked that the people who cook food or process food would be the most interested of anybody in the world in thermal properties, right? But it turns out not to be the case, how many have we sold to foods people, Bryan? (Bryan: "Maybe... seven.") So that turned out not to be the biggest market in the world even though we thought it might. But, oils and coolants we've done some work on that and that's pretty obvious that one of the main functions of oil in an engine is heat transfer, behind lubrication, of course, and the main function of the coolant is heat transfer.

Indirect Applications

(Audience comments.) Indirect applications, there are a bunch of pretty interesting ones there, too. You saw yesterday, that volumetric specific heat is linearly related to water content, and is sensitive. Water has a big specific heat and so you can measure the water content of something by measuring its specific heat. So we've done that a number of places and the nice thing about it is that it's very localized, it's a water content measurement with the best resolution of any that I know of. In fact, a lot of this thermal properties work started when I had somebody come to work with me on sabbatical leave, who did research on peanuts. He wanted to know what the water content of the peanut was, you know after it flowers while it puts the pegs into the ground and the peanuts grow underground, and he wanted to know the water content laws around the pods when they were growing underground, and so he said,"Can't you make something that will do that?" We had been looking at they're doing a lot of work with the single needle probes that we'll talk about today, and those don't do a very good job of water content measurement. So we came up with the dual needle probe that did that. I get messed up in the audiences that I'm talking to sometimes, when I say water potential here that means soil suction to a group of geotechnical engineer so you can measure soil suction, also with heat dissipation sensors.

Outline

So today we want to talk about steady-state methods for measuring thermal properties and then mostly about line heat source method since those are the ones that are most useful for this field that we are working with here. We'll talk about standards and them some about measuring thermal conductivity of rock and concrete and then a little bit about measuring thermal stability.

Steady State Thermal Conductivity

So the steady-state method of it is pretty straightforward. We establish, we have a slab of material that we want to know the thermal conductivity of, we establish a steady heat flow through that material, we know what the heat flow is, we know what the thickness is and we know what the temperature difference is between the two sides in the thermal conductivity we calculate that way. Now I think, Jim, are you going to talk a little bit about guarded plates? One problem with this is that you get heat flow out the sides and Jim will talk a little bit about what you do about that.

Radial Test Cell for Steady State Thermal Conductivity

But, one of the things that you can do is to change the geometry a little bit and for applications like we work in, for soils and gravels and things like that. A lot of times it works a lot better to just go to a radial geometry, then there's a little bit of heat flow out the top and bottom, but if you make the cylinder fairly long and make the measurement out in the middle of it, you don't care much about that heat flow out the ends, you can put

some insulators there and then all you have to do, again, supply a steady heat in the middle of that, measure the temperature of the heater, the temperature of the outer wall, usually make the outer cylinder out of some of high conductivity materials, usually use copper pipe or something like that, so that they and their temperatures pretty uniform there and then do the calculation of thermal conductivity with the equation that's their. So we've used that a lot, usually when you're making measurements with these thermal probes that we'll talk about a bit, that most of you already use. You'd like to have the grain size of the material what you're measuring be small compared to the diameter of the probe, otherwise you get a probe with maybe a pebble or a rock or something. Either right in the place where you're measuring the temperature or not in that place and that can have a big effect on the reading that you get. So how do you measure the thermal conductivity of, say, gravel? Well, the best way we know of doing it is to it to make a setup like this, a cylinder.

Steady State Methods For Determining K

Some of the goods and the bads, the calculation is pretty simple with this large sample so it can average over of the uncertainties to some extent and that's a pretty direct measurement, so one that you can have some confidence in. The possible bad parts talked about the heat flow divergence, it's just a matter though, of designing it properly so that it's easy to get around. Sometimes large samples are a bad thing, instead of a good thing, depending on how much sample you have available to you. It's a laboratory method, not something that you can do in the field and pretty slow. It takes probably a day, at least, for it to reach steady state so you won't make these measurements very rapidly. One of the big things is that you get thermally induced moisture redistribution, like we talked about yesterday. Consequences of Thermally Induced Water Flow

So some of the consequences, some of the things to remember, are that if the sample's dry or if it's fully saturated then moisture redistribution isn't an issue. And even if it's pretty wet it's almost certainly not an issue. But in that kind of critical range, where it's sort of dry, it'll be a big issue and steady-state methods just don't work for those kinds of conditions, you can't get accurate thermal conductivity measurements or resistivity in that kind of, what I would call, around the permanent wilting point of plants, the kind of dry soil.

Line Heat Source Methods for Thermal Properties

The line heat source methods are the ones that are mostly used for measuring thermal properties in soil, those are the transient method, so one some that if there is moisture redistribution that's not serious in making the measurement you can make accurate measurements with this. The way this is done is to place a line heat source in the soil, usually it's a needle that has a heater and a temperature sensor inside it, you apply heat to that source and you measure its temperature over time and then for that line heat source you have a solution to for use equation that applies to that particular geometry and you compare the measured set of temperatures that you have to the model and you adjust that diffusivity and the conductivity in the model until you get those two things to match. Now that probably doesn't sound exactly like you thought it worked, you thought that you just took a set of measurements and plotted them on a semi log curve and fit a straight line to them, but in essence that's what you're doing, is matching that measurements to the model.

Equations for Line Heat Source Measurements

So the solution to the line heat source equation is this; that during the time when the probe is heating, the change in temperature is the heat that you're putting in, this is the watts per meter of length of the probe, the heat that you're putting in divided by 4 π times the thermal conductivity and this is the exponential integral, the probe diameter over four times the diffusivity times the time. And then during the cooling phase, after

you've turned off the heat, then it looks almost the same, except that now you have two exponential integrals, one for the time and one for the time minus the heating time. It's kind of a superposition of solutions, essentially you're subtracting out a solution where the heat is going the opposite direction to cancel it out.

Thermal conductivity: Single needle method

So, this is kind of a typical probe and this is the one that we normally use for soil situations. It's 10 cm long and about 2.5 mm in diameter. If we put heat into that probe and just look at the heating part of that, this is the temperature rise and this is time plotted on a log scale, and you can see that these come out to be straight lines and the slope of those lines is directly proportional to the resistivity of the material.

Why is the Response Linear with Line T?

Now why does it come out to be a straight line on a semi log plot? Well if we go back to that heating solution, the exponential integral is here and we can approximate that by an infinite series. The gamma is a constant, Oilers constant, and then the first term in the series is the logarithm of this, R^2 over DT, and that it is called, in some literature, the Fourier number. You can see it's a kind of a dimensionless time, and then we have terms in A, A^2, A^3, and so on in the series. Notice that time is in the denominator so the bigger T gets, the smaller A gets. And so if we wait a little bit these terms get smaller and smaller and eventually we can ignore them so we end up just with these first two terms that we have to consider.

Pulsed Infinite Line Source, Approximate Solution

If we do a little math on that we come out with this equation: q over 4 π K times the log of T minus the log of some stuff that turns out to be constant. So this is a set of data and you can see that over a pretty wide range of time, that we can fit a straight line to that set of data and then the conductivity is just: q over 4 π times the slope of that line. So this should get us to be thinking about what we need to do here that we can't use all of the data we collect out of this heating curve because some of it won't be right for fundamental reasons that those higher order terms haven't gotten small enough yet.

Example of K Measurement

So here's an example of some data from both the heating and cooling curve, so you can plot either log T for the heating or you can plot log T over T minus 0, T 0 being the heating time for the cooling portion of this. These points that are widely spaced here are those early time points and these are the early time points on the cooling and then we just fit our straight line through the points later on. Now, since this is a log curve it looks like we're ignoring most of the data that we collected when we did this, we got lots of points here but they don't cover of very big range on our log plot. When we do the analysis we get, for this part or row of 153 for the heating part, we get a row of 144 for the cooling part, why are those not the same number? (Audience comments)

Yeah, probably the temperature in the sample was not constant during that time that we made the measurement. Now if what he had not measured both the heating and cooling phases of that we would never know that, would we? And our analysis isn't able to pick that out, it doesn't know the difference between the temperature drift in the change that's occurring when we heat the probe and so it's useful to measure both the heating and cooling phases and for a simple analysis you can just average those two to get an appropriate number.

Heated Needles as Transient Line Heat Sources

(Audience comments) Well you could do that in a pretty analytic way, you know you could go through point by point, let me jump ahead here. Now, this is the graph that's given in the ASTM and they say, "Well you plot this out and you see that there's a part here that doesn't look like it's on a straight

line and there's a part here that looks like its not on a straight line and here's a part that looks kind of straight so ill just put my line through that," and that's not a very good way to do that, I think, I mean that's just completely subjective. And if you look at these data, you can see these first few points, that there are some obvious deviations from the line that goes through those points. There are actually more processes going on here though than we're talking about, a bigger concern than leaving out those higher order terms. The bigger concern turns out to be the contact resistance between the probe and the surroundings, that I'll talk about in just a bit. And so we end up just making, it's not an arbitrary choice but an informed choice; we leave out the first third of the data. So if we are running for 600 seconds we leave out the first 200 seconds of the data. And that takes care of both the heating and cooling and that takes care of both issues as long as you use a long enough heating time, both the issue of the higher-order terms and the contact resistance. (Audience comments)

Heated Needles as Transient Line Heat Sources

So I want to just talk about some of the assumptions that we make when we are doing these calculations and some of the things that we need to watch out for to make sure that the measurements are good. We talked about a solution to the ideal line heat source equation. What does that mean? Well it means that our heat source is infinitely small and infinitely long and that the medium that we placed the source in is uniform. That the temperature is uniform and constant, and that we have intimate contact between the probe and the surroundings.

Real vs. Ideal

Now, what's the real situation? Well, the source is not infinitely long and infinitely small, its 10 cm long and 0.4 mm in diameter. The medium may not be uniform, if it's not; we have big problems because there isn't any way around that that I know of. People say, "Oh, I've got this layered material, sand here and clay here. Can't I just poke the needle down through the two of those and get the average productivity of both bills?" No, you can't. You need to make individual measurements on the material, and it has to be uniform. If you did something like that, depending on where the temperature sensor was, with respect to the interface between those two materials, you would get something that was strongly weighted toward either the sand or the clay. We don't have any way to deal with something that's not uniform. The temperature might vary in space and time. We talked just a little bit about this using the heating and cooling curves to deal with some temperature variation, if the temperature variations are large, though, even that doesn't solve the problem. And the contact resistance, we assume intimate contact, but that usually is not the case.

How Does the KD2-Pro Address These Issues

So, some of the ways that we try to deal with those issues and try to get as accurate measurements as possible. As I said, we use the heating and cooling phase and then turns out that by using long meeting times, you're able to overcome, to some extent, the effect of the contact resistance and I'll try to explain the reason for that in a minute.

Assessing Error From Finite Probe Size

I'll talk just a minute about the errors that come from finite probe size and how we've tried to assess those errors. You can always do a numerical model of a probe. Mike talked yesterday about finite element models and the way he's used those. You can use those same models to model exactly what that performance is of any sort of probe arrangement you want. And so we can take our finite probe size that we have and find that probe length and we can model that with a model like the ones that Mike talked about yesterday or that he'll talk about today and so we can generate heating curves and cooling curves for any set of conditions we want and then we can analyze those curves using the techniques that I

just explained; the line heat source methods.

K Measurement Error For Two Probe Sizes in Water and Sand

And these are some of the results that we get; so we've got here the error in the measurement. In other words the error being the difference between what we measure and what we put into the model and what we get out when we do the simple analysis of the model. As a function of the time over which we make the measurement, for several different situations, the larger needle 2.4 mm diameter, and the smaller needle 1.2 mm diameter, in a high thermal conductivity a 2 and lower conductivity water at 0.6. You can see that for the small needle, that even for fairly short heating times, the error is negligently small but for the larger needle, the one that we tend to use for the soil measurements, that the error, if we used pretty short heating times, could be pretty big. If we go to longer times the errors become much smaller.

Now why don't we just use the small needle instead of the big one? One of the reasons for that is that the IEEE standard, that most people use this for the measurements to go into these ampasity calculations that specifies the size of the needle. And so we're a little bit stuck there, we can say, "Oh, they didn't know what they were doing," but there are some good reasons for using larger needles, as I said little bit ago it's nice to have the needle be larger than the grain size and there are times when you have fairly large grain size. So, we've decided to stick with the larger needle and then to try to deal with these, and go to long enough heating times that these errors become small, but as I said before, they're good reasons, too, for the long heating times.

Assessing Error From Contact Resistance

These contact resistance errors are some of the biggest concerns that you should have in making these measurements, they come about as a result of a poor contact between the probe you have and the surroundings. We talked, yesterday, about the cylindrical geometry. One of the first times a student came into my office and said he wanted to make a measurement of thermal conductivity with a heated probe of a transient measurement. I told him there was no way in the world that that could work. That's a transient measurement and you're measuring steady-state property and you can't do that, and so in the process of trying to prove that I was right and he was wrong, I found out that this usually happens, that he was right and I was wrong.

So then you have to ask, well how is that possible, that you can make a steady-state measurement with the transient experiment? Well the reason that you can is that cylindrical geometry, that you very quickly establish a steady state in the material right around the probe and so the storage is going on farther out, but you have steady state in the material right around the probe. And that means, then, that the measurement is mainly focusing on the material in contact with right around the probe. That's what has by far the strongest influence and when Mike worries about the drying around the cable, you don't have to have a very big layer of dry material around the cable for it to act just as if all of the material around the cable were dry. So that means that that contact between the probe and the material you're trying to measure has to be good. Well if it isn't so good, how do you get around that? If you have excellent thermal contact with the material around the probe you might get a graph that looks like that (demonstrates graph). If you have poor contact the temperature might jump up here and then go like that, but if you're mainly looking at the slope of this line, the slope of this one and the slope of this one, once that initial jump has happened, will be the same. So the key is to wait a long enough time until that has settled out and then make the measurement. So, how do we analyze that? Well, same way as before, we set up an element finite on the different model of

simulations with known conductivity and then fit

our simpler solution to that and compute the error.

K Error From Contact Resistance

This compares now, again, the error and the time for the different conductivity materials with no contact resistance and with contact resistance. And you can see that the finite probe size and the contact resistance errors, to some extent, cancel out. That short times, we get these errors where we're getting too high a conductivity for larger probes. At short times the contact resistivity gives us too low conductivity, but if we wait out here to longer times those errors become quite small. We've tried a lot but have not, so far, been able to come up with a way to do the analysis to eliminate that contact resistance. That's not to say it's impossible, we still are working on it and maybe at some future, one of these things will say, "This is how you do it you can make the measurements anyway you want to because we can model all of those processes," but so far we haven't figured out how to do it yet.

Conclusions on contact resistance

So with respect to contact resistance, the things to remember are that you have those errors anytime. You have a poorly fitting probe or any kind of air gaps around the probe. The most critical ones are the ones that temperatures measured right in the center of the probe and that's the worst place to have a gap. For a given gap, the error increases with the size of the thermal conductivity because the gap is a low conductivity and so if the material's high conductivity you just are not able to get the heat into the material. We don't know of a simple correction and even complicated corrections. We haven't figured out how to make them work yet, but long read times tend to minimize the error and tend to get the most problem in dry materials, but moisture tends to bridge some of this problem.

Standards For Thermal Conductivity or Resistivity

I'll say a few words about the standards. The ones that normally apply in this kind of work, are the ASTM 5334-08, IEEE 442 and then one that's not often cited but, in my opinion, probably is the best of the three is the Soil Science Society one. Are there any other standards that any of you know of that you cite for this?

Comparison of Standards

A few comparisons between those; the ASTM one and the IEEE seemed to kind of go along in parallel for while, but the IEEE standard hasn't been updated for 30 years or more so that's pretty out of date. It still wants you to do your analysis with a pencil and a piece of graph paper and not very many people do that now. It still wants you to record the data by hand, not many people do that now. The probe length and the diameter are specified in the IEEE standard. You notice that these other standards have just tried to give some guidelines, now, and have not specified that, recognizing that there might be situations where one probe size would work better than another one. I don't know exactly what's going on with the IEEE standard; that really is the one that is best and, I think, apply to most everybody in this group and we tried pretty hard to get that updated a few years ago, got the committee reactivated and supposed be working on it but then the whole thing went dead again, so I don't know if that's ever going to get up updated. For a while they were just reaffirming it every, five years or however often they were supposed to even though it wasn't being updated, they converted it to an electronic format, there must not have been a source when they did that, so I think that they just scanned it and ran it through an optical character converter and it converted some of the words to the wrong word and nobody ever proofread the thing and so it even sounds a little ridiculous. Soil, I think, was one of the words that it couldn't get right and I can't remember what it substituted for soil. But, any way it hasn't had much care, unfortunately, because, it really has good information in it and important information for the kind of work we do here, so take it with a grain of salt.

IEEE and Old ASTM Analysis

We talked about this, probably, as much as we need to.

Important Points

And probably, we've been on these points as much as we need to, as well, the large probes specified by the IEEE and the old ASTM standards, we need to use fairly long times with those in order for the line heat source analysis to be correct but that's okay because we probably want to use fairly long times anyway to make sure that we don't get contact resistance errors. We can take out the temperature drift errors, as long at they're fairly small, by analyzing both the heating and cooling phases. We'd need to make sure, though, that we're dealing with homogeneous material and we want to maximize the contact. We can sometimes improve contact by using thermal grease and in some dry materials we'd do that. When we're making measurements on rock and concrete we always use thermal grease, so that's pretty important there.

(Audience comments) So the question is whether the thermal grease influences the thermal conductivity measurement that you make. Again, it's a time issue. If you wait long enough for that effect of the heating right around to dissipate out into the material and you get correct measurement of the thermal conductivity surrounding the probe. (Audience comments) There's another way around that, too and that's just to put an awful lot of heat in. We've tended to not want to do that because of the moisture migration issues. We may have been more worried about that than we should have been because I've been trying to put in enough heat to actually dry the soil around the probe, lately, and I'll get to that in a minute. It's been a hard thing to do, so it could be that we could go to quite a bit higher heating rates and then those temperature drift errors would be smaller. (Audience comments) That's something we used to think was necessary, I think our stance now is that we trust the theory more than we trust, I mean one of the hard things with thermal properties measurements is that there just aren't very many good standards, especially up in the rain of wet soils. Water is a good standard, Glycerin is a good standard and so what we would recommend now is checking against those things to make sure that everything is working right, but as long as we use long enough feeding times for those probe size errors and contact resistance to go away, that we can base it on the theory and that we're more confident in the theory than we are in standards, that we've been able to find. But I think you'll come out the same either way, with that the longer heating times we get the same result, say with a glycerin standard or water standard, that the theory says we should.

Finding Thermal Properties: Your Options

So what are our options if we need to provide thermal properties measurements to a client? Well, one of the ways we can do it would be to just go and measure water contents and densities and mineralogy's temperatures and model the whole thing; we talked about models yesterday, those models are pretty reliable and so you could just provide people with modeled values and that probably would be about as good as anything that you could do, but it may not satisfy your clients and it may not be the easiest, or the least expensive way to go. Another possibility would be to go and measure one point in the field so that you could at least tie it to the particular material that you had and then determine the water content and the density of that sample and use the model to extrapolate from that point to the other points that you wanted to get. Another possibility would be to bring samples back to the laboratory and make measurements on the set of samples, and I think a number of you do that. You start out, dry the sample out, pack it, make measurements and then add water, make more measurements. The problem with that is that you can't pack dry soil very well and so your dry resistivity numbers are way too hard because the bolt densities are way too low. The thing to remember is that if you go out and just make a

single measurement, the temptation is somebody says, "Well, what's the thermal resistivity of the soil?" So you go out there with your meter and poke it in the soil and you get a measurement and you send them the number and say, "This is the resistivity." Well, we know that that varies with water content and a bunch of other things so we would like to give, at least, the worst conditions that they might experience but more likely the range of conditions that they might experience.

Thermal Dryout Curves

What we usually do is provide them with a dryout curve with the relationship between the water content and the thermal resistivity or thermal conductivity for the specific density usually at room temperature and then, of course, the mineralogy with whatever material is provided in the sample.

Dryout Curves – Measurement and Modeling

Jim will talk more about dryout curves and the worked that they've done in Wisconsin in the next lecture and so I don't want to spend too much time on this, but a method that has seemed to work well for us for getting these dryout curves is to do kind of a combination of the models that I talked about yesterday and the measurements that I'm talking about here. So you start out with a sample that's packed, probably to maximum density or to some fraction of maximum density as you would with a good geotechnical practice, saturate the sample with water and make a measurement of the thermal resistivity or thermal conductivity. And that's a reliable measurement, the saturation point is a reliable point, you weigh the sample and then you put it in the oven and dry it out all the way. When it's dry you can make another reliable measurement and that measurement then is on a sample that's at the density that you intended it to be and from the measurements that you made that you can calculate the water content of the sample and the density of the sample and then use the model that we talked about yesterday to fit between those points.

Dryout Curves on Sand

So here's a set of data: thermal conductivity versus water content, and there's our wet point and there's our dry point and then we did measure some points in between to see how that would work out. You can see the line that's fit through those points here, and that's just based on the physical properties of the soil so you can see that does a good job of catching the critical point here, that if we do a good job of estimating our clay fraction we do a good job of fitting that point then, so we fit the line all the way through well.

So - What's Needed for the Combined Approach?

So what we have to know for this? We need a wet conductivity that we get by packing and saturating the sample, we need a dry conductivity that we get after we dried out the sample, we need to know the volume fraction of solids, which we can compute from our bulk density and then we need to know a clay content and for running a texture analysis anyway we'll know the clay content from the texture analysis, if not we can get that by field or some other method. The equations for doing this you can see on an application note on Decagon's website that tells how we do this, that is the quickest method for getting a dryout curve, I think it's a pretty reliable way of getting it and it gets you the one point that Mike wants, which is that dry point for doing the analysis. (Audience comments)

Measuring Thermal Conductivity of Concrete

With concrete, their might be a couple of situations there were you're measuring thermal resistivity or conductivity. One might be on newly poured concrete where you're able to get samples on side of the concrete and if you can do that, you can put those in standard cylinders and if you just put a pin in those, a stainless steel pin that we supply, you can make a place for the thermal conductivity needle to go and it'll be a tight fit in that place and when the concrete has hardened you pull the pin out, pull the thermal conductivity needle in and make the measurement. The main

thing that you have to ensure is that the density of the concrete in your sample is the same as the density of the concrete as port, and of course you would do that anyway for strength test and the other kinds of tests that you're doing on concrete.

Important Points For Concrete

Gaps are an important thing so you want to make sure that you don't have gaps and you want to put a little bit of grease on the pin before you put it in or you won't be able to get it out again, we worry about air gaps and you can use these samples for both dry and saturated measurements but, as was pointed out yesterday in their discussion, concrete doesn't dry or saturate very fast, it takes a little bit of time to do that.

Measuring Thermal Conductivity of Cured Concrete or Rock

Now, the other possibility, the other situation is one where you want to make a measurement on concrete that's already in place or on rock. We've just now, come out with a new probe that works pretty well for that, it's a shorter fatter size such that we can use the smallest of the rotor hammer bits easily with it and so you just drill a hole in the concrete or in the rock, put a little bit of thermal grease in this tube here in the bottom of the hole, so that when you push the probe in it squeezes up past the probe and then makes the measurement. I think in our practicum today, Doug is going to take you through some of that.

Measuring Thermal Stability with a Heated Needle

The last thing I wanted to mention, briefly, is that thermal stability measurement. A number of you have looked in the literature and have noticed that a lot of work was done on thermal resistivity and thermal stability. There's a lot published on that, but it was quite a while ago and a lot of the work was done in the 50's and 60's and 70's and 80's and then it all, for some reason, kind of went dead. There hasn't been an awful lot of stuff published on that, but Bill Black at Georgia Tech was one of the prime movers in a bunch of this stuff and this is a paper that he sent me a while ago that I haven't looked at much until I was trying to prepare for this presentation.

One of the things that he talks about there is a probe to measure thermal stability and the idea of the probe is that you can put a probe like the ones that we use for measuring thermal resistivity in the soil, you can put an amount of heat into that, comparable to what you would put into a buried cable, and if the soil is thermally unstable, again, there will be a period of time here where we could do our normal measurement of thermal resistivity. But, then they'll come a point at which the slope of line will change and if we were to fit a line to that part of the curve that would be the thermal conductivity or resistivity of dry soil. In this time to where that occurs, he uses that to make an estimate of the thermal stability or instability of the soil.

Now, that's a pretty appealing idea; appealing if you just want to make measurements, you could get both your wet and dry measurement on the same soil sample without putting them in the oven or anything else, it's appealing because it works like the buried cable does, you can put in an amount of heat comparable to the buried cable, you can scale this up to the buried cable by plotting this axis not as time but as that Fourier number that I mentioned a while ago that scales as the square of the diameter of the heater that's in it, so you can scale up to cable size things. A lot of appealing things about this.

A week ago I started thinking I want to make some of these measurements so that I can show them to you and show you how wonderfully this works. So far I have not been able to dry out a needle, so all of the samples that I have, I guess you would say, were thermally stable because I never did transport enough water to get the thing to dry out. One of them I left for probably 12 hours and that was a sand, I had set it up so that it should have dried out and it went for 12 hours and to really

discourage me it went here on out here and then it actually went down a little bit instead of going up.

(Audience comments) And I was trying one's higher than that; I went close to 100 to try to get it to dry out, I still couldn't do it. So anyway, I'm determined that I'm going to do it, so when we get back we'll work on it some more. What Bill Black told me was a simple straightforward way, he wanted to get instituted as an IEEE standard that people could follow and I think there was a committee set up in IEEE to do that and that committee has worked on things for 20 years or something and still have not been able to implement it. But they've gone a little bit different way than the way Bill wanted them to. (Audience comments) No, this was, they call it, Georgia red clay, that must be what they work on at Georgia Tech.

(Audience comments.) I wondered that, he actually has more graphs of this for different heating rates and I had thought that originally; I thought it's just the point at which that slope of the saturation vapor pressure curve gets high enough that it will dry out. But it turns out it works just the opposite, that that higher heating rates this moves downscale instead up, and so it comes down to just the amount of energy that it takes to dry out that layer of soil around the heater on the probe. (Audience comments) That's one of Bill Black's big gripes, I guess you would say, that committee that idea of the temperature got established somehow as a kind of rule of thumb early on in the power industry, and they're not very willing to give it up, and he says it doesn't have anything to do with anything and that's why that committee has fought all of these years. That there's a group that thinks that there's that critical temperature and then the group that understands the physics of heat and water flow and they just have never been able to get together. I suppose what happens is that they'll all die off and a new bunch will come on and then they'll be able to make some progress.

Conclusions

The conclusions; methods exist for easily and reliably measuring thermal conductivity and resistivity of soils, even know we can make those measurements reliably there's still plenty of uncertainties in terms of providing information to clients, though. We were discussing some of that last night at dinner, furnishing a number without knowing how that number will be used because of the variation that's possible; standards exist and the newer standards are more reliable in terms of the way we would actually do the measurement, but the IEEE standard, still, I think, if we can ignore the pencil and paper aspect of it and other things that hopefully we wouldn't be held to, still, is the best one to apply for the kinds of things that we're wanting to do here. Does any one have any points or questions anybody wants to make? (Audience comments) That's a good point; on the heating phase the contact resistance is an issue, on the cooling phase it's less of an issue. It doesn't completely go away because the probe has some heat capacity so there has to be a little bit of heat transfer but it's a much smaller thing and so we have given consideration to that. If you did a pulse thing like that we don't have the mathematics to analyze that yet. (Audience comments) Are there any other questions? Okay, thank you.

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