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DEVELOPMENT OF A NEW TEST METHOD FOR MEASURING BULK SPECIFIC GRAVITY OF FINE AGGREGATES

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DISCLAIMER

ABSTRACT

Bulk specific gravity of the fine aggregate is used in hot mix asphalt (HMA) volumetric mix design (including Superpave) to determine the amount of asphalt binder absorbed by the aggregate and the percentage of the voids in the mineral aggregate (VMA). The current test method (AASHTO T84) uses a cone method to establish the saturated surface dry (SSD) condition of the sample, which is necessary to conduct the test. This method does not work satisfactorily for fine aggregates which are very angular and have rough surface texture, and, therefore, do not slump readily when in SSD condition.

This research project was undertaken to develop an automated equipment and method of establishing the SSD condition of the fine aggregate. The wet sample of the fine aggregate is placed in a rotating drum and is subjected to a steady flow of warm air. The temperature gradient of the incoming and outgoing air and the relative humidity of the outgoing air are monitored to establish the SSD condition.

Two prototypes devices were constructed. The test results obtained with the second prototype device are encouraging and have been reported in the paper. Further improvements to be made to the second prototype device to improve the repeatability and reproducibility of the test, have been identified.

KEY WORDS: bulk specific gravity, fine aggregate, saturated surface dry, Superpave, hot mix asphalt, mix design

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INTRODUCTION AND OBJECTIVE

Bulk specific gravity of the fine aggregate is used in Superpave volumetric mix design calculations to determine the amount of asphalt binder absorbed by the aggregate and the percentage of the voids in the mineral aggregate (VMA). The current test method of measuring the bulk specific gravity of fine aggregate (AASHTO T84 or ASTM C128) does not have satisfactory reproducibility. This method does not work satisfactorily for certain fine aggregates which are very angular and have rough surface texture. These materials do not slump readily when tested by the cone method specified in these standard tests to determine the saturated surface dry condition (SSD). This lack of precision in obtaining the bulk specific gravity of fine aggregate affects the Superpave volumetric mix design. The optimum asphalt content can be underestimated resulting in lean and brittle mixture (raveling and cracking) or can be overestimated resulting in rich and plastic mixture (flushing or rutting). There is an urgent need to develop an accurate and more reproducible test method for determining the bulk specific gravity of the fine aggregates.

This study was undertaken to develop an automated equipment and method of determining the saturated surface dry condition of the fine aggregate so that its bulk specific gravity can be measured with satisfactory precision and accuracy.

REVIEW OF LITERATURE

Bulk specific gravity is the ratio of weight in air of a given volume of a permeable material (including both permeable and impermeable voids normal to the material) at a stated temperature to the weight in air of an equal volume of distilled water at a stated temperature. The bulk specific gravity of an aggregate, as defined by the ASTM, equals the oven-dry weight of the aggregate (A) divided by the sum of the aggregate solid volume (Vs), the volume of the permeable voids (Vp), and the volume of the impermeable voids (Vi) times the unit weight of water (γw). Those voids that cannot be filled with water after a 24-hour soaking are referred to as impermeable.

$$bulk\ \ specific\ \ gravity\ =\ \frac{A}{(Vs + Vp + Vi)\ \ \gamma w}$$

The bulk specific gravity of an aggregate is determined in the laboratory using the following formula:

$$bulk\ \ specific\ \ gravity\ =\ \frac{A}{B - C}$$

where A is the oven-dry weight of the aggregate, B is the saturated surface-dry weight (in grams) of the material in air, and C is the weight (in grams) of saturated material in water.

Bulk specific gravity of both coarse and fine aggregate are used in hot mix asphalt (HMA) mix design to calculate the amount of asphalt binder absorbed by the aggregate and the percentage of voids in the mineral aggregate (VMA). Accurate determination of bulk specific gravity of the aggregates is, therefore, necessary to calculate the realistic volumetric properties of the compacted HMA mixtures.

Experience has shown that, for some materials, the results of bulk specific gravity are very difficult to reproduce. This is mainly caused by the personal element involved in judging the point at which the wet aggregate has dried out sufficiently to reach the "saturated surface-dry (SSD) condition" which is theoretically the point at which all the surface moisture has gone from the particles but with the permeable pores remaining completely filled.

ASTM Standard Methods C 127 and C 128 outline means for determining absorption and bulk specific gravity of coarse and fine aggregates, respectively. These standards call for immersion of material in water, followed by drying until the surface-dry state is attained. Coarse aggregates are rolled in an absorbent cloth until all visible films of water are gone. The establishment of the SSD condition of coarse aggregates is simple and reasonably reproducible. However, the same is not true for fine aggregates.

Fine aggregates are spread on a pan and exposed to a gentle current of warm air until a free-flowing condition is reached. The aggregate is then lightly tamped into a specified conical mold. If the cone stands when the mold is removed, the fine aggregate is assumed to have moisture on its surface, and it is dried further. When the cone just begins to slump after removal of the cone, it is assumed to be in a saturated surface-dry state. In addition to variation caused by individual judgement, the fact that large particles tend to dry more quickly than small particles may lead to overdrying of the larger particles, unless the precaution is taken of recognizing and handling these particles separately. These variations become significant in the case of aggregates having a rough and porous surface.

For natural, well-graded fine aggregates, the saturated surface-dry condition is usually reproducible. The end point is more erratic for crushed fine aggregates because the angularity of the particles does not permit a definite slump condition as do the rounded surfaces of natural sands. Besides, the higher percentage of material passing the 0.15 mm (No. 100) sieve also poses a problem in achieving the slump condition.

Various attempts have been made in the past to pinpoint the saturated surface-dry condition of the aggregates to improve the reproducibility of the bulk specific gravity test results. These include Howard's glass jar method (*1*, *2*), Martin's wet and dry bulb temperature method (3), Saxer's absorption time curve procedure (*4*), and Hughes and Bahramian's saturated air-drying method (5). However, the various modifications either offer little improvement or are too elaborate to be of practical value in the field or average laboratory.

Kandhal and Lee (*6*) developed a colorimetric procedure, also mentioned in ASTM C 128, to establish the SSD condition of both coarse and fine aggregates. This method involves soaking the aggregate in water containing a special chemical dye. On removal from water, the aggregate acquires the color of the wet dye. However, this dye changes color when dry (for example, cobalt chloride changes color from red to blue). As soon as the fine aggregate particles change color (when subjected to drying with a fan), the saturated surface dry condition (SSD) has been reached. However, the following problems are associated with this method:

a. The dyes do not show well on dark colored aggregates;
b. An efficient method of mixing the fine aggregate during the drying operation is needed so that larger particles do not dry out sooner than finer particles; and
c. Detection of the color change needs to be automated so that the subjective judgement of the operator is eliminated.

Dana and Peters (*7*) of Arizona Department of Transportation directly measured the surface moisture conditions of mineral aggregate using basic principles of thermodynamics. The wet fine aggregate sample was placed in a small rotating drum. Hot air was blown into one end of the drum to dry the tumbling aggregate uniformly. Thermocouples mounted in the inlet and outlet tubes of the prototype rotating drying drum monitored the temperatures of the incoming and outgoing hot air. A millivolt strip chart recorder displayed the difference in temperature (thermal gradient) of the thermocouples. As long as there was free surface moisture on the aggregate a steady value of the thermal gradient was observed. As soon as the saturated surface dry (SSD) condition was achieved, the thermal gradient reduced suddenly. At that time, the sample is taken out of the drum and tested. The preliminary prototype equipment gave encouraging results, however, the development of the equipment was not finalized and it was recommended to test a wide variety of fine aggregates.

Krugler, Tahmoressi and Rand (*8*) have reported four procedures to establish the saturated-surface-dry (SSD) condition of fine aggregates:

1. An oven-dry aggregate sample is placed side-by-side with the test sample which is being dried. The SSD condition is defined as the point when the test sample has the same color as the oven-dry comparison sample. It is preferred to err on the dry side of the SSD condition because the bulk specific gravity does not change significantly with additional drying.
2. Observe how the test sample slides down the bottom of a tilted pan. When the test sample no longer adheres to the bottom and flows freely, it is judged to be surface dry.
3. Observe how the test sample flows off a tilted masonry trowel. When the test sample no longer adheres to the trowel and flows off freely as individual particles, it is considered surface dry.
4. Use a strip of packaging tape (Supreme Superstandard Gummed Paper Tape, two-inch medium duty) attached to a small block of wood. The tape is placed on the test sample for five seconds and lifted. The SSD condition is reached if not more than one test sample particle adheres to the tape on two consecutive checks. (The water-soluble glue of the tape is activated by moisture in the test sample.)

The SSD condition must be established by using at least two criteria of the four Texas DOT procedures described above. Obviously, some subjectivity is involved in all procedures.

The review of literature on establishing the SSD condition of the fine aggregate indicates that the concept used by the Arizona Department of Transportation (*7*) had the most potential of developing an automated equipment to accomplish this. The difficulties encountered in the Arizona experiments are likely to be surmounted with the modern day electronic technology. It was also decided to measure the humidity of the outgoing warm air in addition to the temperature gradient used in those experiments. This was attempted in this study.

EXPLANATION OF TEMPERATURE AND HUMIDITY GRADIENT APPROACH

If a wet sample of fine aggregate is subjected to drying with hot air, then the free moisture on the surface of the aggregate evaporates first, followed by the absorbed water. If the aggregates are dried uniformly, past studies have indicated that a sharp break point can be obtained in a plot of time versus temperature difference (gradient) of incoming and outgoing air at the saturated surface dry condition (Figure 1) (*7*). The different phases can be explained as follows. At the beginning of the test there is a sharp difference between the incoming and outgoing air temperature, since the temperature of the incoming air is extremely high. In the second phase, the entire chamber or drum is at a constant high temperature, and the free water from the surface of the aggregates is driven off at a relatively constant rate. This is indicated by the relatively constant temperature gradient. In the third phase there is an increase in the temperature gradient. This happens because at this point there is a very thin layer of surface water surrounding the aggregate particles, and the rate of evaporation is very high, higher than that in Phase 2. In the fourth phase, there is a sudden break in the curve, indicating that there is no more free surface water on the aggregate, and hence no more high evaporation rate and cooling rate. Therefore, the sudden break point indicates the point of saturated surface dry (SSD) condition. After this point,

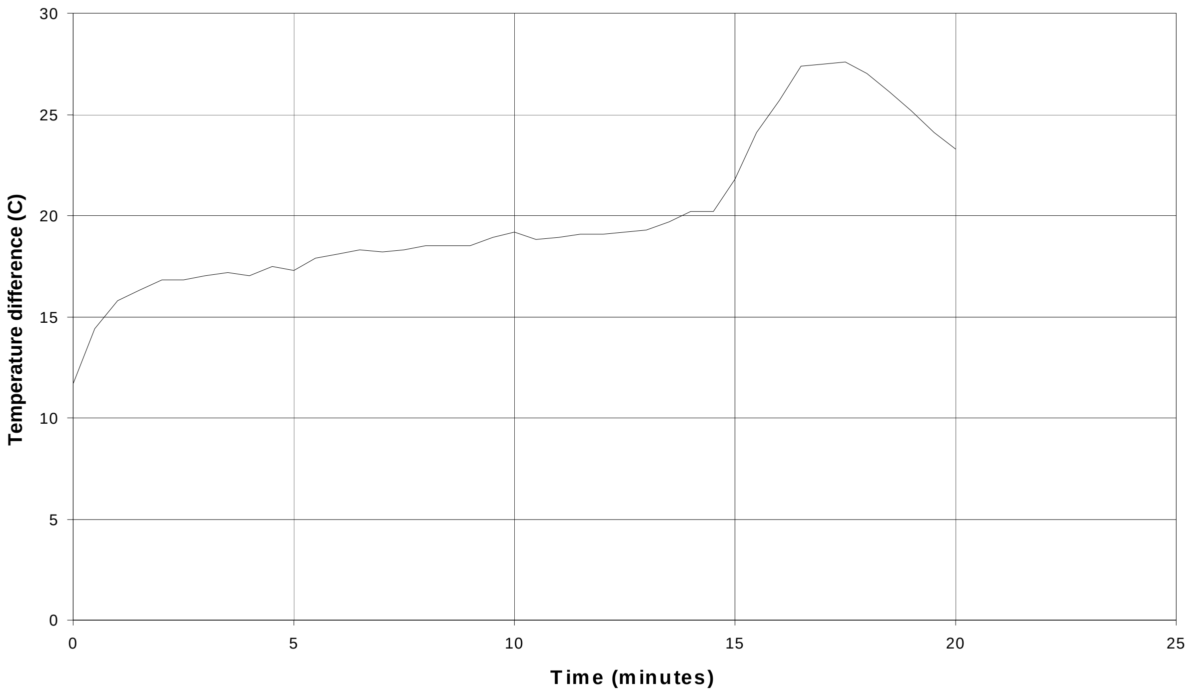

Figure 1. Typical Time Versus Temperature Gradient Plot

the aggregates absorb more heat, to drive off the absorbed water, causing an increase in the temperature of the outgoing air. The increase in the temperature of the outgoing air therefore decreases the temperature gradient. Hence, the key thing is to stop the test when the aggregate reaches the saturated surface dry condition, by looking at the temperature gradient plot and capturing the peak. However, one important thing is that if the test is stopped at the peak, the aggregate undergoes some additional drying while it is being taken out and tested. Hence, a better method will be to stop the test sufficiently ahead of the peak, so that the aggregate, when tested for weight and volume, is at the same state as it would have been at the peak of the temperature gradient plot.

Another possible approach that was tried by the researchers of the National Center for Asphalt Technology (NCAT) study is the analysis of humidity of outgoing air. An example of humidity of outgoing air versus time plot is shown in Figure 2. It is seen that in general the humidity of the outgoing air is high at the beginning of the test, then it drops off rapidly as the aggregate loses moisture. In the next phase the humidity increases slightly, and ultimately reaches a peak and then drops off. This point where it drops off is considered to be the saturated surface dry condition. The different phases can be explained as follows. At the beginning of the test, a large amount of moisture is driven off because of the high inlet air temperature. The humidity of the outgoing air falls and becomes constant as the entire chamber heats up, and there is a constant rate of evaporation from the entire aggregate mass. In the next phase, because of the presence of a relatively thin layer of moisture around aggregate particles, the rate of evaporation increases, and the resultant humidity of the outgoing air also increases and reaches a peak, and then drops off. The peak indicates the point of SSD, beyond which there is no free moisture on the surface.

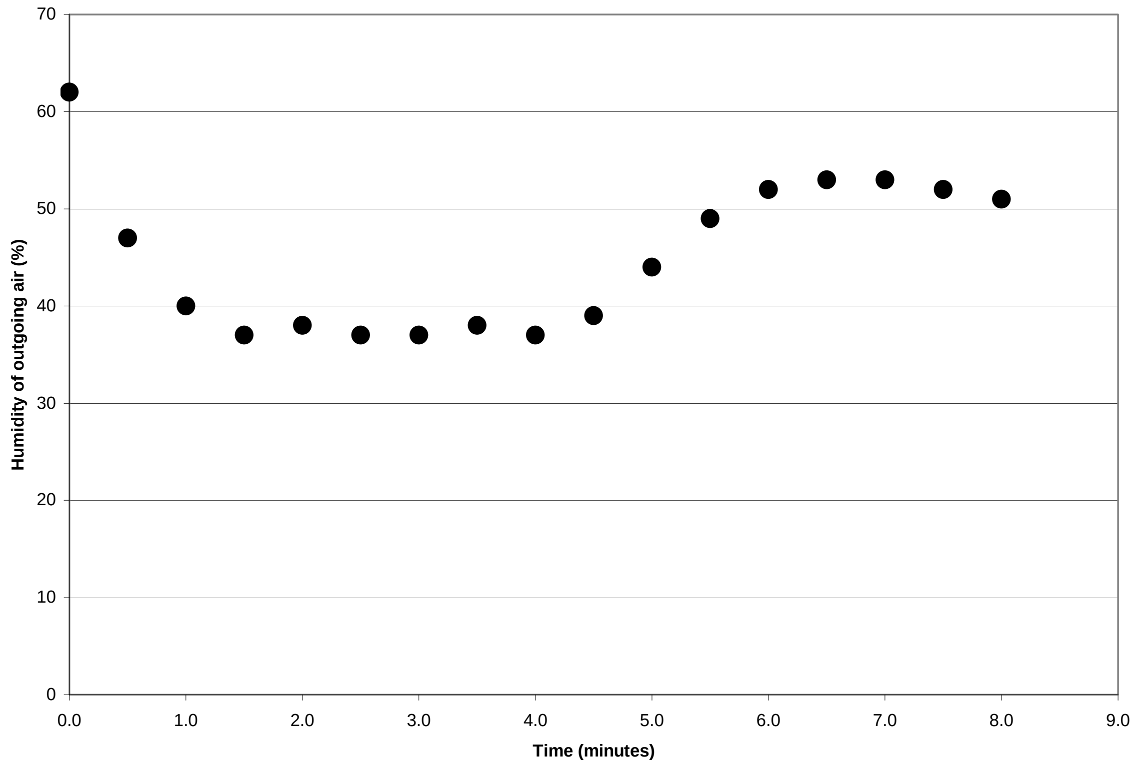

Figure 2. Typical Time Versus Humidity Plot

DEVELOPMENT OF THE FIRST PROTOTYPE TEST EQUIPMENT

The first equipment was developed essentially on the basis of the equipment that was used by the researchers at Arizona DOT (7). Figure 3 and Figure 4 show a schematic and a photo of the equipment. Basically, the device consisted of a rotating Plexiglas drum, mounted on caster wheels, and driven by a belt through a motor. Air was blown with a dryer fan (a hair dryer was used) at one end of the drum, and sensors for temperature were installed at either end of the drum for measuring temperature of incoming and outgoing air. The drum was made out of Plexiglas for convenience of viewing the aggregate inside the drum during testing.

Two flights in the rotating drum provided reasonably consistent drying of the test sample. This drum also utilized a “bumping” device in its rollers to reduce the amount of fines sticking to the walls of the drum. The sample of fine aggregate was confined in the dryer drum by utilizing screens on both the inlet and outlet sides of the drum. A sample of about 1300 grams was used in all experiments. This gives at least 500 grams for determining the weight and volume of the SSD sample, and at least 500 grams for obtaining the oven-dry weight of the SSD sample. The temperature sensors were monitored and recorded on a 30-second cycle during testing for establishing the SSD condition.

Initially, natural sand was subjected to the drying process in the first prototype equipment. Temperature gradient versus time plots from tests with eight samples of natural sand are shown in Figure 5. The plots show expected trends as discussed earlier. However, the data was not very consistent, and the peaks indicating SSD condition are not within a small range of time for the different samples. The samples were taken out at the observed peak and tested for specific gravity. Comparison samples of the same natural sand were tested with the sand cone method (ASTM C128) for specific gravity. The results from both tests are shown in Table 1 (first set).

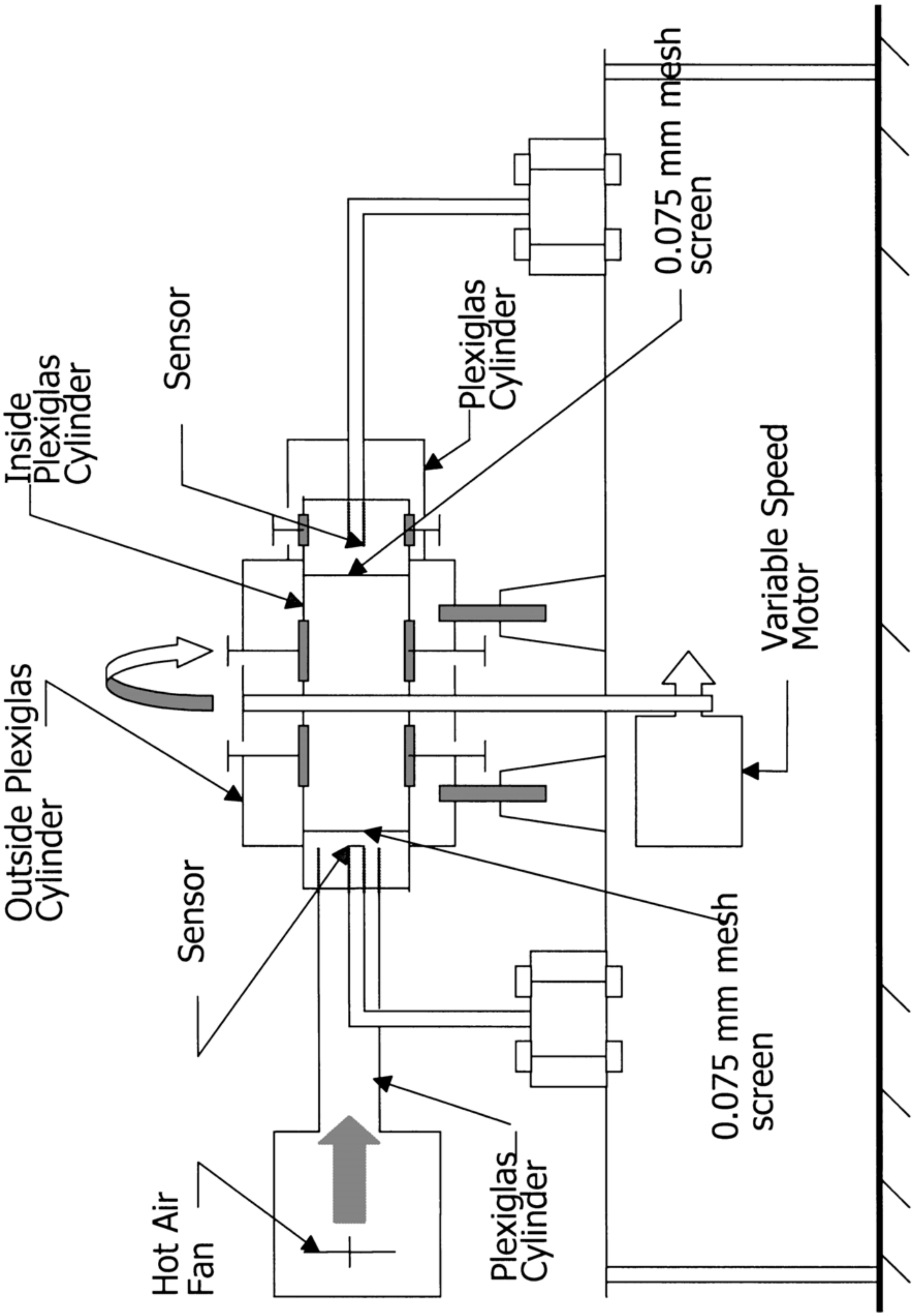

Figure 3. Schematic of the First Prototype Test Equipment

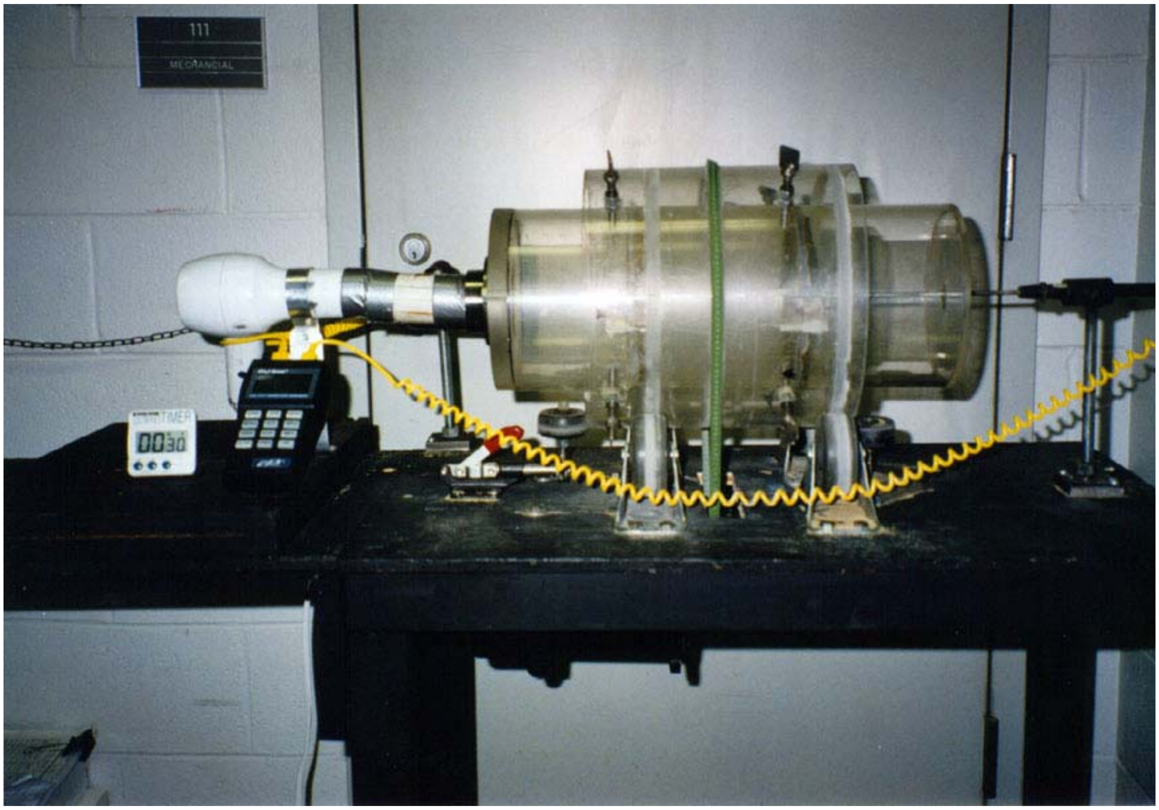

Figure 4. Photograph of the First Prototype Test Equipment

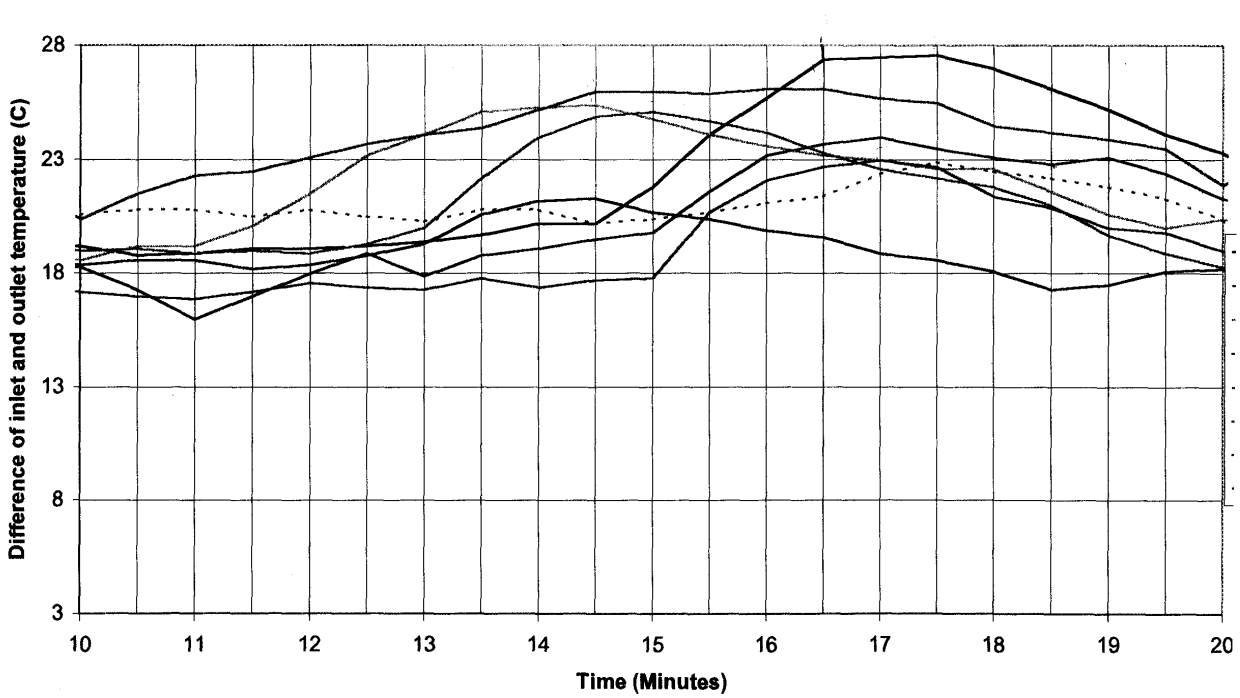

Figure 5. Time Versus Temperature Gradient Plots for Eight Samples of Natural Sand (First Prototype Test Equipment)

The observations were that the samples were mostly too wet when taken out, indicating that the SSD condition had not been reached yet, or the samples were too dry, indicating that the samples were past the point of SSD. It seemed that the SSD condition was being affected by the inlet air temperature, and the amount of sand that was sticking to the sides of the inside wall of the rotating chamber. It was decided to stop the test at the base of the peak of the temperature gradient plot and take out the sample and test them. The criterion for determining the base of the peak was at least a 1-degree increase in temperature. However, specific gravities and absorption of samples run this way did not match with specific gravities and absorption run by the sand cone method (Table 1, second set) and in both cases the samples were found to be over dried. The conclusion was that to use this method successfully, the results should be more consistent, and there should be a rational and practical method of identifying the approaching SSD condition and stopping the test at the right time for specific gravity determination. From the results of this phase of the study, the following conclusions were made:

1. The temperature gradient versus time plot, although consistent with theory, did not seem to be a reliable method of predicting the SSD condition.
2. There was too much sticking of fine particles on the inside of the drum, which could affect the results significantly by resulting in non-uniform drying of the sand.
3. Some of the sand was being blown out near the SSD condition, resulting in loss of materials.
4. The drum has to be re-designed in such a way that the sample can be taken out immediately after achieving the SSD condition for measuring its weight and volume. With the first prototype, it took 3-5 minutes to disassemble the drum and get the sample out.

Table 1. Comparison of Specific Gravity and Absorption Data (First Prototype Test Equipment)

Sample	New Method (Drum)		Sand Cone Method		Observation
	Absorption	Specific Gravity	Absorption	Specific Gravity	
First Set					
1	0.482	2.472	0.583	2.616	Too wet
2	3.219	2.443	0.624	2.618	Too wet
3	2.311	2.501			Too wet
4	0.040	2.650			Too dry
5	0.664	2.605			Slightly wet
Second Set					
1	0.09	2.649	0.583	2.616	Too dry
2	0.10	2.649	0.624	2.618	Too dry

SECOND PROTOTYPE TEST EQUIPMENT

To rectify the problems encountered with the first prototype equipment, the second prototype (Figures 6 and 7) was made with the following changes and modifications:

1. The dryer drum was made out of polished aluminum rather than plexiglass. Gears and rollers improved the rotation system. This made the overall device sturdier, more durable, and easier to work with.
2. The drum consisted of three segments with "quick-snap" clamps to hold it together. Also, the configuration of the second prototype device allows the drum itself to be quickly mounted or removed from the roller/dryer system. These two changes enable the operator to break down the system and drum in approximately 20-30 seconds, minimizing the time between achieving SSD condition and physically obtaining the SSD sample for testing.
3. The first prototype had screens glued into the drum and these screens could not be changed easily. The second prototype utilizes screen inserts that can be changed quickly. Since this device is still under development, the ability to change screen sizes is necessary.
4. A "tapping" device contacting the outside wall of the aluminum drum was installed in the second prototype to shake off fines sticking to the interior of the drum. The first protoype used a "bumping" device. The aluminum drum was also coated with teflon to reduce the sticking of fines to the wall of the drum.
5. A variable speed mechanism was provided to vary the rotational speed of the drum during the developmental stage.

Preliminary tests indicated that there was no significant sticking of sand on the inside surface of the new drum. However, there was some significant blowing of fines which blinded the screen resulting in a rise in the air temperature inside the drum. It was interesting to note that the screen blinding problem was occurring at about the same time the sample was achieving the SSD condition. Because of the blinding problem, the tests were completed on plus 0.6 mm material only to prove that the concept works.

Since the plots of temperature gradient versus time did not provide a distinct way of identifying the SSD condition in the first set of tests, it was decided to observe both temperature gradient and relative humidity of the outgoing air. Typical plots of time versus relative humidity for five different fine aggregates are shown in Figure 8. The data was analyzed, and it was observed that the trend of the humidity plot is more consistent for a particular aggregate than the trend of the temperature gradient plot. As Table 2 shows, the point at which the peak humidity was reached is significantly more consistent than the point at which the peak of the temperature gradient was observed. A SSD criteria was established to take the aggregate out when there were two successive decreases in relative humidity. The magnitude of these two successive decreases generally ranged from 1 to 2 percent as shown in the fifth column of Table 2. Specific gravities were run with this aggregate, and the values were compared to the values obtained by the sand cone test method. Tables 3 and 4 show the data of water absorption and bulk specific gravity of samples, respectively, tested by the new (drum) method and by the sand cone method. Comparisons of average values and standard deviation of water absorption values are shown in Figures 9 and 10, respectively. Comparison of average values and standard deviation of bulk specific gravity values from both tests are shown in Figures 11 and 12.

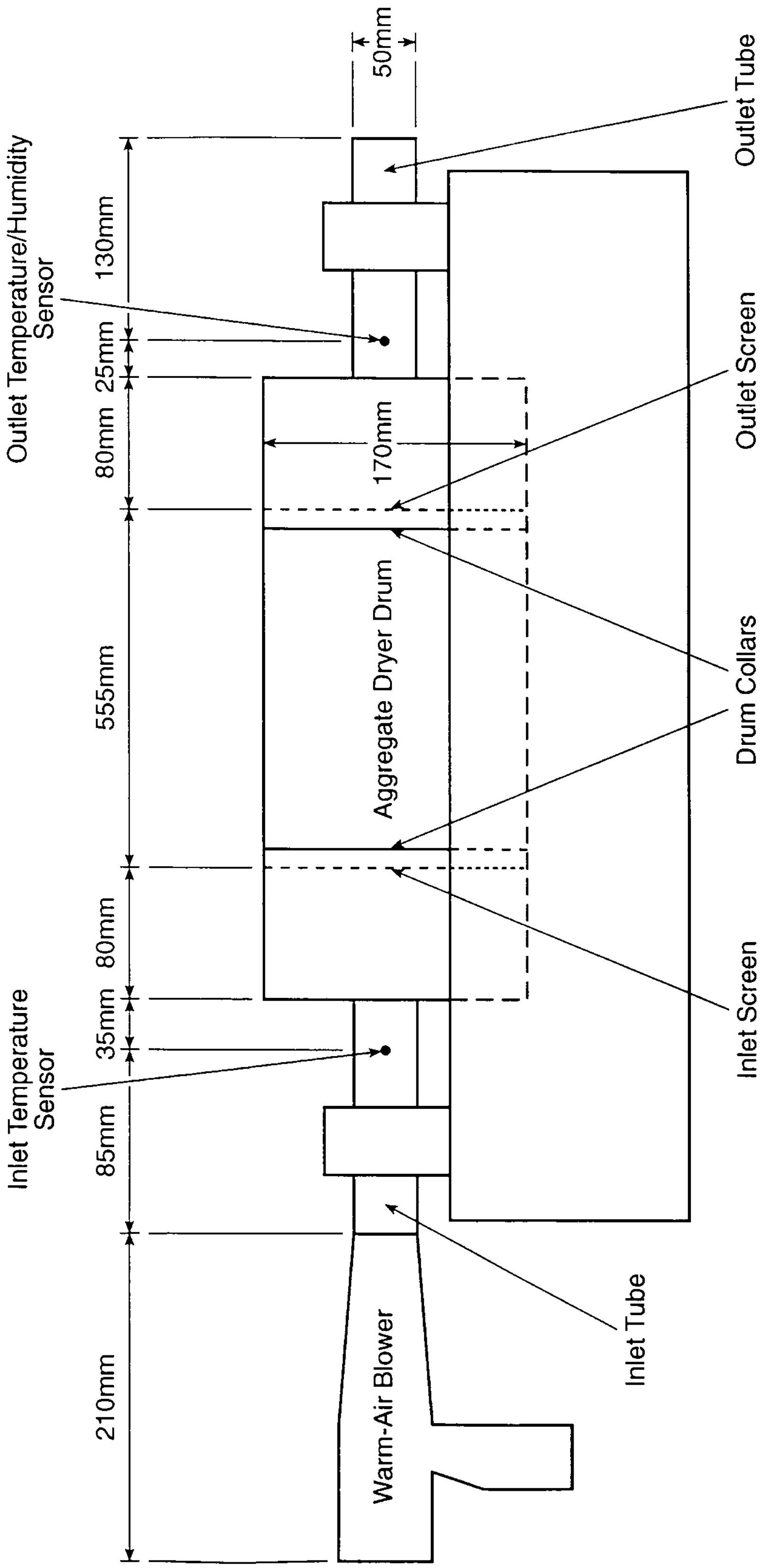

Figure 6. Schematic of the Second Prototype Test Equipment

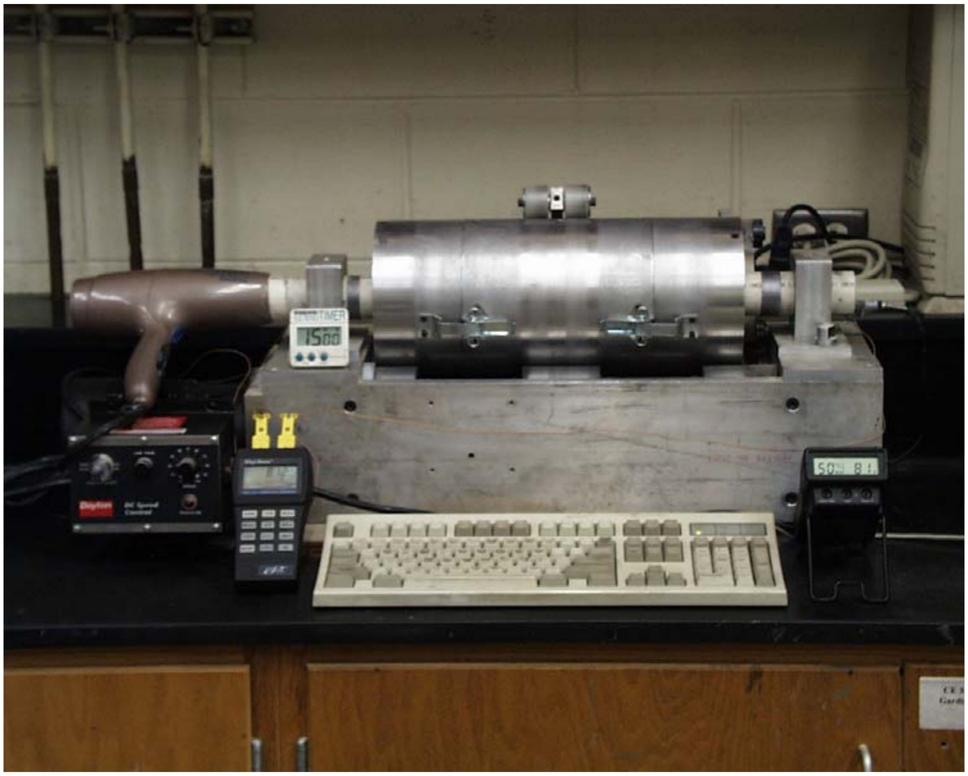

Figure 7(a). Photo of the Second Prototype Equipment

Figure 7(b). Photo of the Second Prototype Equipment with the Data Acquisition System

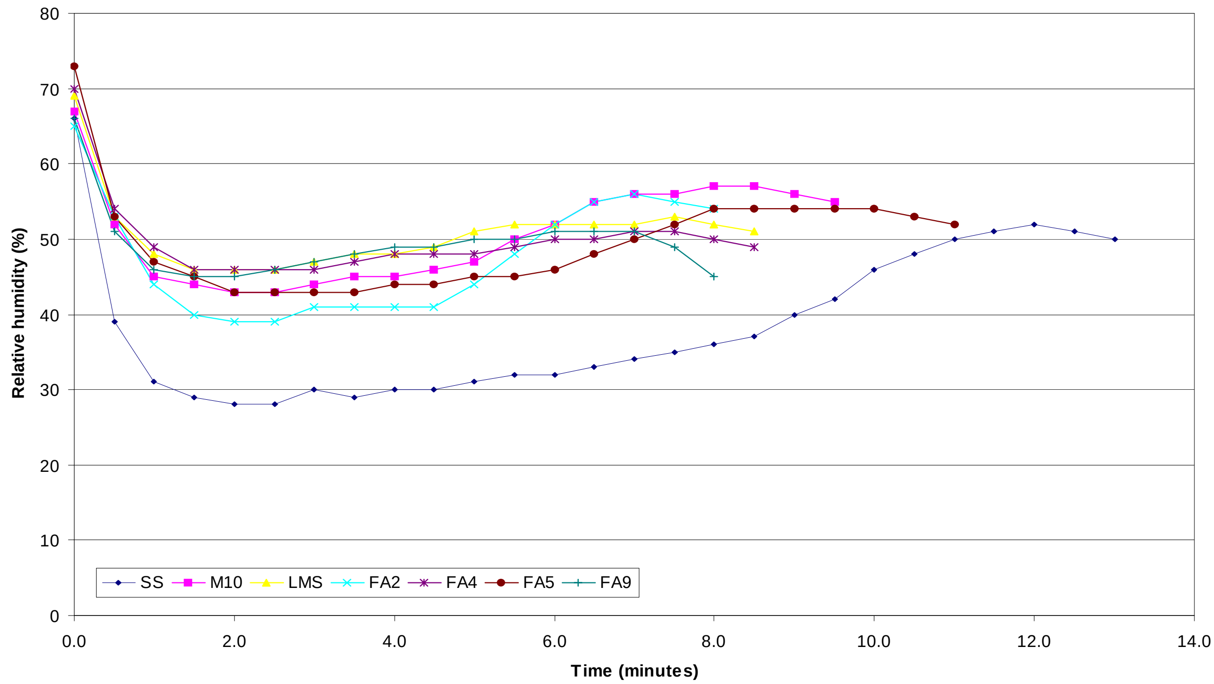

Figure 8. Typical Time Versus Humidity Plot for Seven Different Aggregates (Second Prototype Equipment)

Table 2. Time Versus Peak Humidity and Peak Temperature Gradient Data (Second Prototype Test Equipment)

Fine Aggregate	Sample	Peak Time Versus Humidity (minutes)	Peak Humidity (percent)	) Between Two Successive Humidity Readings After Peak (-ve indicates drop), %	Peak Time Versus Temperature Difference (minutes)	Peak Temperature Difference (°C)	) Between Two Successive Temperature Readings After Peak (°C)
Granite	1	10.0	54	-1,-2	11.0	20.7	Test Stopped
	2	8.5	57	-1,-1	8.0	19.3	-0.3,0.1
	3	9.5	52	-1,-2	9.5	20.1	-0.1,-0.55
	4	9.0	54	-1,-1	10.0	20.2	Test Stopped
	5	9.5	54	-2,- 2	9.5	20.9	-0.2,-0.2
	6	8.5	52	-1,-1	7.0	20.8	-0.3,0.1
	7	9.0	53	-2,-2	9.0	20.2	-0.2,-0.1
	8	9.5	53	-1,-2	9.5	21.8	-0.55,-0.9
	9	8.5	53	-1,-1	8.5	20.7	-0.2,0.1
	10	9.5	54	-1,-2	9.0	20.3	-0.1,0.1
Shorter Sand (Natural)	1	11.5	52	-1,-2	11.5	20.1	-0.4,-0.1
	2	13.0	50	-1,-3	14.0	20.4	Test Stopped
	3	11	50	-1,-2	11	20.1	-0.3,0
	4	12.5	52	-1,-1	13.5	20.1	Test Stopped
	5	12.0	51	-1,-1	13.0	20.3	Test Stopped
	6	12.5	51	-1,-1	12.0	20.2	-0.4,0
	7	11.0	49	-1,-1	12.0	18.8	Test Stopped
	8	13.0	53	-1,-1	14.0	20.3	Test Stopped
	9	11.0	52	-1,-1	11.5	20.0	-0.2
	10	12.0	52	-1,-1	13.0	20.8	Test Stopped

Table 2. Time Versus Peak Humidity and Peak Temperature Gradient Data (Second Prototype Test Equipment)

Fine Aggregate	Sample	Peak Time Versus Humidity (minutes)	Peak Humidity (percent)	) Between Two Successive Humidity Readings After Peak (-ve indicates drop), %	Peak Time Versus Temperature Difference (minutes)	Peak Temperature Difference (°C)	) Between Two Successive Temperature Readings After Peak (°C)
Sandstone	1	10.0	49	-3	10.5	19.5	Test Stopped
	2	8.5	49	-1,-2	7.5	18.2	-0.4,-0.1
	3	6.0	47	-1,0	6.0	18.5	-0.5,0.1
	4	8.0	48	-1,-1	8.0	17.9	-0.7,-0.1
	5	7.5	51	-1,-2	8.0	19.1	-0.6,0.3
	6	7.0	50	-1,0	6.5	18.8	-0.2,-0.1
	7	7.0	54	-1,0	6.5	18.6	-0.3,-0.1
	8	8.0	51	-1,-1	8.5	16.9	-0.6
	9	7.5	51	-1,-1	8.5	17.6	Test Stopped
	10	7.5	53	-1,-2	6.5	18.4	-0.5,0.2
Diabase	1	8.5	49	-2,-2	7.5	20.8	-0.55,-0.6
	2	7.5	47	-2,-3	7.5	19.2	-0.3,-0.1
	3	7.5	49	-1,-2	7.5	20.1	-0.5,0.1
	4	7.0	50	-1,-2	6.0	20.3	-0.1,-1.4
	5	7.0	51	-2,-4	5.5	20.7	-0.3,-0.1
Dolomite	1	10.0	54	-1,-1	10.5	20.5	-0.6
	2	9.5	53	-1,-1	10.5	20.2	Test Stopped
	3	9.0	53	-1,-2	10.0	21.1	Test Stopped
	4	8.5	52	-1,-1	8.0	20.4	-0.5,0.4
	5	8.5	52	-1,-1	7.5	20.2	-0.1,-0.5
Limestone	1	9.5	57	-1,-1	7.5	20.3	0.2,-0.1
	2	9.0	56	-1,-1	7.5	19.5	-0.7,0
	3	10.5	56	-1,-3	9.0	19.6	-0.1,-0.1
	4	11.0	55	-1,-2	8.5	18.5	-0.3,-0.2
	5	7.5	53	-1,-1	7.5	20.7	-0.8,0.5
Quartz Sand	1	8.0	54	-1,-1	8.5	20.9	-0.55
	2	7.0	56	-1,-1	8.0	20.4	Test Stopped
	3	7.0	53	-1,-1	7.5	19.7	-0.2
	4	6.0	53	-1,-1	5.5	19.6	-0.1,-0.5
	5	7.5	53	-1,-2	8.0	21.3	-0.6

Table 3. Comparison of Absorption Data (Second Prototype Test Equipment)

Sample Number	Shorter Sand (46.0)*		Granite Screenings (49.3)*		Limestone Screenings (45.8)*		Fine Agg #2 Quartz Sand (42.6)*		Fine Agg # 4 Sandstone (49.7)*		Fine Agg #5 Dolomite (50.3)*		Fine Agg #9 Diabase (50.1)*	
	Cone	Drum	Cone	Drum	Cone	Drum	Cone	Drum	Cone	Drum	Cone	Drum	Cone	Drum
1	0.46	0.60	0.58	0.76	0.77	0.80	3.20	2.20	1.33	1.81	0.62	1.10	1.21	1.55
2	0.52	0.32	0.42	1.00	0.68	0.74	2.73	2.69	1.44	1.72	0.68	1.05	1.27	1.56
3	0.48	0.40	0.52	1.15	0.70	0.75	3.02	2.60	1.38	1.84	0.64	0.95	1.15	1.59
4	0.38	0.54	0.64	0.93	0.70	0.62	2.86	3.27	1.36	1.62	0.72	1.12	1.40	1.64
5	0.36	0.48	0.40	1.18	0.83	0.83	2.79	2.49	1.45	1.24	0.68	1.32	1.15	1.47
6	0.38	0.50	0.62	0.99					1.56	1.70				
7	0.40	0.42	0.56	0.84					1.48	1.49				
8	0.38	0.46	0.58	1.15					1.58	1.71				
9	0.42	0.36	0.56	0.88					1.23	1.92				
10	0.26	0.56	0.64	0.96					1.56	1.70				
Average	0.40	0.46	0.55	0.98	0.74	0.75	2.92	2.65	1.44	1.68	0.67	1.11	1.24	1.56
Std. Dev.	0.07	0.09	0.08	0.14	0.06	0.08	0.19	0.39	0.11	0.19	0.04	0.14	0.10	0.06

* The values in parentheses are fine aggregate angularity (FAA) values in accordance with AASHTO T304, Method A.

Table 4. Comparison of Specific Gravity Data (Second Prototype Test Equipment)

Sample Number	Shorter Sand (46.0)*		Granite Screenings (49.3)*		Limestone Screenings (45.8)*		Fine Agg #2 Quartz Sand (42.6)*		Fine Agg # 4 Sandstone (49.7)*		Fine Agg #5 Dolomite (50.3)*		Fine Agg #9 Diabase (50.1)*	
	Cone	Drum	Cone	Drum	Cone	Drum	Cone	Drum	Cone	Drum	Cone	Drum	Cone	Drum
1	2.608	2.607	2.661	2.645	2.692	2.691	2.428	2.484	2.691	2.668	2.809	2.693	2.895	2.861
2	2.607	2.600	2.668	2.629	2.694	2.694	2.429	2.455	2.688	2.672	2.783	2.705	2.892	2.860
3	2.623	2.608	2.663	2.618	2.694	2.694	2.446	2.461	2.689	2.667	2.800	2.728	2.891	2.857
4	2.62	2.617	2.653	2.633	2.701	2.699	2.444	2.421	2.691	2.677	2.785	2.688	2.874	2.852
5	2.614	2.605	2.668	2.616	2.690	2.690	2.461	2.467	2.678	2.694	2.798	2.641	2.907	2.869
6	2.612	2.612	2.652	2.629					2.682	2.673				
7	2.607	2.613	2.666	2.640					2.683	2.683				
8	2.624	2.602	2.654	2.618					2.681	2.673				
9	2.615	2.597	2.661	2.637					2.692	2.664				
10	2.600	2.620	2.651	2.631					2.675	2.673				
Average	2.613	2.608	2.659	2.630	2.694	2.694	2.446	2.458	2.685	2.674	2.795	2.691	2.891	2.860
Std. Dev.	0.007	0.007	0.006	0.009	0.004	0.003	0.0136	0.023	0.006	0.008	0.010	0.0320	0.011	0.006

* The values in parentheses are fine aggregate angularity (FAA) values in accordance with AASHTO T304, Method A.

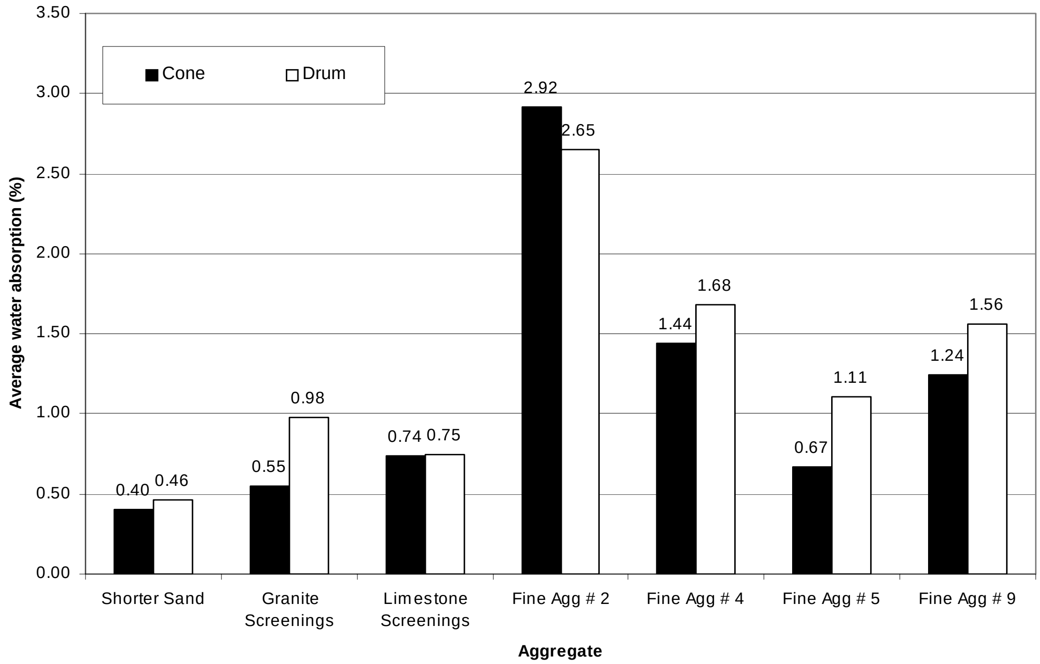

Figure 9. Comparison of Average Water Absorption Data (Second Prototype Test Equipment)

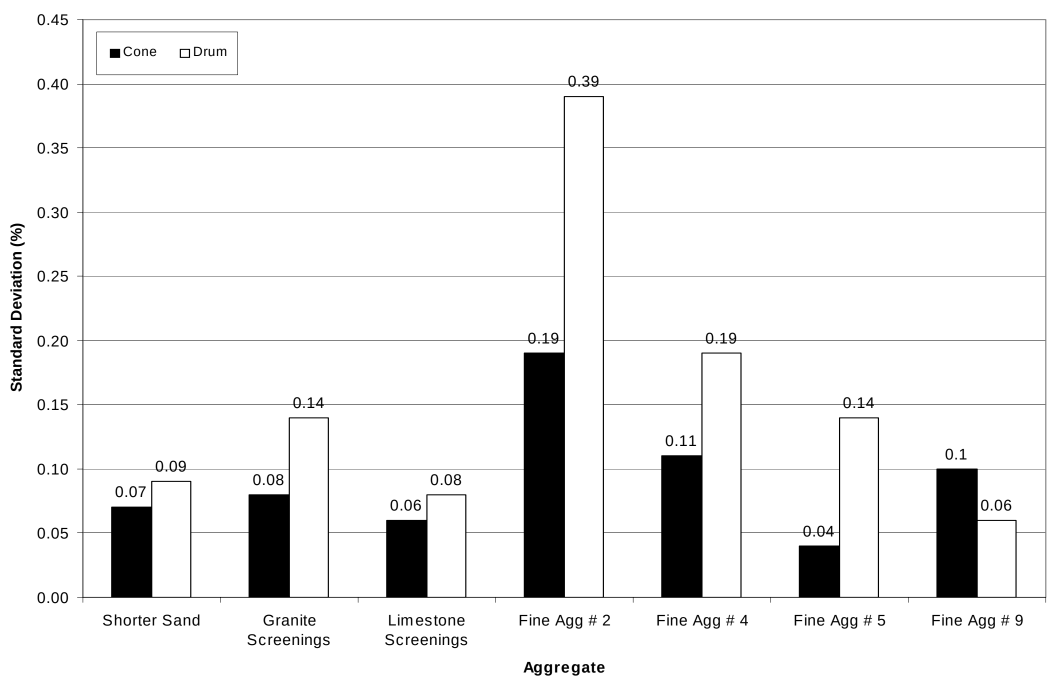

Figure 10. Comparison of Standard Deviation of Water Absorption Data (Second Prototype Test Equipment)

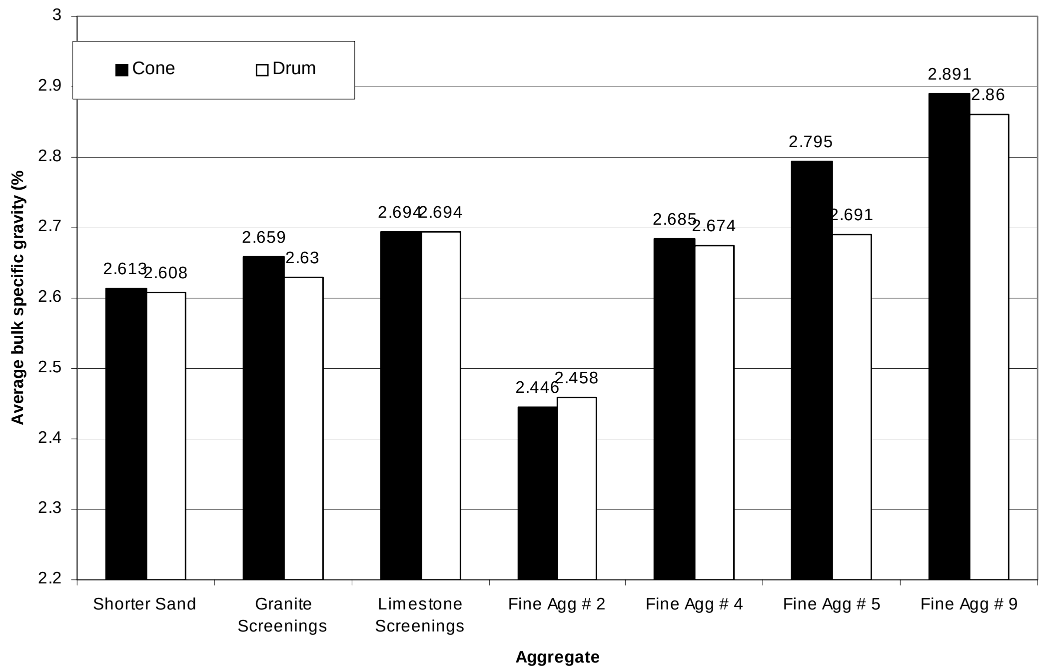

Figure 11. Comparison of Average Bulk Specific Gravity (Second Prototype Test Equipment)

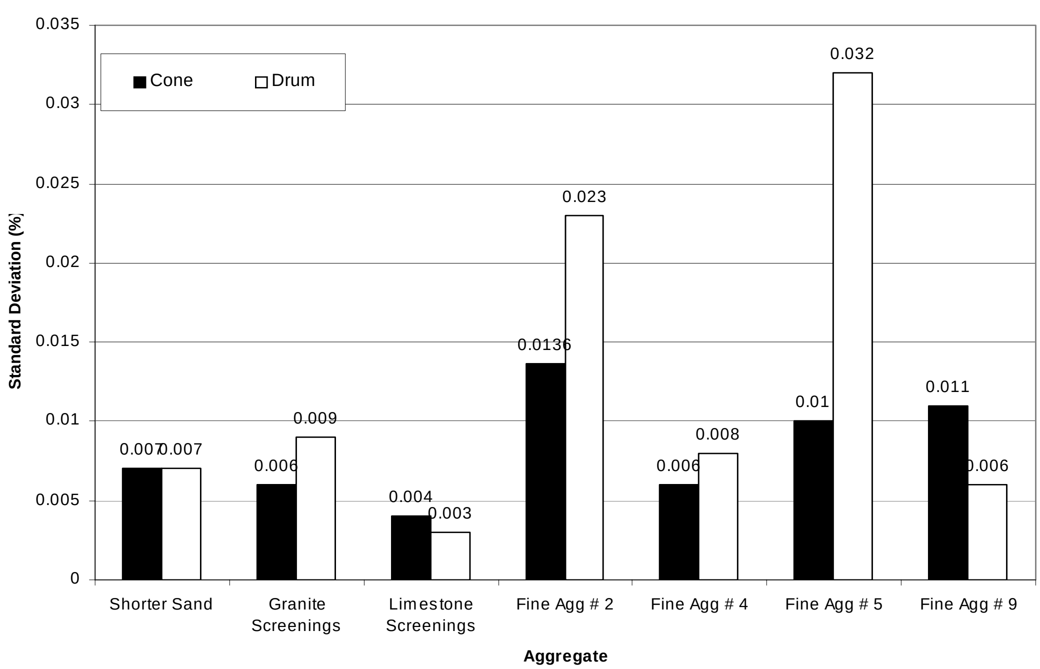

Figure 12. Comparison of Standard Deviation of Bulk Specific Gravity (Second Prototype Test Equipment)

The average bulk specific gravity value of the natural (Shorter) sand obtained from the drum test method (proposed new method) is not significantly different from the value obtained from tests with the cone (currently used) method. The sand cone method is believed to work best with natural sands and, therefore, it is encouraging to see that both methods give similar test results (Table 4, Figure 11). The water absorption values of crushed fine aggregates (Table 3, Figure 9) are generally lower in case of sand cone method compared to drum method. This obviously results from over drying of the crushed, angular fine aggregates to cause the slump. The resulting bulk specific gravity values are, therefore, higher in case of sand cone method compared to drum method (Table 4, Figure 11).

Tables 3 and 4 also give the fine aggregate angularity (FAA) values for the seven fine aggregates used. It is interesting to note that the average water absorption and bulk specific gravity values obtained from both methods are not significantly different for three fine aggregates (shorter sand, limestone, and quartz sand) with FAA values of 46.0 or less. The differences are significant for the remaining four fine aggregates with FAA values of more than 49. Higher FAA values indicate more angular and rough textured aggregate. Therefore, the apparent bulk specific gravity values obtained by the sand cone method for aggregates with high FAA values may not be the true or actual bulk specific gravity values.

However, the standard deviation values from the drum method are slightly greater than the standard deviation values from the cone test method in case of four out of seven aggregates (Table 4, Figure 11). This can probably be attributed to the fact that the stopping of the test at the SSD condition is done manually, and the time taken to observe the humidity data, stop the test, and transport the material for testing can cause significant variation in the subsequent testing. An ideal approach would to be to automate the test completely, so that the drum stops automatically once the SSD condition is reached.

It is proposed to build a third prototype equipment to accomplish the following:

1. Prevent the screen from blinding so that the entire fine aggregate (retained on 75 :m sieve) can be tested. One suggestion is to increase the surface area of the screen by using a spherical screen.
2. Automate the equipment so that it shuts down when the SSD condition is reached.
3. Enhance the capability of the personal computer already in use to automate the data acquisition system.

Equipment manufacturers were invited to build the commercial version of the NCAT's SSD device reported in this paper, which will be evaluated by NCAT. If the commercial version has the capacity of continuously monitoring the mass of the fine aggregate while it is drying in the drum, the sample does not have to be taken out of the drum for weighing when it reaches the SSD condition. The drying can then continue until the sample is completely dry to obtain its dry mass while in the drum. The difference between the SSD mass and the dry mass is the water absorption of the fine aggregate. The apparent specific gravity of the aggregate, which does not involve the SSD condition and is reasonably reproducible, can be measured in a separate test. The bulk specific gravity of the fine aggregate can be calculated by a formula using its percent water absorption, obtained in the NCAT SSD device and its apparent specific gravity.

CONCLUSIONS AND RECOMMENDATIONS

It has been demonstrated that the concept of monitoring the temperature gradient of incoming and outgoing air or relative humidity of the outgoing air, while a sample of wet fine aggregate is dried in a rotating drum, can be used to establish the saturated surface dry (SSD) condition of the fine aggregate. The humidity of the outgoing air appears to establish the SSD condition more distinctly than the temperature gradient.

The second prototype device built by the National Center for Asphalt Technology (NCAT) surmounted many problems encountered in the first prototype device. However, blinding of the screen as soon as the SSD condition is achieved still remains to be a problem. Also, the device needs to be automated further so that it shuts down as soon as the criteria for the SSD condition is met. This will enhance the repeatability and reproducibility of the test. A third prototype device, therefore, needs to be constructed and evaluated as soon as possible. If the device has the capacity of continuously monitoring the mass of fine aggregate while it is drying in the drum, the sample does not have to be taken out of the drum for weighing when it reaches the SSD condition.

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