Standard Method of Test for

Determining the Dynamic Modulus and Flow Number for Asphalt Mixtures Using the Asphalt Mixture Performance Tester (AMPT)

AASHTO Designation: T 378-17

Technical Section: 2d, Proportioning of Asphalt–Aggregate Mixtures

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1. SCOPE

1.1. This standard describes test methods for measuring the dynamic modulus and flow number for asphalt mixtures using the Asphalt Mixture Performance Tester (AMPT). This practice is intended for dense- and gap-graded mixtures with nominal-maximum aggregate sizes up to 37.5 mm.

1.2. *This standard may involve hazardous materials, operations, and equipment. This standard does not purport to address all of the safety concerns associated with its use. It is the responsibility of the user of this standard to establish appropriate safety and health practices and determine the applicability of regulatory limitations prior to use.*

2. REFERENCED DOCUMENTS

2.1. *AASHTO Standard*:

- R 83, Preparation of Cylindrical Performance Test Specimens Using the Superpave Gyratory Compactor (SGC)

2.2. *Other Publication*:

- Equipment Specification for the Simple Performance Test System, Version 3.0, Prepared for National Cooperative Highway Research Program (NCHRP), October 16, 2007

3. TERMINOLOGY

3.1. *Definitions*:

3.1.1. *confining pressure*—the stress applied to all surfaces in a confined test.

3.1.2. *deviatoric stress*—the difference between the total axial stress and the confining pressure in a confined test.

3.1.3. *dynamic modulus*, |E*|—the absolute value of the complex modulus calculated by dividing the peak-to-peak stress by the peak-to-peak strain for a material subjected to a sinusoidal loading.

3.1.4. *flow number*—the number of load cycles corresponding to the minimum rate of change of permanent axial strain during a repeated-load test.

3.1.5. *phase angle*, δ—the angle in degrees between a sinusoidally applied stress and the resulting strain in a controlled stress test.

3.1.6. *permanent deformation*—the nonrecovered deformation in a repeated-load test.

4. SUMMARY OF METHOD

4.1. This test method describes procedures for measuring the dynamic modulus and flow number for asphalt mixtures.

4.2. In the dynamic modulus procedure, a specimen at a specific test temperature is subjected to a controlled sinusoidal (haversine) compressive stress of various frequencies. The test may be conducted with or without confining pressure. The applied stresses and resulting axial strains are measured as a function of time and used to calculate the dynamic modulus and phase angle.

4.3. In the flow number procedure, a specimen at a specific test temperature is subjected to a repeated haversine axial compressive load pulse of 0.1 s every 1.0 s. The test may be conducted with or without confining pressure. The resulting permanent axial strains are measured as a function of the load cycles and numerically differentiated to calculate the flow number. The flow number is defined as the number of load cycles corresponding to the minimum rate of change of permanent axial strain.

5. SIGNIFICANCE AND USE

5.1. The dynamic modulus is a performance-related property that can be used for mixture evaluation and for characterizing the stiffness of asphalt mixtures for mechanistic-empirical pavement design.

5.2. The flow number is a property related to the resistance of asphalt mixtures to permanent deformation. It can be used to evaluate and design asphalt mixtures with specific resistance to permanent deformation.

6. APPARATUS

6.1. *Specimen Fabrication Equipment*—For fabricating dynamic modulus test specimens as described in R 83.

6.2. *Dynamic Modulus Test System*—Meeting the requirements of the equipment specification for the Simple Performance Test (SPT) System, Version 3.0, except for the following provisions: In the referenced equipment specification, Sections 10.7 and 11.3 shall require a temperature sensor range of 0 to 75°C (32 to 167°F) and Section 11.1 shall require a temperature control range from 4 to 70°C (39 to 158°F).

6.3. *Conditioning Chamber*—An environmental chamber for conditioning the test specimens to the desired testing temperature. The environmental chamber shall be capable of controlling the temperature of the specimen over a temperature range from 4 to 70°C to an accuracy of ±0.5°C. The chamber shall be large enough to accommodate the number of specimens to be tested plus a "dummy" specimen with a temperature sensor mounted in the center for temperature verification.

Note 1—The temperature range required for the Dynamic Modulus Test System and the Conditioning Chamber is a function of the anticipated test temperature. The temperature control range provided in Sections 6.2 and 6.3 is intended to be inclusive of all areas of the U.S. In many climatic regions, it may not be necessary to have equipment capable of controlling the temperature up to 70°C.

6.4. *TFE-Fluorocarbon Sheet*—0.25 mm thick, to be used as a friction reducer between the specimen and the loading platens in the dynamic modulus test.

6.5. *Latex Membranes*—100-mm diameter by 0.3 mm thick, for use in confined tests and for manufacturing "greased double latex" friction reducers to be used between the specimen and the loading platens in the dynamic modulus and flow number tests.

6.6. *Silicone Grease*—Dow Corning "Stopcock Grease" or equivalent, for manufacturing greased double latex friction reducers.

6.7. *Balance*—Capable of determining mass to the nearest 0.01 g. The balance is used to determine the mass of silicone grease during fabrication of greased double latex friction reducers.

7. HAZARDS

7.1. This practice and associated standards involve handling of hot asphalt binder, aggregates, and asphalt mixtures. It also includes the use of sawing and coring machinery and servohydraulic testing equipment. Use standard safety precautions, equipment, and clothing when handling hot materials and operating machinery.

8. STANDARDIZATION

8.1. *Verification with Proving Ring*:

8.1.1. Verify the normal operation of the AMPT weekly or at the beginning of a new testing program using the manufacturer-provided proving ring and following the proving ring manufacturer's use instructions. Perform a dynamic modulus test on the proving ring using a target strain of 100 microstrain at 1.0 Hz. The dynamic modulus of the proving ring should be within ±3 percent of the value obtained on the proving ring for the same testing conditions during the last calibration.

8.2. *Calibration*:

8.2.1. The following systems on the AMPT shall be calibrated annually, when the AMPT system is moved, or when any of its components are changed:

- Load Measuring System
- Actuator Displacement Measuring System
- Specimen-Mounted Deformation Measuring System
- Confining Pressure Measuring System
- Temperature Measuring System

Methods for calibration of each of these systems are included in Annex B.

9. PROCEDURE A—DYNAMIC MODULUS TEST

9.1. *Test Specimen Fabrication*:

9.1.1. Testing shall be performed on 100-mm diameter by 150-mm tall test specimens fabricated in accordance with R 83.

9.1.2. Prepare at least two test specimens at the target air void content ±0.5 percent and with the aging condition in accordance with R 83.

Note 2—The number of specimens to test depends on the desired accuracy of the analysis. Refer to Table 4 for guidance on the reproducibility of dynamic modulus and phase angle measurements.

9.2. *Test Specimen Instrumentation (Standard Glued-Gauge-Point System)*:

9.2.1. Attach the gauge points to the specimen in accordance with the manufacturer's instructions.

9.2.2. Confirm that the gauge length is 70 mm ± 1 mm, measured center-to-center of the gauge points.

9.3. *Loading Platens and End-Friction Reducers*:

9.3.1. For the dynamic modulus test, the top platen shall be free to rotate.

9.3.2. Either greased double latex or TFE fluorocarbon end-friction reducers can be used in the dynamic modulus test.

9.3.2.1. Teflon end-friction reducers are made from 0.25-mm thick TFE fluorocarbon sheet, cut to a size slightly larger than the loading platen.

9.3.2.2. Greased double latex friction reducers are fabricated from 0.3-mm thick latex membranes as described in Annex A.

9.4. *Procedure*:

9.4.1. *Unconfined Tests*:

9.4.1.1. Place the specimens to be tested in the environmental chamber with the "dummy" specimen and monitor the temperature of the dummy specimen to determine when testing can begin.

9.4.1.2. Place platens and friction reducers inside the testing chamber. Turn on the AMPT, set the temperature control to the desired testing temperature, and allow the testing chamber to equilibrate at the testing temperature for at least 1 h.

9.4.1.3. When the dummy specimen and the testing chamber reach the target temperature, open the testing chamber. Remove a test specimen from the conditioning chamber and quickly place it in the testing chamber.

9.4.1.4. Assemble the specimen to be tested with platens in the following order from bottom to top: bottom loading platen, bottom friction reducer, specimen, top friction reducer, and top loading platen.

9.4.1.5. Install the specimen-mounted deformation measuring system on the gauge points per the manufacturer's instructions. Ensure that the deformation measuring system is within its calibrated range. Ensure that the top loading platen is free to rotate during loading.

9.4.1.6. Close the testing chamber and allow the chamber temperature to return to the testing temperature.

9.4.1.7. Procedures in Sections 9.4.1.3 through 9.4.1.6, including the return of the test chamber to the target temperature, shall be completed in 5 min.

9.4.1.8. Enter the required identification and control information into the dynamic modulus software.

9.4.1.9. Follow the software prompts to begin the test. The AMPT will automatically unload when the test is complete and will display the test data and data quality indicators.

9.4.1.10. Review the data quality indicators as discussed in Section 9.5. Retest specimens with data quality indicators above the values specified in Section 9.5.

9.4.1.11. Once acceptable data have been collected, open the test chamber and remove the tested specimen.

9.4.1.12. Repeat procedures in Sections 9.4.1.3 through 9.4.1.11 for the remaining test specimens.

9.4.2. *Confined Tests*:

9.4.2.1. Assemble each specimen to be tested with the platens and membrane as follows: place the bottom friction reducer and the specimen on the bottom platen. Stretch the membrane over the specimen and bottom loading platen. Install the lower O-ring seal. Place the top friction reducer and top platen on top of the specimen and stretch the membrane over the top platen. Install the upper O-ring seal. When performing confined tests, the specimen must be vented to atmospheric pressure through the drainage lines. Ensure that the friction reducers have holes to allow air to be vented from inside the membrane.

9.4.2.2. Encase the “dummy” specimen in a membrane.

9.4.2.3. Place the specimen and platen assembly in the environmental chamber with the dummy specimen and monitor the temperature of the dummy specimen to determine when testing can begin.

9.4.2.4. Turn on the AMPT, set the temperature control to the desired testing temperature, and allow the testing chamber to equilibrate at the testing temperature for at least 1 h.

9.4.2.5. When the dummy specimen and the testing chamber reach the target temperature, open the testing chamber. Remove a test specimen and platen assembly and quickly place it in the testing chamber. When performing confined tests, the specimen must be vented to atmospheric pressure through the drainage lines. Properly connect the drainage lines to the loading platens, and ensure that they are vented to atmospheric pressure through the bubble chamber to identify leaks.

9.4.2.6. Install the specimen-mounted deformation measuring system outside the membrane on the gauge points per the manufacturer’s instructions. Ensure that the deformation measuring system is within its calibrated range. Ensure that the top loading platen is free to rotate during loading.

9.4.2.7. Close the testing chamber, and allow the chamber temperature to return to the testing temperature.

9.4.2.8. Procedures in Sections 9.4.2.5 through 9.4.2.7, including the return of the test chamber to the target temperature, shall be completed in 5 min.

9.4.2.9. Enter the required identification and control information into the dynamic modulus software.

9.4.2.10. Follow the software prompts to begin the test. The AMPT will automatically unload when the test is complete and will display the test data and data quality indicators.

9.4.2.11. Review the data quality indicators as discussed in Section 9.5. Retest specimens with data quality indicators above the values specified in Section 9.5.

9.4.2.12. Once acceptable data have been collected, open the test chamber and remove the tested specimen.

9.4.2.13. Repeat procedures in Sections 9.4.2.3 through 9.4.2.12 for the remaining test specimens.

9.5. *Computations and Data Quality*:

9.5.1. The calculation of dynamic modulus, phase angle, and the data quality indicators is performed automatically by the AMPT software.

9.5.2. Accept only test data meeting the data quality statistics given in Table 1. Table 2 summarizes actions that can be taken to improve the data quality statistic. Repeat tests as necessary to obtain test data meeting the data quality statistics requirements.

Table 1—Data Quality Statistics Requirements

Data Quality Statistic	Limit
Deformation drift	In direction of applied load
Peak-to-peak strain	75 to 125 microstrain for unconfined tests 85 to 115 microstrain for confined tests
Load standard error	10%
Deformation standard error	10%
Deformation uniformity	30%
Phase uniformity	3 degrees

Note 3—The data quality statistics in Table 1 are reported by the AMPT. If a dynamic modulus test system other than the AMPT is used, refer to the equipment specification for the Simple Performance Test (SPT) System, Version 3.0, for algorithms for the computation of dynamic modulus, phase angle, and data quality statistics.

Table 2—Troubleshooting Guide for Data Quality Statistics

Item	Cause	Possible Solutions
Deformation drift not in direction of applied load	Gauge points are moving apart	Reduce LVDT spring force. Add compensation springs. Reduce test temperature.
Peak-to-peak strain too high	Load level too high	Reduce load level.
Peak-to-peak strain too low	Load level too low	Increase load level.
Load standard error >10%	Applied load not sinusoidal	Adjust tuning of hydraulics.
Deformation standard error >10%	1. Deformation not sinusoidal 2. Loose gauge point 3. Excessive noise on deformation signals 4. Damaged LVDT	1. Adjust tuning of hydraulics. 2. Check gauge points. Reinstall if loose. 3. Check wiring of deformation sensors. 4. Replace LVDT.
Deformation uniformity >30%	1. Eccentric loading 2. Loose gauge point 3. Sample ends not parallel 4. Poor gauge point placement 5. Nonuniform air void distribution	1. Ensure specimen is properly aligned. 2. Check gauge points. Reinstall if loose. 3. Check parallelism of sample ends. Mill ends if out of tolerance. 4. Check for specimen nonuniformity (segregation, air voids). Move gauge points. 5. Ensure test specimens are cored from the middle of the gyratory specimen.
Phase uniformity >3°	1. Eccentric loading 2. Loose gauge point 3. Poor gauge point placement 4. Damaged LVDT	1. Ensure specimen is properly aligned. 2. Check gauge points. Reinstall if loose. 3. Check for specimen nonuniformity (segregation, air voids). Move gauge points. 4. Replace LVDT.

9.6. *Reporting*:

9.6.1. *For each specimen tested, report the following*:

9.6.1.1. Test temperature,

9.6.1.2. Test frequency;

9.6.1.3. Confining stress level,

9.6.1.4. Dynamic modulus,

9.6.1.5. Phase angle, and

9.6.1.6. Data quality statistics.

9.6.2. Attach the AMPT dynamic modulus test summary report for each specimen tested.

9.7. *Precision and Bias*:

9.7.1. *Single-Operator Precision (Repeatability)*—The coefficient of variation of the dynamic modulus and the standard deviation of the phase angle were found to be a function of the dynamic modulus of the mixture and the nominal maximum aggregate size. Equation 1 presents the single-operator coefficient of variation (1s%) for the dynamic modulus. Equation 2 presents the single-operator standard deviation (1s) for the phase angle.

$$s_r\% = \left[29.8e^{(0.014\times NMAS)}\right]\times\left|E^*\right|^{-\left[0.189e^{(0.012\times NMAS)}\right]} \tag{1}$$

where:

$s_r\%$ = repeatability coefficient of variation for $|E^*|$, percent;
$NMAS$ = mixture nominal maximum aggregate size, mm; and
$|E^*|$ = average dynamic modulus, MPa.

$$s_r = \left[4.67e^{(0.022\times NMAS)}\right]\times\left|E^*\right|^{-0.23} \tag{2}$$

where:

s_r = repeatability standard deviation of phase angle, degree;
$NMAS$ = mixture nominal maximum aggregate size, mm; and
$|E^*|$ = average dynamic modulus, MPa.

9.7.1.1. Results obtained in the same laboratory, by the same operator using the same equipment in the shortest practical period of time, should not be considered suspect unless the range exceeds that given in Table 3.

Table 3—Single-Operator Precision for Dynamic Modulus and Phase Angle

Nominal Maximum Aggregate Size, mm	Average $\lvert E^*\rvert$, MPa	Dynamic Modulus						Phase Angle					
		$s_r\%$ %	Acceptable Range for *n* Specimens, % of Average					$s_r°$	Acceptable Range for *n* Specimens, degrees				
			n=2	*n*=3	*n*=4	*n*=5	*n*=6		*n*=2	*n*=3	*n*=4	*n*=5	*n*=6
9.5	≥137 to <200	15	43	51	55	60	61	1.8	5.1	6.0	6.5	7.1	7.3
9.5	≥200 to <500	13	36	42	46	50	51	1.5	4.2	4.9	5.4	5.8	6.0
9.5	≥500 to <1000	11	31	36	39	43	44	1.3	3.5	4.1	4.5	4.9	5.0
9.5	≥1000 to <2000	9	26	31	34	37	38	1.1	3.0	3.5	3.8	4.2	4.3
9.5	≥2000 to <5000	8	22	26	28	31	31	0.9	2.5	2.9	3.2	3.4	3.5
9.5	≥5000 to <10 000	7	19	22	24	26	27	0.7	2.1	2.4	2.6	2.9	2.9
9.5	≥10 000 to <16 400	6	16	19	21	23	23	0.6	1.8	2.1	2.3	2.4	2.5
12.5	≥137 to <200	17	47	55	60	65	67	1.9	5.4	6.4	7.0	7.6	7.8
12.5	≥200 to <500	14	39	46	50	54	55	1.6	4.5	5.3	5.7	6.2	6.4
12.5	≥500 to <1000	12	33	39	42	46	47	1.3	3.7	4.4	4.8	5.2	5.3
12.5	≥1000 to <2000	10	28	33	36	39	40	1.1	3.2	3.8	4.1	4.4	4.6
12.5	≥2000 to <5000	8	23	28	30	33	33	0.9	2.6	3.1	3.4	3.7	3.7
12.5	≥5000 to <10 000	7	20	23	25	28	28	0.8	2.2	2.6	2.8	3.1	3.1
12.5	≥10 000 to <16 400	6	17	20	22	24	24	0.7	1.9	2.2	2.4	2.6	2.7
19	≥137 to <200	20	56	66	72	78	80	2.2	6.3	7.4	8.1	8.7	9.0
19	≥200 to <500	16	46	54	59	64	65	1.8	5.2	6.1	6.6	7.2	7.4
19	≥500 to <1000	14	38	45	49	53	55	1.5	4.3	5.1	5.6	6.0	6.2
19	≥1000 to <2000	12	32	38	42	45	46	1.3	3.7	4.3	4.7	5.1	5.3
19	≥2000 to <5000	9	27	31	34	37	38	1.1	3.0	3.6	3.9	4.2	4.3
19	≥5000 to <10 000	8	22	26	28	31	32	0.9	2.5	3.0	3.3	3.5	3.6
19	≥10 000 to <16 400	7	19	22	24	26	27	0.8	2.2	2.6	2.8	3.0	3.1
25	≥137 to <200	24	66	78	85	92	94	2.6	7.2	8.4	9.2	10.0	10.2
25	≥200 to <500	19	53	62	68	74	76	2.1	5.9	6.9	7.6	8.2	8.4
25	≥500 to <1000	16	44	51	56	61	62	1.8	4.9	5.8	6.4	6.9	7.1
25	≥1000 to <2000	13	37	43	47	51	52	1.5	4.2	5.0	5.4	5.9	6.0
25	≥2000 to <5000	11	29	35	38	41	42	1.2	3.5	4.1	4.5	4.8	4.9
25	≥5000 to <10 000	9	24	29	31	34	35	1.0	2.9	3.4	3.7	4.0	4.1
25	≥10 000 to <16 400	7	20	24	26	28	29	0.9	2.5	2.9	3.2	3.4	3.5

Note: AMPT calibrated range is 137 MPa to 16 400 MPa.

9.7.2. *Multilaboratory Precision (Reproducibility)*—The multilaboratory coefficient of variation of the dynamic modulus and the multilaboratory standard deviation of the phase angle were found to be a function of the dynamic modulus of the mixture. Equation 3 presents the multilaboratory coefficient of variation (1s%) for the dynamic modulus. Equation 4 presents the multilaboratory standard deviation (1s) for the phase angle.

$$s_R\% = 223.81\times\lvert E^*\rvert^{-0.312} \tag{3}$$

where:

$s_R\%$ = reproducibility coefficient of variation for |E*|, percent; and
$|E^*|$ = average dynamic modulus, MPa.

$$s_R = 31.4 \times \left|E^*\right|^{-0.346} \qquad (4)$$

where:

s_R = reproducibility standard deviation for phase angle, degrees; and
$|E^*|$ = average dynamic modulus, MPa.

9.7.2.1. Results obtained by two different operators testing the same material in two different laboratories should not be considered suspect unless the difference exceeds the values given in Table 4.

Table 4—Multilaboratory Precision for Dynamic Modulus and Phase Angle

Average $\lvert E^*\rvert$ MPa	Dynamic Modulus						Phase Angle					
	$s_R\%$ %	Acceptable Difference for Average of *n* Specimens, % of Average					$s_R°$	Acceptable Difference for Average of *n* Specimens, degrees				
		n=2	*n*=3	*n*=4	*n*=5	*n*=6		*n*=2	*n*=3	*n*=4	*n*=5	*n*=6
≥137 to <200	47	33	27	23	21	19	5.5	3.9	3.2	2.8	2.5	2.3
≥200 to <500	36	25	21	18	16	15	4.1	2.9	2.4	2.1	1.9	1.7
≥500 to <1000	28	20	16	14	13	12	3.2	2.2	1.8	1.6	1.4	1.3
≥1000 to <2000	23	16	13	11	10	9	2.5	1.8	1.4	1.3	1.1	1.0
≥2000 to <5000	18	12	10	9	8	7	1.9	1.3	1.1	0.9	0.8	0.8
≥5000 to <10 000	14	10	8	7	6	6	1.4	1.0	0.8	0.7	0.6	0.6
≥10 000 to <16 400	11	8	6	6	5	5	1.1	0.8	0.7	0.6	0.5	0.5

Note: AMPT calibrated range is 137 to 16 400 MPa.

Note 4—The precision estimates given in Table 3 and Table 4 are based on three materials tested in eight laboratories. Details are presented in NCHRP Report 702: Precision of the Dynamic Modulus and Flow Number Tests.

9.7.3. *Bias*—No information can be presented on the bias of the dynamic modulus or phase angle because no material having acceptable reference values is available.

10. PROCEDURE B—FLOW NUMBER TEST

10.1. *Test Specimen Fabrication*:

10.1.1. Testing shall be performed on 100-mm-diameter by 150-mm-tall test specimens fabricated in accordance with R 83.

10.1.2. Prepare at least three test specimens at the target air void content ±0.5 percent and with the aging condition in accordance with R 83.

Note 5—The number of specimens to test depends on the desired accuracy of the analysis. Refer to Table 6 for guidance on the reproducibility of flow number tests.

10.2. *Loading Platens and End-Friction Reducers*:

10.2.1. For the flow number test, the top platen shall not be free to rotate.

10.2.2. Prepare two greased double latex end-friction reducers for each specimen that will be tested using the procedure specified in Annex A. It is recommended that new friction reducers be used for each test.

10.3. *Procedure*:

10.3.1. *Unconfined Tests*:

10.3.1.1. Place the specimens to be tested in the environmental chamber with the dummy specimen and monitor the temperature of the dummy specimen to determine when testing can begin.

10.3.1.2. Place platens and greased double latex friction reducers inside the testing chamber. Turn on the AMPT, set the temperature control to the desired testing temperature, and allow the testing chamber to equilibrate at the testing temperature for at least 1 h.

10.3.1.3. When the dummy specimen and the testing chamber reach the target temperature, open the testing chamber. Remove a test specimen from the conditioning chamber and quickly place it in the testing chamber.

10.3.1.4. Assemble each specimen to be tested with platens in the following order from bottom to top: bottom loading platen, bottom greased double latex friction reducer, specimen, top greased double latex friction reducer, and top loading platen.

10.3.1.5. Close the testing chamber and allow the chamber temperature to return to the testing temperature. Ensure that the top loading platen is not permitted to rotate during loading.

10.3.1.6. Procedures in Sections 10.3.1.3 and 10.3.1.5, including the return of the test chamber to the target temperature, shall be completed in 5 min.

10.3.1.7. Enter the required identification and control information into the flow number software. Refer to Appendix X2.3 for example of Flow Number test parameters to be entered into the flow number software.

10.3.1.8. Follow the software prompts to begin the test. The AMPT will automatically unload when the test is complete.

10.3.1.9. Upon completion of the test, open the test chamber and remove the tested specimen.

10.3.1.10. Repeat procedures in Sections 10.3.1.4 through 10.3.1.9 for the remaining test specimens.

10.3.2. *Confined Tests*:

10.3.2.1. Assemble each specimen to be tested with the platens and membrane as follows: place the bottom greased double latex friction reducer and the specimen on the bottom platen. Stretch the membrane over the specimen and bottom loading platen. Install the lower O-ring seal. Place the top greased double latex friction reducer and top platen on top of the specimen, and stretch the membrane over the top platen. Install the upper O-ring seal. When performing confined tests, the specimen must be vented to atmospheric pressure through the drainage lines. Make sure that the friction reducers have holes to allow air to be vented from inside the membrane.

10.3.2.2. Encase the dummy specimen in a membrane.

10.3.2.3. Place the specimen and platen assembly in the environmental chamber with the dummy specimen and monitor the temperature of the dummy specimen to determine when testing can begin.

10.3.2.4. Turn on the AMPT, set the temperature control to the desired testing temperature, and allow the testing chamber to equilibrate at the testing temperature for at least 1 h.

10.3.2.5. When the dummy specimen and the testing chamber reach the target temperature, open the testing chamber. Remove a test specimen and platen assembly and quickly place it in the testing chamber. When performing confined tests, the specimen must be vented to atmospheric pressure through the drainage lines. Properly connect the drainage lines to the loading platens and make sure they are vented to atmospheric pressure through the bubble chamber to identify leaks.

10.3.2.6. Close the testing chamber and allow the chamber temperature to return to the testing temperature. Ensure that the top loading platen is not permitted to rotate during loading.

10.3.2.7. Procedures in Sections 10.3.2.5 and 10.3.2.6, including the return of the test chamber to the target temperature, shall be completed in 5 min.

10.3.2.8. Enter the required identification and control information into the flow number software.

10.3.2.9. Follow the software prompts to begin the test. The AMPT will automatically unload when the test is complete.

10.3.2.10. Upon completion of the test, open the test chamber and remove the tested specimen.

10.3.2.11. Repeat procedures in Sections 10.3.2.5 through 10.3.2.10 for the remaining test specimens.

10.4. *Calculations*:

10.4.1. The calculation of the permanent strain for each load cycle and the flow number for individual specimens is performed automatically by the AMPT.

10.4.2. Compute the average and standard deviation of the flow numbers for the replicate specimens tested.

10.4.3. Compute the average and standard deviation of the permanent strain at the load cycles of interest.

10.5. *Reporting*:

10.5.1. Report the following:

10.5.1.1. Test temperature,

10.5.1.2. Average applied deviatory stress,

10.5.1.3. Average applied confining stress,

10.5.1.4. Average and standard deviation of the flow numbers for the specimens tested, and

10.5.1.5. Average and standard deviation of the permanent strain at the load cycles of interest.

10.5.2. Attach the AMPT flow number test summary report for each specimen tested.

10.6. *Precision and Bias*:

10.6.1. *Single-Operator Precision (Repeatability)*—The coefficient of variation for unconfined flow number tests was found to be a function of the nominal maximum aggregate size. Equation 5 presents the single-operator coefficient of variation (1s%) for the flow number from unconfined testing.

$$s_r\% = 37.0 \times \ln(NMAS) - 50.4 \tag{5}$$

where:

$s_r\%$ = flow number repeatability coefficient of variation, percent; and

$NMAS$ = mixture nominal maximum aggregate size, mm.

10.6.1.1. Results obtained in the same laboratory, by the same operator using the same equipment in the shortest practical period of time, should not be considered suspect unless the range exceeds the values given in Table 5.

Table 5—Single-Operator Precision for Unconfined Flow Number

NMAS, mm	$s_r\%$ percent	Acceptable Range for n Specimens, % of Average				
		n=2	*n*=3	*n*=4	*n*=5	*n*=6
9.5	32.9	92	109	118	128	132
12.5	43.1	121	142	155	168	172
19	58.5	164	193	211	228	234
25	68.7	192	227	247	268	275

10.6.2. *Multilaboratory Precision (Repeatability)*—The multilaboratory coefficient of variation of unconfined flow number tests was found to be a function of the nominal maximum aggregate size. Equation 6 presents the multilaboratory coefficient of variation (1s%) for the flow number from unconfined testing.

$$s_R\% = 34.2 \times \ln(NMAS) + 1.1 \tag{6}$$

where:

$s_R\%$ = flow number reproducibility coefficient of variation, percent; and

$NMAS$ = mixture nominal maximum aggregate size, mm

10.6.2.1. Results obtained by two different operators testing the same material in two different laboratories should not be considered suspect unless the difference exceeds the values given in Table 6.

Table 6—Multilaboratory Precision for Unconfined Flow Number

NMAS, mm	$s_R\%$ percent	Acceptable Difference for Average of *n* Specimens, % of average				
		n=2	*n*=3	*n*=4	*n*=5	*n*=6
9.5	78.1	55	45	39	35	32
12.5	87.5	62	51	44	39	36
19	101.8	72	59	51	46	42
25	111.2	79	64	56	50	45

Note 6—The precision estimates given in Table 5 and Table 6 are based on three materials tested in eight laboratories using zero confining pressure, 600-kPa repeated deviatoric stress, and 30-kPa contact deviatoric stress. Details are presented in NCHRP Report 702: Precision of the Dynamic Modulus and Flow Number Tests.

10.6.3. *Bias*—No information can be presented on the bias of the flow number because no material having acceptable reference values is available.

11. KEYWORDS

11.1. Dynamic modulus; flow number; permanent deformation; phase angle; repeated load testing.

ANNEX A—METHOD FOR PREPARING "GREASED DOUBLE LATEX" END-FRICTION REDUCERS FOR FLOW NUMBER TEST

(Mandatory Information)

A1. PURPOSE

A1.1. This annex presents a procedure for fabricating greased double latex end-friction reducers for the flow number test.

A1.2. These end-friction reducers are mandatory for the flow number test.

A2. SUMMARY

A2.1. Greased double latex end-friction reducers are fabricated by cutting two circular latex sheets from a latex membrane used for confining specimens, applying a specified mass of silicone grease evenly over one of the latex sheets, and then placing the second latex sheet over the first.

A3. PROCEDURE

A3.1. Cut a 0.3-mm-thick latex membrane along its long axis to obtain a rectangular sheet of latex. The sheet will be approximately 315 by 250 mm.

A3.2. Trace the circumference of the loading platen on the sheet of latex; then cut along the tracing to form circular latex sheets that are slightly larger than the loading platen. Four circular latex sheets are needed to fabricate friction reducers for the top and bottom of the specimen.

A3.3. Place one circular latex sheet on the balance, and apply 0.25 ± 0.05 g of silicone grease onto the middle of the latex sheet.

A3.4. Spread the silicone grease evenly over the latex sheet by rubbing in a circular motion from the center to the outside of the sheet.

A3.5. Place the second circular latex sheet on top of the silicone grease.

A3.6. If the friction reducer will be used in confined tests, cut or punch a hole through both latex sheets at the location of the vent in the loading platen.

ANNEX B—PROCEDURES FOR CALIBRATING THE AMPT

(Mandatory Information)

B1. PURPOSE

B1.1. This Annex presents procedures for calibrating the measuring systems on the AMPT.

B2. SUMMARY

B2.1. The following components of the AMPT are calibrated using the procedures contained in this Annex:

- Load Measuring System
- Actuator Displacement Measuring System
- Specimen-Mounted Deformation Measuring System
- Confining Pressure Measuring System
- Temperature Measuring System

B3. REFERENCED STANDARDS

B3.1. *ASTM Standards*:

- D5720, Standard Practice for Static Calibration of Electronic Transducer-Based Pressure Measurement Systems for Geotechnical Purposes
- D6027, Standard Test Method for Calibrating Linear Displacement Transducers for Geotechnical Purposes (withdrawn 2013)
- E4, Standard Practices for Force Verification of Testing Machines
- E74, Standard Practice of Calibration of Force-Measuring Instruments for Verifying the Force Indication of Testing Machines
- E83, Standard Practice for Verification and Classification of Extensometer Systems

B4. PROCEDURE

B4.1. *Load Measuring System Calibration*:

B4.1.1. The load measuring system shall have a maximum error of 1 percent of the indicated value over the range of 0.12 kN (25 lb) to 13.5 kN (3.0 kips) when verified in accordance with ASTM E4.

B4.1.2. The resolution of the load measuring system shall comply with the requirements of ASTM E4.

B4.1.3. Perform load measuring system verification in accordance with ASTM E4.

B4.1.4. All calibration load cells used for the load calibration shall be certified according to ASTM E74 and shall not be used below their Class A loading limits.

B4.1.5. When performing the load verification, apply at least two verification runs of at least five loads throughout the range selected.

B4.1.6. If the initial verification loads are within ±1 percent of the reading, these values can be applied as the as-found values, and the second set of verification forces can be used as the final values. Record return-to-zero values for each set of verification loads.

B4.1.7. If the initial verification loads are out of tolerance, calibration adjustments shall be made according to the manufacturer's specifications until the values are established within the ASTM E4 recommendations. Two applications of verification loads shall then be applied to determine the acceptance criteria for repeatability according to ASTM E4.

B4.1.8. At no time will correction factors be applied to corrected values that do not meet the accuracy requirements of ASTM E4.

B4.2. *Actuator Displacement and Specimen-Mounted Deformation Measuring Systems Calibration*:

B4.2.1. The actuator displacement measuring system shall have a minimum resolution of 0.0025 mm (0.0001 in.).

B4.2.2. The actuator displacement measuring system shall have a maximum error of 0.03 mm (0.001 in.) over the 12-mm (0.47-in.) range when verified in accordance with ASTM D6027.

B4.2.3. The specimen-mounted deformation measuring system shall have a minimum resolution of 0.0002 mm (7.8 μin.).

B4.2.4. The specimen-mounted deformation measuring system shall have a maximum error of 0.0025 mm (0.0001 in.) over the 1-mm (0.04-in.) range when verified in accordance with ASTM D6027.

B4.2.5. Perform verification of the actuator displacement and specimen-mounted deformation measuring systems in accordance with ASTM D6027.

B4.2.6. The micrometer used shall conform to the requirements of ASTM E83.

B4.2.7. When performing verification of the actuator displacement and specimen-mounted deformation measuring systems, each transducer and associated electronics must be verified individually throughout its intended range of use.

B4.2.8. Mount the appropriate transducer in the micrometer stand and align it to prevent errors caused by angular application of measurements.

B4.2.9. Apply at least five verification measurements to the transducer throughout its range. Rezero and repeat the verification measurements to determine repeatability.

B4.2.10. If the readings of the first verification do not meet the specified error tolerance, perform calibration adjustments according to manufacturer's specifications and repeat the applications of measurement to satisfy the error tolerances.

B4.3. *Confining Pressure Measuring System Calibration*:

B4.3.1. The confining pressure measuring system shall have a minimum resolution of 0.5 kPa (0.07 psi).

B4.3.2. The confining pressure measuring system shall have a maximum error of 1 percent of the indicated value over the range of 35 kPa (5 psi) to 210 kPa (30 psi) when verified in accordance with ASTM D5720.

B4.3.3. Perform verification of the confining pressure measuring system in accordance with ASTM D5720.

B4.3.4. All calibrated pressure standards shall meet the requirements of ASTM D5720.

B4.3.5. Attach the pressure transducer to the pressure standardizing device.

B4.3.6. Apply at least five verification pressures to the device throughout its range and record each value. Determine if the verification readings fall within ±1 percent of the value applied.

B4.3.7. If the readings are within tolerance, apply a second set of readings to determine repeatability. Record the return-to-zero values for each set of verification pressures.

B4.3.8. If the readings are out of tolerance, adjust the device according to the manufacturer's specifications and repeat the dual applications of pressure as described above to complete verification.

B4.4. *Temperature Measuring System Calibration*:

B4.4.1. The temperature measuring system shall be readable and accurate to the nearest 0.25°C (0.5°F).

B4.4.2. Verification of the temperature measuring system shall be performed using an NIST-traceable reference thermal detector that is readable and accurate to 0.1°C (0.2°F).

B4.4.3. A rubber band or O-ring will be used to fasten the reference thermal detector to the system temperature sensor.

B4.4.4. Comparisons of the temperature from the reference thermal detector and the system temperature sensor shall be made at six temperatures over the operating range of the environmental chamber.

B4.4.5. Once equilibrium is obtained at each temperature setting, record the temperature of the reference thermal detector and the system temperature sensor.

B4.4.6. If the readings are out of the specified tolerance, adjust the device according to the manufacturer's specifications and repeat the measurements as described above to complete verification.

B4.5. *Dynamic Performance Verification*:

B4.5.1. The verification of the dynamic performance of the equipment shall be performed after calibration of the system.

B4.5.2. The dynamic performance verification shall be performed using the verification device provided with the system by the manufacturer.

B4.5.3. First, measure and record the modulus of the verification device for a diameter of 100 mm (4 in.) under static loading conditions using applied stresses of 65, 575, 1100, and 1600 kPa (10, 85, 160, and 230 psi).

B4.5.4. Then, use the verification device to simulate the dynamic modulus test conditions. Measure the dynamic modulus of the verification for a diameter of 100 mm (4 in.) using applied stresses of 65, 575, 1100, and 1600 kPa (10, 85, 160, and 230 psi) at frequencies of 0.1, 1, and 10 Hz (a total of 12 measurements).

B4.5.5. The 12 moduli from the dynamic loading shall be within ±2 percent of that value obtained for the same stress level from the static measurement. The 12 phase angles from the dynamic loading shall be less than ±1 degree.

APPENDIXES

(Nonmandatory Information)

X1. MODEL USED FOR IDENTIFYING THE FLOW NUMBER

X1.1. *Explanation for Using the Francken Model*:

X1.2. The flow number is defined as the point where the permanent strain rate reaches a minimum value. It is found by differentiating the permanent strain versus load cycles curve measured in the flow number testing and searching for the minimum value. Various algorithms have been proposed for identifying the flow number in the flow number test. Two of these algorithms have been implemented in the Asphalt Mixture Performance Tester: (1) smoothed central difference and (2) Francken model.

X1.3. In the smoothed central difference algorithm the derivative at each point is calculated using the raw permanent strain data and Equation X1.1.

$$\frac{d(\varepsilon_p)_i}{dN} \cong \frac{(\varepsilon_p)_{i+\Delta N} - (\varepsilon_p)_{i-\Delta N}}{2\Delta N} \tag{X1.1}$$

where:

$d(\varepsilon_p)_i/dN$ = rate of change of permanent axial strain with respect to cycles or permanent strain rate at cycle i 1/cycle;

$(\varepsilon_p)_i-\Delta N$ = permanent strain at $i-\Delta N$ cycles;

$(\varepsilon_p)_i+\Delta N$ = permanent strain at $i+\Delta N$ cycles; and

ΔN = sampling interval.

X1.4. The permanent strain rate for each cycle is then smoothed using a moving average of the permanent strain rate at the point in question and two points before and after the point in question. Early testing with this algorithm indicated that the flow number was sensitive to the sampling interval used. Additionally, for a sampling interval of one, the flow number from replicate tests on the same material was highly variable due to electrical noise on the deformation transducer signal.

X1.5. Researchers at the Arizona State University recommended a different, more stable approach for computing the permanent strain rate and the flow number.[2] In this approach, the raw permanent strain versus load cycle curve is fit to the Francken model. This model given in Equation X1.2 is a combination of a power model and an exponential and is able to fit various shapes of permanent deformation curves.

$$\varepsilon_p = An^B + C\left(e^{Dn} - 1\right) \tag{X1.2}$$

where:

ε_p = permanent axial strain;

n = number of cycles; and

A, B, C, and D = fitting coefficients.

X1.6. The fitting coefficients are determined by numerical optimization. Once fitted, the first and second derivatives of the Francken model are easily determined analytically.

The first and second derivatives of the Francken model are easily determined analytically as given below:

First Derivative (Permanent Axial Strain Rate):

$$\frac{d\varepsilon_p}{dn} = ABn^{B-1} + CDe^{Dn} \qquad (X1.3)$$

Second Derivative:

$$\frac{d^2\varepsilon_p}{dn^2} = AB(B-1)n^{B-2} + CD^2e^{Dn} \qquad (X1.4)$$

X1.7. The flow number is the cycle where the second derivative changes from negative to positive.

X1.8. Using the Francken model with a sampling interval of one standardizes the flow number computation and leads to reduced variability in flow number tests on replicate specimens. A similar approach is used in the Bending Beam Rheometer (BBR) to calculate the m-value. In the BBR, a polynomial is fit to the log stiffness versus log time data and then differentiated to determine the m-value.

X2. EVALUATION OF RUTTING RESISTANCE USING THE FLOW NUMBER TEST

X2.1. *Scope*:

X2.1.1. This procedure establishes a method to evaluate the rutting resistance of hot mix asphalt (HMA) and warm mix asphalt (WMA) paving mixtures using the T 378 flow number (Fn) test in the Asphalt Mixture Performance Tester (AMPT).

X2.2. *Test Specimen Fabrication*:

X2.2.1. Perform *Short-Term Conditioning for Mixture Mechanical Property Testing* for the test specimens in accordance with R 30 using the criteria listed in Table X2.1.

Table X2.1—Flow Number Specimen Conditioning Criteria

Criteria	HMA	WMA
Conditioning time	4 h ± 5 min	2 h ± 5 min
Conditioning temperature	135 ± 3°C	Field compaction temperature, °C

X2.2.2. Prepare four flow number test specimens in accordance with R 83 at a target air void content of 7.0 ± 0.5 percent; determined after cylindrical coring and sawing of ends.

X2.3. *Procedure*:

X2.3.1. Determine the High Adjusted PG Temperature using the LTPPBind Version 3.1 software, selecting the project location climatic data from the nearest weather station and using the evaluation parameters listed in Table X2.2.

Table X2.2—LTTP Bind Version 3.1 Temperature Evaluation Parameters

Evaluation Parameter		HMA and WMA
Desired reliability, %		50
Target rut depth, mm		12.5
Adjustment for traffic loading and speed		0.0
Depth of layer, mm	Surface layers	20
	Intermediate and base layers	Depth at the top surface of the layer

X2.3.2. Input the test parameters listed in Table X2.3 into the AMPT control software for the flow number test.

Table X2.3—Flow Number Test Parameters

Test Parameter	Value
Test temperature	Adjusted PG temperature[a]
Repeated axial stress	600 kPa
Contact stress[b]	30 kPa
Confining stress	0 kPa (unconfined)

[a] Determined in accordance with Appendix X2.3.1.

[b] The contact stress is calculated as 5 percent of the repeated axial stress.

X2.3.3. Conduct flow number testing. Record the specimen flow number results from the Francken model computation according to Section 10. Compute the average flow number of the four specimens tested and record the results. Compare the average flow number with the minimum criteria in Table X2.4.

Table X2.4—Minimum Average Flow Number Requirements[a]

Traffic Level, million ESALs	HMA Minimum Average Flow Number	WMA Minimum Average Flow Number
<3	—	—
3 to <10	50	30
10 to <30	190	105
≥30	740	415

[a] Minimum flow number values were established using the average of four specimens, using the short-term conditioning criteria in Table X2.1 and the flow number test parameters in Table X2.3.

X3. USE OF SMALL TEST SPECIMENS

X3.1. *Small Test Specimens*:

X3.1.1. Test specimens smaller than the standard AMPT geometry can be obtained from constructed pavement layers to measure the dynamic modulus for use in applications such as forensic investigations and field monitoring of test sections. 38-mm diameter specimens can be cored horizontally from within the bounds of construction lifts that are at least 50 mm thick. The ends of the core are then trimmed to create a specimen with a recommended height of 110 mm. No precision statements have been developed for these sample sizes as yet. The same gauge points, same gauge length, same type of friction reducers, same specimen extensometers and same AMPT software and inputs are used. The top and bottom platens used with standard size geometry should not be used, and smaller platens with smaller friction reducers are recommended. Reduced-size sample geometry is only intended for unconfined dynamic modulus characterization. Prismatic specimens 25 mm by 50 mm by 100 mm have also been evaluated for thinner construction lifts; calculate the rectangular cross-sectional area and then calculate the effective circular diameter that yields the same cross-sectional area to be entered in to the AMPT test control software.

X3.2. *Data Quality Indicators for Small Test Specimens*:

X3.2.1. Data quality indicators identified in TP 79, Table 1 are applicable for 19 mm and smaller nominal maximum aggregate size (NMAS) mixtures for small cylindrical 38 mm by 100 mm specimens. Data quality indicators for small-size samples require careful review for temperatures higher than 38°C and/or larger NMAS. (See Li, X. and N. Gibson, “Using Small Specimens for AMPT Dynamic Modulus and Fatigue Tests,” Asphalt Paving Technology, *Journal of the Association of Asphalt Paving Technologists*, pp. 579–615, Vol. 82, 2013).