



Towards an Absolute Mechanical Specification for Gyratory Compaction

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I. Introduction

Gyrotory compaction, developed and improved¹⁻¹³ over the past 50 years, now enjoys popularity throughout the worldwide community of hot mix asphalt producers. This compaction method is widely used in France,³⁻⁶ Australia,⁷⁻¹² Scandinavia,¹³⁻¹⁵ Texas,¹⁶⁻¹⁸ and the rest of the United States,¹⁹⁻²⁴ and the development of a European norm²⁵ promises to spread its use further. There are an increasing number of gyrotory compactor models available on the worldwide market, manufactured by companies located in Finland, France, England, Australia, and the United States. There are likely more than 3000 gyrotory compactors now in use worldwide.

The popularity of gyrotory compaction can be traced to the excellent reproducibility of gyrotory compaction results. Indeed, for any given model located in any given laboratory, the repeatability for compacted specimen density²⁰ is typically better than 10 kg/m³. This level of reproducibility permits gyrotory compaction to be used in production quality control applications, as in the US Superpave²¹ system, where volumetric mix design is based entirely upon gyrotory compaction. Additional mix information, such as shear strength²⁶⁻²⁷ and workability,⁶ can also be derived from gyrotory compaction.

Despite its excellent single laboratory reproducibility, the principle challenge that always confronts a large community of gyrotory compactor users is obtaining comparable results from different gyrotory compactor models. Overcoming this difficulty is particularly important in quality assurance applications, where a (public) governmental laboratory must verify the results reported by a (private) contractor laboratory. If each laboratory owns a different gyrotory compactor model, then the two laboratories must be assured that both models provide comparable results.

While one might expect that comparable results could be assured by carefully specifying certain critical parameters (i.e., consolidation pressure, angle of gyration, temperature, mould dimensions, etc.), small variations in machine compliance from one model to another can significantly²⁸ alter compaction results. The proposed European norm²⁵ for gyrotory compaction alludes to this problem in Section 4:

Due to different mechanical characteristics of gyrotory compactors, angle f and force F shall be traceable according to a calibration chain in order to give the same void content for a fixed number of gyrations.

In particular, the compliance issues associated with the angle of gyration²⁹⁻³⁰ have been the subject of much recent scrutiny.

Confronted with no convenient means to account for such compliance issues, previous large scale implementations of gyrotory compaction (in France, Australia, and the United States) have been based on so-called *type testing*. While the specific details of type testing in each country differ slightly, they all share four points in common:

- (1) All initial gyrotory compactor research was performed on a particular compactor model. By default, the densification characteristics obtained from this original model become a kind of “standard” for subsequent implementation of gyrotory compaction.
- (2) All new gyrotory compactor models must demonstrate the ability to reproduce the “standard” densification characteristic. Such a demonstration (*i.e.*, the “type test”) involves a direct comparison of the new model with the original and/or an ability to produce the “expected” result for a set of well-known standard mixes.
- (3) Any such type test must be carried out at a nationally recognized laboratory. Such testing consumes significant resources because of the large quantity of hot mix asphalt that must be compacted.
- (4) In the case of failure to compare, the manufacturer of the new gyrotory compactor model makes any required mechanical adjustments (usually by altering the angle of gyration) until the new compactor produces the “expected” results.

In the United States, type testing uses four standard mixes²⁰ to directly compare a new gyrotory compactor model to one of two existing standard models. In France,⁶ the behaviour of a new compactor is evaluated using two standard mixes. Likewise, the European norm²⁵ for gyrotory compaction (based on the French method) proposes the use of two standard mixes. And in Australia, a recent report¹² describes the need to use a single mixture to evaluate compaction results:

There is no standard material that can be used to check compactive effort in the same way that an oil can be used to check a viscometer. In the case of viscosity measurement, suitable oils can be purchased which have been tested in such a way that their viscosity can be related back to international standard measures of length, mass, etc.

Since there is no standard compaction material, gyrotory compactors have to be checked by comparing the results from a large number of like devices which have been used to test the same material. In this case, no single compactor is deemed to be correct but the mean result for the material is taken as the best estimate of its property. Compactors which produce a result very different from this mean value are likely to be in error and should be examined for faults.

A significant point made by the Australian author is that the current system is not based upon an absolute reference traceable to international standards. Rather, a composite hot mix asphalt material, derived from naturally occurring sources of variable composition, forms the entire basis for a kind of “relative standard” of gyrotory compaction. Clearly, a more desirable system would make exclusive use of international standards to traceably calibrate ram pressure, angle of gyration, gyration rate, mould dimensions, and the like. With the exception of the angle of gyration, in fact, all of the other parameters are quite easily traced to international standards.

Internal Angle Devices

To address the difficulty in measuring the angle of gyration, new devices have recently been developed that purport to measure the “internal” angle of gyration. Given that any measure the external tilt angle of the mould (**a**) will fail to take into account the relative orientation of the end plates (see **Figure 1**), it is thought that a better place to measure the angle of gyration is from within the mould itself. Designed to fit inside the mould, these new devices can measure both the top (**d_T**) and bottom (**d_B**) internal angles of gyration. One such device²⁹⁻³⁰ is the Dynamic Angle Validator (DAV) developed in the United States by the Federal Highway Administration (see **Figure 2**), and another such device³¹ is the Internal Load Simulator (ILS) developed in Finland by Invelop Oy (see **Figure 3**).

The Dynamic Angle Validator (DAV). The DAV device, which is also known as the Angle Validation Kit (AVK), is capable of measuring the angle of gyration on any gyrotory compactor equipped with a 150 mm diameter mould. When placed inside the mould below a sample of hot mix asphalt, the DAV measures the bottom internal angle (see **Figure 2a**). Likewise, when placed above the sample, the DAV measures the top internal angle (see **Figure 2b**). The DAV is traceable to international standards by means of a “static angle block” machined with known calibration angles (see **Figure 2c**). The amount of load placed on the compactor frame during angle measurement depends upon the size of the asphalt specimen (see **Figure 2d**).

The Internal Load Simulator (ILS). The ILS device also works with any compactor equipped with a 150 mm diameter mould (see **Figures 3a, 3b**). A dial gauge with an exposed probe (see **Figure 3c**) records the angle of gyration. If the probe is oriented upwards, then the top internal angle of gyration is measured. Conversely, if the probe is oriented downwards, then the bottom internal angle of gyration is measured. Unlike the DAV device, the ILS does not require a sample of hot mix asphalt to induce a load on the compactor frame. Instead, various loads are “simulated” using pairs of metal rings (see **Figure 3d**) affixed to the top and bottom of the ILS. Both the ring diameters and the dial gauge are traceable to international standards.

Because each device can measure the internal angles while the frame is placed under load, it should be possible to account for any differences in machine compliance. If two or more compactors use the very same compaction parameters (ram pressure, total gyrations, gyration rate, etc.) and are adjusted to the same “internal” angle setting, then it is anticipated that these compactors might all produce specimens of nearly equivalent density. Such a favourable result would suggest that an “absolute” standard for gyrotory compaction might one day replace the present day “relative” standards based on type testing. This report describes a preliminary experiment that produced such a favourable result.

II. Experimental

Hypothesis. If a gyrotory compactor is set to a specific internal angle and a specific pressure then specimens prepared using this compactor of a specific mix compacted to a specific number of gyrations should have the same average density as specimens from another compactor which has also been set to the same specific internal angle and a specific pressure as the first one.

To define what is meant by “same average density”, it is noted that a provisional specification²⁰ used in the United States declares that two gyrotory compactors are considered to compare favourably when the average density of specimens produced with the two compactors agrees within 10 kg/m^3 . The conditions required for this comparison are quite rigid: (1) the two compactors must be located *in the same laboratory*, (2) a *laboratory -prepared mixture* must be used, (3) a total of *six replicate specimens* must be prepared on each compactor and (4) the final specimen dimensions must be $150 \text{ mm OD} \times 115 \pm 5 \text{ mm}$.

For the small-scale, pilot experiment described in this report, enough mixture was procured to permit six replicate specimens to be prepared on each compactor. However, the mixture was produced at an asphalt plant, and the compactors were not placed in the same laboratory. So for this preliminary experiment, the rigid criteria of the US specification (10 kg/m^3) may not be applicable.

Mixture Properties. A large sample of a plant-produced mixture was obtained from a Dutch asphalt plant and brought to the laboratory in metal cans. The mixture was reheated in the laboratory and carefully portioned into the appropriate sample sizes to produce a set of specimens with the same final dimensions ($150 \text{ mm OD} \times 115 \pm 5 \text{ mm H}$). See Appendix B for mix specifications.

Compactor Models. The main portion of the study involved three gyrotory compactors (see **Figure 4** located in the Netherlands: Pine AFGC125X (Rasenberg Contractors, Breda), ELE/IPC Servopac (KOAC Dutch Road Laboratories, Apeldoorn), and Invelop Oy ICT-150RB (ROHAC Contractors, Rotterdam). Additional internal angle measurements reported here were obtained on gyrotory compactors located in the United States.

Compaction Parameters. Each compactor involved in the density comparison experiment was adjusted to the same compaction parameters. The ram pressure was $600 (\pm 30) \text{ kPa}$, the gyration rate was $30 (\pm 2) \text{ RPM}$, and the moulds had an inner diameter of 150 mm . A total of 80 gyrations were applied to each specimen.

Internal Angle Adjustment. The ILS device was used to adjust the angle on all of the compactors involved in the density comparison experiment. First, the internal angle was measured on one of the compactors (Pine AFGC125X), and then the other compactors (ELE Servopac and Invelop Oy ICT-150RB) were adjusted to nearly the same angle.

Experimental Protocol. See Appendix A.

Density Measurement. The density of compacted specimens was computed by dividing the dry mass of the specimen by the volume occupied by the specimen. However, the volume of the specimen was computed in three different ways. In the first method, the volume was computed from the diameter of the mould and the final specimen height reported by the compactor. In the second method, the volume was computed (after the specimen had cooled) by physically measuring the height and diameter of the specimen. In the third method, the specimen volume was measured by water displacement.³²

III. Results

Angle Adjustments

Shear forces are induced during internal angle measurement by a pair of rings permanently affixed to the top and bottom of the ILS device (one ring is on the top, and the other ring is on the bottom). The diameter of these two rings is 45,0 mm. According to the manufacturer, this ring diameter causes the ILS to create a load that is approximately the same as that created by a hot mix asphalt specimen with a height of $115 \text{ mm} \pm 5 \text{ mm}$. Thus, the ILS makes internal angle measurements under loading conditions that are similar to those caused by compacting an actual specimen. (A second pair of larger diameter rings is also provided with the ILS, and these are discussed in the next section.)

Using the smaller rings, replicate internal angle measurements were made on a Pine AFGC125X compactor (see **Table I**). The owner of this compactor reported that its external angle of gyration (**a**) was 1,28 degrees (not loaded). Using the ILS device, the top internal angle was consistently lower than the bottom internal angle, and the overall average internal angle (**d**) was 1,175 degrees. These ILS results are nearly the same as DAV results previously reported³⁰ for this compactor model.

Next, the other two gyrotory compactors were adjusted to the same internal angle of gyration as the Pine AFGG125X compactor (see **Table II**). For the ELE/IPC Servopac, which has software adjustable angle of gyration, the average internal angle was adjusted to 1,174 degrees by setting the external angle to 1,20 degrees. For the Invelop Oy ICT-150RB compactor, which has an angle that is easily adjusted mechanically, the average internal angle was adjusted to 1,186 degrees by setting the angle to 23 mrad on scale.

Note that for all three compactors, the internal angle is always lower than the external angle. Previous reports have primarily attributed the lower internal angle to the fact that the end plates can deflect independently of the mould. That is, the end plates may not always be parallel and the general tendency is for any deflection to work in opposition to the forces maintaining the angle. The net result is a lower internal angle of gyration due to end plate deflection.

Also, for all three compactors, the top internal angle is smaller than the bottom internal angle (see **Table II**). This can be explained by the fact that on all three models, the compaction ram pushes against the top of the specimen, while the bottom of the specimen is supported by a rather rigid surface. Thus, there is more opportunity for deflection of the top end plate, and the top internal angle is smaller.

Gyrotory Compactor Stiffness

As mentioned above, a second set of larger diameter rings can be installed on the top and the bottom of the ILS. These larger diameter rings produce a greater simulated

load, so that the ILS can be used as a tool to study the response of a compactor to variations in loading. For an ideal compactor with “infinite” stiffness, the angle of gyration would remain unchanged regardless of the load, but in reality, all gyrotory compactors react to the load placed on the frame. Usually, a greater load causes the angle of gyration to decrease.

The ILS manufacturer suggests that the way to quantify the load simulated by the ILS device is to compute a physical moment. The product of the total vertical force and the *radius* of the ring yields a moment referred to as the *tilting load*. For the experiment described here, the ram pressure is 600 kPa, which corresponds to a vertical force of 10602 newtons. For the 45,0 mm ring, this produces a 238,5 N m tilting load. For the 86,0 mm ring, the “tilting load” is 455,9 N m.

Four gyrotory compactors were analysed using both ILS ring diameters. A plot of the internal angle versus the tilting load (see **Figure 5**) shows how each compactor responds to an increase in the load simulated by the ILS. The amount of angle change due to increased loading (*i.e.*, the slope on the plot) provides a way to quantify the stiffness of a given gyrotory compactor. All four gyrotory compactors analysed in this fashion had stiffness slopes less than 0,013 mrad / N m.

Density Comparisons

Two of the compactors involved in this study were adjusted to nearly the same internal angle of gyration (Pine AFGC125X and ELE/IPC Servopac, see **Table II**). Replicate hot mix asphalt samples were compacted on each machine, and the density of the compacted specimens was computed using three different methods (see **Tables III and IV**). Comparing the average hydrostatic density³² measurements (water displacement method), very good agreement was observed (to within 11 kg/m³) between these two compactors. Given that these compactors were located in two different laboratories, it is remarkable that the agreement actually approaches the 10 kg/m³ criteria²⁰ typically applied only to single laboratory comparisons.

It was originally planned to include a third compactor (Invelop Oy ICT-150RB) in the density comparison experiment, but an unfortunate miscommunication led to improper compaction of the specimens using this third compactor. This compactor had also been adjusted to nearly the same internal angle of gyration as the other two machines. By the time the error was discovered, it was only possible to produce a single specimen in the proper fashion. Interestingly, this single specimen had a hydrostatic density equal to 2413 kg/m³, which falls between the results from the other two compactors. While basing any conclusions on the result from a single specimen is tenuous at best, the density of this specimen is consistent with the results from the other two compactors.

IV. Discussion

The excellent agreement observed in the density comparison experiment points to the possibility of creating a standard for gyratory compaction that is based entirely upon traceable, absolute measurements of pressure, angle, height, etc. Specifically, the new internal angle measurement devices (DAV and ILS) offer the possibility of obtaining equivalent densification from different gyratory compactor models without the need for traditional, time consuming type testing. Indeed, the need for any kind of special “standard” hot mix asphalt is eliminated when using the simulated loading provided by the ILS device. While the scope of this study is quite limited and a larger study is certainly required, the prospect of a new standard for gyratory compaction looks promising.

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Table I
Replicate ILS Internal Angle Measurements for a Pine AFGC125X Compactor
(unloaded, external angle set at 1.28 degrees)

| replicate | top internal angle | bottom internal angle | average |
|-----------|--------------------------|-----------------------------|--------------|
| 1 | 1,160 | 1,187 | |
| 2 | 1,174 | 1,184 | |
| 3 | 1,166 | 1,183 | |
| 4 | 1,166 | 1,184 | |
| 5 | 1,163 | 1,180 | |
| average | 1,166 | 1,184 | 1,175 |

Table II
Gyrotory Compactor Angle Measurements (External set and Internal)

| | Pine AFGC125X | Invelop Oy ICT-150RB | ELE/IPC Servopac |
|--|-----------------------|-------------------------|-----------------------|
| external angle | 1,28 | 1,32 | 1,20 |
| average internal angle (standard deviation) | 1,175 0,003 | 1,186 0,011 | 1,174 0,011 |
| total replicates | 5 | 3 | 4 |
| average top angle (standard deviation) | 1,166 0,005 | 1,145 0,012 | 1,149 0,013 |
| average bottom angle (standard deviation) | 1,184 0,003 | 1,226 0,010 | 1,199 0,012 |
| top to bottom difference | 0,018 | 0,081 | 0,050 |

Table III
Density (kg/m³) of Specimens Compacted using Pine AFGC125X
(internal angle set at 1,175 degrees, 80 total gyrations)

| replicate | Density Computation Method | | |
|----------------------|----------------------------|--------------------------|--------------------------|
| | D _{gyratory} | D _{dimensional} | D _{hydrostatic} |
| 1 | 2372 | 2385 | 2407 |
| 2 | 2379 | 2389 | 2411 |
| 3 | 2381 | 2391 | 2407 |
| 4 | 2371 | 2382 | 2408 |
| 5 | 2372 | 2388 | 2407 |
| 6 | 2374 | 2390 | 2404 |
| 7 | 2381 | 2395 | 2408 |
| 8 | 2381 | 2395 | 2407 |
| average | 2376 | 2389 | 2407 |
| (standard deviation) | 4.53 | 4.50 | 1.92 |

Table IV
Density (kg/m³) of Specimens Compacted using IPC/ELE Servopac
(internal angle set at 1,174 degrees, 80 total gyrations)

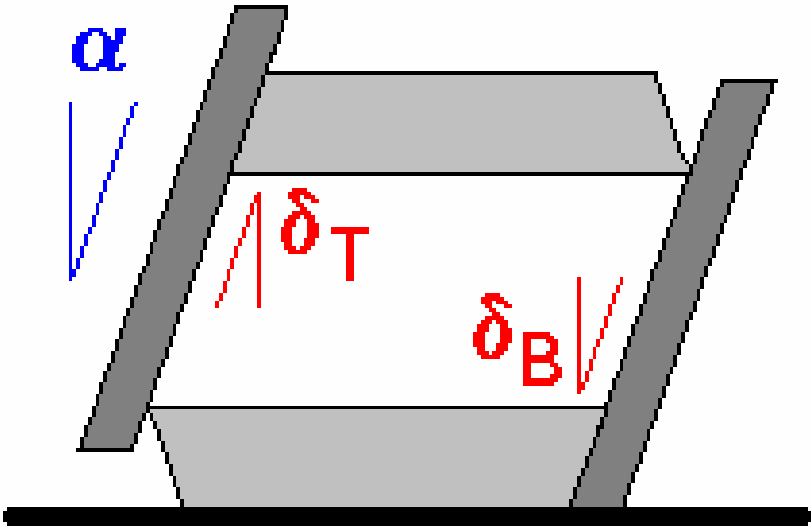
| replicate | Density Computation Method | | |
|----------------------|----------------------------|--------------------------|--------------------------|
| | D _{gyratory} | D _{dimensional} | D _{hydrostatic} |
| 1 | 2387 | 2405 | 2419 |
| 2 | 2397 | 2412 | 2418 |
| 3 | 2387 | 2407 | 2416 |
| 4 | 2386 | 2410 | 2418 |
| 5 | 2389 | 2411 | 2418 |
| 6 | 2384 | 2406 | 2417 |
| 7 | 2379 | 2405 | 2419 |
| 8 | 2380 | 2404 | 2416 |
| average | 2386 | 2408 | 2418 |
| (standard deviation) | 5.62 | 3.07 | 1.19 |

D_{gyratory} This method divides the specimen mass by a volume computed from the mould diameter and the final specimen height reported by the gyratory compactor.

D_{dimensional} This method divides the specimen mass by a volume computed from the diameter and height measured after the specimen has cooled.

D_{hydrostatic} This method³² divides the specimen mass by a volume measured by means of water displacement.

Figure 1
Illustration of the Relationship between Internal and External Angle of Gyration



- (a) The external angle of gyration is the tilt of the mould with respect to the vertical axis.

- (d) The internal angles of gyration at the top and bottom of the mould (δ_T and δ_B) are usually less than the external angle of gyration, given that the end plates deflect to non-parallel orientations.

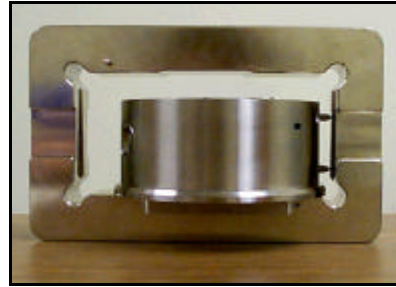
Figure 2
Photographs of the Dynamic Angle Validator (DAV)
developed by the United States Federal Highway Administration



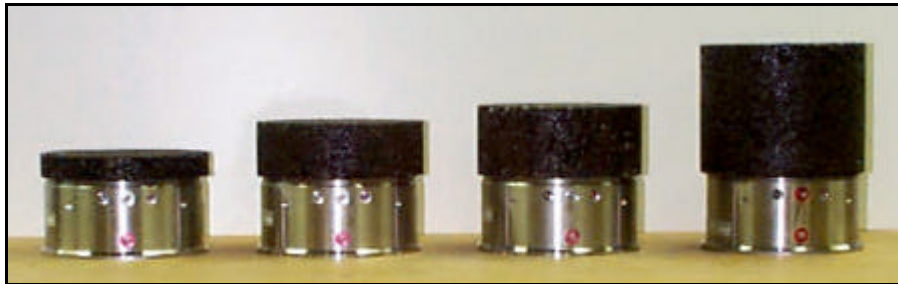
(a)



(b)



(c)



(d)

- (a) The DAV is placed beneath a hot mix asphalt sample when measuring the bottom internal angle of gyration.
- (b) The DAV is placed above a hot mix asphalt sample when measuring the top internal angle of gyration.
- (c) The DAV is routinely calibrated against a Static Angle Block machined with four different known angles.
- (d) The internal angle can be measured under different shear loads by varying the amount of asphalt placed in the mould with the DAV. The more asphalt that is in the mould, the greater the shear load placed on the compactor.

Figure 3
Photographs of the Internal Load Simulator (ILS)
developed by Invelop Oy in Finland



- (a) The ILS shown with a 150 mm diameter mould for the ELE ServoPac gyrotory compactor.
- (b) The ILS shown with a 150 mm diameter mould for the Pine AFGC125X Superpave gyrotory compactor.
- (c) The ILS includes a dial gauge for recording the internal angle of gyration. The dial gauge probe is pointed upwards when measuring the top internal angle or downwards when measuring the bottom internal angle.
- (d) The internal angle can be measured under various “simulated” shear loads simply by using rings of various diameters on top and bottom of the ILS. The 45,0 mm diameter ring is permanently attached to the ILS. A larger ring (86,0 mm diameter) can be attached in order to simulate a greater load.

Figure 4
Photographs of Three Gyratory Compactors Models Used in this Study



(a)



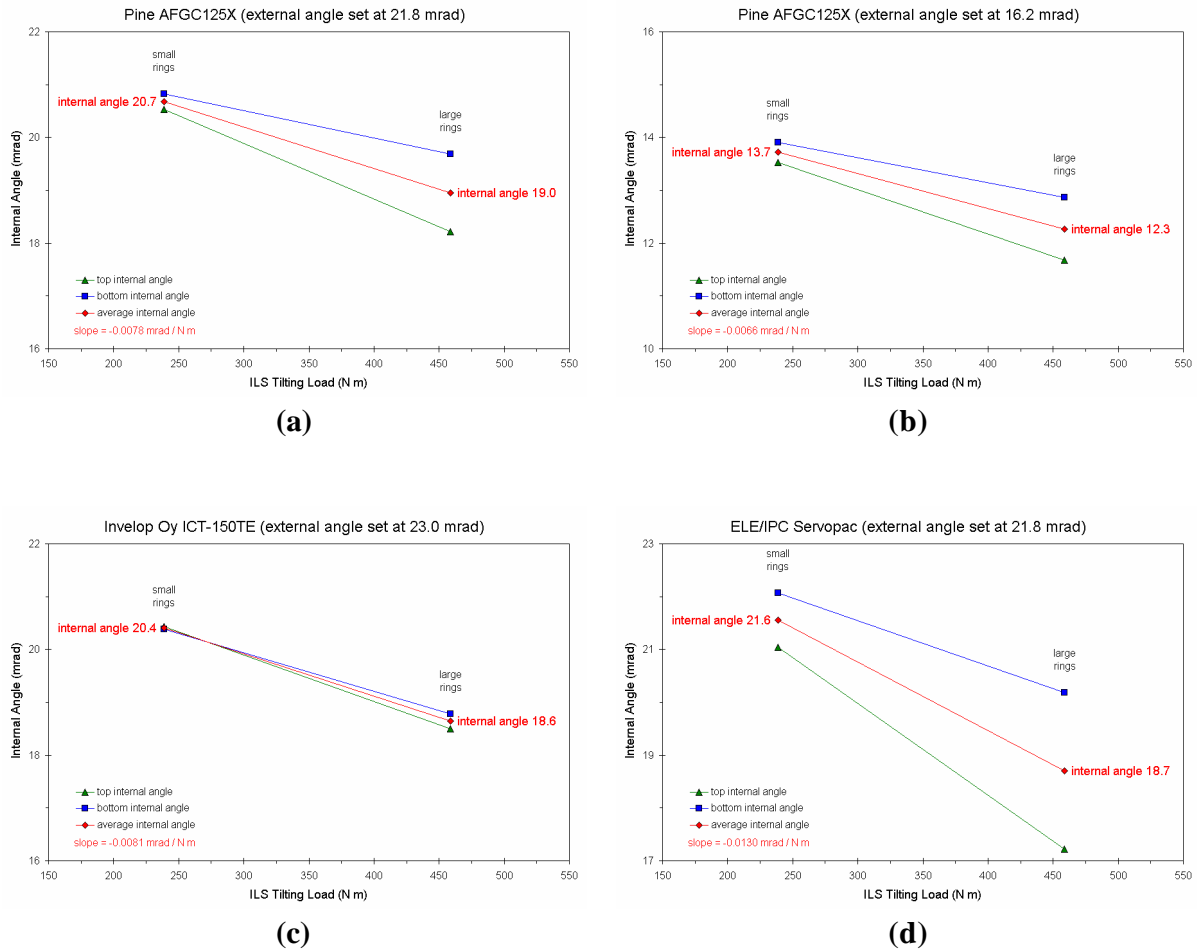
(b)



(c)

- (a) Invelop Oy ICT -150RB Gyratory Compactor (Designed in Finland).
- (b) ELE ServoPac Gyratory Compactor (Designed in Australia).
- (c) Pine AFGC125X Superpave Gyratory Compactor (Designed in the United States)

Figure 5
Plots of ILS Internal Angle of Gyration versus “Simulated” Tilting Load



- (a) Pine AFGC125X Compactor, External Angle Set at 21.8 mrad (1.25°)
 (b) Pine AFGC125X Compactor, External Angle Set at 16.2 mrad (0.93°)
 (c) Invelop Oy ICT-150TE Compactor, External Angle Set at 23.0 mrad (1.32°)
 (d) ELE/IPC ServoPac Compactor, External Angle Set at 21.8 mrad (1.25°)

APPENDIX A – Experimental Protocol Details

The following protocol is the original plan for this experiment.

- (1) Obtain a large quantity of hot mix asphalt from a convenient asphalt plant. It is preferable to use a small size (i.e., less than 12.5 mm), continuously graded mixture. Use metal cans to collect the mixture and transport it back to the laboratory. (Approximately 50 kg of material will be needed for each compactor involved in the study.)
- (2) Determine the mass of this mixture required to produce a gyrotory specimen with a final height somewhere between 110 mm and 120 mm. This target mass will typically fall somewhere between 4800 g and 5000 g.
- (3) Carefully reheat the mixture in each laboratory (in the cans), pour it out on to a large table, and then split it into specimens which have the **target mass** (+/- 1 gram).
- (4) Be sure every gyrotory compactor has been thoroughly checked and maintained by the manufacturer or by a skilled technician.
- (5) Calibrate the force, height, and angle systems on each gyrotory compactor according to the manufacturer's instructions. Adjust all compactors to the same **target pressure** (i.e., 600 kPa).
- (6) Measure the internal angle of gyration on each compactor. This angle measurement must be made under a load (tilting load of 250 Nm).
- (7) Make adjustments to each gyrotory compactor so that the internal angle is set to a desired target internal angle (preferably 1.16 degrees, but it may be some other value for this "light" test, if needed). In general, the results from step (6) should be helpful for determining by how much the angle should be changed.
- (8) Measure the internal angle of gyration on each compactor again. All gyrotory compactors should be adjusted to the **same target internal angle** (+/- 0.01 degrees). Preferably, all internal angle measurements are performed by the same person.
- (9) Compact six specimens on each gyrotory compactor. The mass of these specimens should be the target mass. **IMPORTANT:** All 6 specimens must be prepared on each compactor on the same day by the same person. The compaction sequence should be similar in other laboratories for the other compactors (the coordinator should take care that the operator practices are reasonably similar).
- (10) Determine the density (bulk specific gravity) for each specimen using an appropriate method. Compute the average density for each compactor. Also report the geometric densities determined from the mass and final height of the specimen (i.e., using the final height reported by the compactor).

Notes:

For the Pine compactor only one mould was available. To keep the procedure as similar as possible also one mould was used at the other compactors. After compaction the specimen was extruded and the mould was reheated in the oven. The specimen was placed on a flat surface to cool down to room temperature.

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| APPENDIX B – Mixture Design Details |
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The mix used in this study was produced at a batch plant (Rasenberg Contractors, Breda The Netherlands). The original mix design information provided by the contractor is as follows:

Code : STAB 0/22 50% PR (Steenslagasfaltbeton with 50% RAP)

| | | "IN" |
|-----------------------|---------|-------|
| Course stone 16/22 mm | 13,3 % | 12,7 |
| Course stone 11/16 mm | 13,3 % | 12,7 |
| Riversand | 22,4 % | 21,4 |
| Baghouse dust | 1,0 % | 1,0 |
| RAP | 50,0 % | 50,4 |
| | | |
| Total | 100,0 % | |
| Binder in RAP | 2,6 % | |
| New binder 70/100 | 1,9 % | 1,8 |
| | | |
| | 104,5 % | 100,0 |

Gradation

| Sieve size | Percent passing |
|------------------------|-----------------|
| | |
| C31.5 | 100,0 |
| C22.4 | 99,5 |
| C16 | 87,8 |
| C11.2 | 72,0 |
| C 8 | 61,8 |
| C 5.6 | 52,3 |
| 2 mm | 42,9 |
| 500 um | 31,0 |
| 180 um | 10,4 |
| 63 um | 5,9 |
| | |
| Compaction temperature | 140°C |