Instrument Company

Test Equipment Division

PineShear+ User Guide

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PineShear+UserGuide
Version 032714
27-MAR-2014

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I. PineShear+™ Workbook

The *PineShear+* Microsoft Excel workbook provides calculations for various parameters related to SGC compaction including signals collected with shear instrumentation. The information may be applicable for asphalt mixture analysis including workability, compactability, aggregate structure development and stability, as well as mixture compaction aid evaluation.

The desired end use application will guide the selection of compaction parameters used to evaluate the material. Asphalt mixtures differing in binder type or aggregate structure may be compared at the same temperature or over a range of temperatures; or a single mixture may be evaluated over several temperatures.

1.1 System Requirements

Operating System: Windows® XP, 7, 8, Windows® Vista®

Utility Program: Microsoft® Excel® 2007 (or later). Utility programs which emulate Windows® to run Excel® workbooks may also work.

1.2 Trademark/Copyright

II. Gyratory Shear Overview

The term Gyratory Shear has roots in the Corps of Engineers Gyratory Testing Machine (GTM) where a force (F) acting at a distance L (lever arm) from the vertical axis of rotation generated a measure of the material resistance (tilting moment), which was then divided by the specimen volume to calculate what was labeled gyratory shear stress (S_G) with units of kPa. The value obtained from this measure represents the resistance of the material to the gyratory action induced by the compactor under the conditions of compaction (confinement, etc.). In a Superpave Gyratory Compactor (SGC), a constant normal force (600 kPa consolidation pressure) is applied along with a constant strain (angle of gyration) applied at a constant rate of strain (30 gyrations per minute). The combined manipulation by the normal force acting on the specimen along with the gyratory action in the confinement of a cylindrical mold imparts forces into the material specimen which result in compaction.

Gyratory shear has been given consideration as a signal that might be reflective of the asphalt mixture field performance. Several studies suggested that the signal was indicative of the performance of the aggregate structure and might represent a materials resistance to rutting[5,4]. Other studies suggested the gyratory shear signal might be useful as a quality control signal which has the capability of providing nearly instantaneous feedback of a change in the material during production[8]. While a number of studies suggested that gyratory shear is a potentially useful measure, it failed to gain widespread use and was investigated only as a research measure.

With the advent of Warm Mix Asphalt technologies, researchers looked to evaluate how materials behave at the lower compaction temperatures associated with these technologies. Researchers have utilized gyratory shear concepts to evaluate both workability and compactability of asphalt mixtures. While the metrics developed to investigate workability and compactability of asphalt mixtures vary, at their core is the measure of the resistance to gyratory action in the Superpave Gyratory Compactor.

Gyratory Shear in current usage describes generally the measure of the resistance to the gyratory motion during compaction and may mean more than just how the term applied to the GTM. A number of metrics and indexes have been developed which are associated with the measure of the resistance to gyratory motion (gyratory force). This force can be captured with instrumentation integrated into the SGC or with secondary devices.

Pine Instrument Company's PineShear+™ Excel® workbook presents a compilation of the various metrics that can be calculated from gyratory shear data. The workbook is designed to be used with the AFG2AS Superpave Gyratory Compactor equipped with shear instrumentation and simplifies the effort needed to evaluate the various metrics that have been developed. The workbook includes several metrics that utilize the response of the gyratory shear instrumentation and also metrics that have been developed which use only the specimen height available from the SGC.

The workbook is designed with six material groups with each group comprising of up to four replicate specimens (same material and compaction temperature). The workbook is designed to compare two (2) materials compacted at three (3) temperature, or three (3) materials compacted at two (2) temperatures each. Each group should represent a single material and compaction temperature.

Compacting the mixture at temperatures lower than typical laboratory compaction temperatures can provide insight into material workability and compactability characteristics. Compacting in the laboratory with the gyratory compactor at temperatures associated with construction operations may provide insight into the material behavior at those temperatures.

2.1 Terminology

Gyro File Name: SGC Data Source Name, *.dat

Diameter (mm): Specimen Diameter, typically 150mm

Pressure (kPa): Compaction pressure, typically 600 kPa

Final Ht. (mm): Specimen Final Height

Angle (Deg.): Internal Angle of Gyration, typically 1.16°

G_{mm}: Maximum Theoretical Specific Gravity

G_{mb}: Bulk Specific Gravity

$\%G_{mm}$: Relative Specimen Density (percent of maximum density)

N_{92}: Number of gyrations to 92% G_{mm}

Temp. (°C): Specimen Compaction Temperature (°C)

Gyratory Shear (Sg) – The term Gyratory Shear originated with the Corps of Engineers Gyratory Testing Machine (GTM) where a force (F) acting at a distance L (lever arm) from the vertical axis of rotation generates a tilting moment, which is then divided by the specimen volume to calculate the gyratory shear stress.[2] The tilting moment described by (F x L) is the applied compaction force F multiplied by the eccentric distance (e) noted in more recent literature.[5] A higher Sg value suggests a stiffer material.

$$Sg = \frac{2(Fe)}{Ah}\ (kPa)$$

where:

F = force (N), this is the compaction force from 600kPa applied pressure.
e = distance (m), this is the distance from the specimen axis the compaction force acts.
A = specimen area (m^2), typically based on a150mm diameter specimen
h = specimen height (m), as measured by the gyratory compactor each gyration

ASTM D3387 gyratory shear includes a means for estimating the wall friction and is calculated by the equation[1]:

ASTM D3387 Equation A1.1 $Sg = \frac{2(F_R * L + F_W * a) + N * b}{A * h}$ (kPa) where:

Sg = gyratory shear D3387:

$2*F_R*L$ = the tilting moment, same as 2(F*e*) in Equation 1

Note: The ASTM equation utilizes P which is changed to F_R in this document to avoid confusion with P representing compaction pressure.)

$2*F_w*a$ = the mold wall friction

N*b = the additive moment from the tilted specimen (normal force shifted by angle over the height of the specimen.

A*h = specimen volume

Note: The calibration of the AFG2AS Shear Instrumentation includes the friction of the simulated moment device (dynamic calibration). This friction component is assumed to be similar to the friction during compaction therefore, the PineShear+ workbook utilizes the simplified Sg formula without the wall friction.

Resistive Effort* (w) *[kPa] – The gyratory shear signal based Resistive effort (*w*) developed by Bahia et al. is a slight modification of gyratory shear. "Measure of the resistance of a bituminous mixture to compaction using the work done during compaction per unit volume, per gyration. This parameter has units of stress."[5] A higher *w* value suggests a stiffer material.

$$w = \frac{4eF\theta}{Ah}\ (kPa)$$

where:

w = Resistive Effort (kPa)

e = Eccentricity of the Resultant Force (m)

F = Magnitude of Resultant Force (kN)

θ = Internal Angle of Tilting (radians)

A = Area of the specimen (m2)

h = Height of specimen at a given gyration

Compaction Force Index (CFI) [kPa] – This shear signal index is derived from the *Resistive Effort*. "Measure of the workability of a bituminous mixture characterized as the area under the Resistive Effort vs. Gyrations curve from the second gyration (N=2) to 92% maximum theoretical specific gravity (N_{92})."[5] A higher CFI indicates more effort was required to achieve 92% G_{mm}.

$$CFI = \sum_{N=2}^{N92} w$$

Traffic Force Index (TFI) [kPa] – The TFI is a shear signal index derived from the *Resistive Effort* obtained during compaction. Estimate of the stability of a bituminous mixture over its service life. Characterized by the area under the Resistive Effort vs. Gyrations curve from 92% G_{mm} (N_{92}) to 98% G_{mm} (N_{98}).[5] A higher TFI indicates more effort was required to consolidate from 92% to 98% G_{mm}.

$$TFI = \sum_{N_{92}}^{N_{98}} w$$

Construction Densification Index (CDI) [kPa] – This specimen height based index represents the area under the densification curve from density at 8 gyrations to density of 92% G_{mm}[5]. This specimen height based measure does not include shear measurement or the effort required to compact the material up to the 8th gyration (~$N_{initial}$). Superpave specifications originally limited the specimen density at N_{ini} (~8 depending on traffic level) to a maximum of 89% G_{mm}. Therefore, the CDI metric includes only the effort to compact from approximately 89% to 92% G_{mm} for Superpave mixtures.

$$CDI = \sum_{N=8}^{N_{92}} \%G_{mm}$$

Locking Point [Gyration] – This specimen height based parameter is derived from the pattern where the second gyration of two consecutive gyrations having the same sample height which may differ from other Locking Point definitions.[7] Some research has suggested the locking point may be related to the point where the material aggregate structure becomes fully skeletonized and further gyration is not desirable. Various locking point criteria have been applied in research applications.

Workability Energy Index (WEI) [(N-m)/gyration] – This specimen height based index developed by Dessouky et al. is inversely related to the effort required to compact the material, a lower WEI reflects a material requiring more effort to compact in the gyratory compactor. "Workability of the mix can be assessed by defining the energy needed to compact the mix to 92% Gmm. Higher WEI is associated with easier and faster mat compaction during construction."[8]

$$WEI = \frac{\left(\frac{\pi d^2}{4}\right) P(h_{n=0} - h_{92})}{N_{92} - N_{n=0}} (N \cdot m)/gyration$$

where:

P: Compaction Pressure (kPa)
d: diameter (mm)
$h_{n=0}$: Specimen Height (mm) at gyration 0
h_{92}: Specimen Height (mm) at 92% Gmm
$N_{n=0}$: Gyration 0
N_{92}: Gyration at 92%G_{mm}

Compactability Energy Index (CEI) [(N-m)/gyration] – This specimen height based index developed by Dessouky et al. is inversely related to the potential stability of the mix during the service life of the pavement. A higher CEI suggests a less stable material. "The CEI examines the compactability and stability of the mix against loading over the service life of the pavement. Mixes that deform less and take more traffic loading cycles would have better stability. Lower CEI is associated with higher stability during trafficking."[8]

$$CEI = \frac{\left(\frac{\pi d^2}{4}\right) P(h_{92} - h_{96})}{N_{96} - N_{92}} \ (N \cdot m)/gyration$$

where:

P: Compaction Pressure (kPa)
d: Specimen diameter (mm)
h_{92}: Specimen Height (mm) at 92% G_{mm}

h_{96}: Specimen Height (mm) at 96% G_{mm}
N_{92}: Gyration at 92%G_{mm}
N_{96}: Gyration at 96%G_{mm}

Note: The above described *Compactability Energy Index (CEI)*[8] developed by Dessouky et al. should not be confused with other CEI acronyms utilized in various gyratory compactor research efforts and described as *Contact Energy Index (CEI)*[6] and *Compaction Energy Index (CEI)*[5].

Normalized Shear ($S_{g\ Norm}$) – This gyratory shear based value represents the percentage of maximum shear at each gyration and thus has a value from 0 to 1. Butcher states: "Shear stress results are, however, more illustrative when presented as the percentage of maximum shear stress...".[3] Normalizing the shear value in this manner also helps address the variations in gyratory compaction frictional forces that may be part of the shear instrumentation signal.

$$S_{g\,Norm} = \frac{S_g}{S_{g\,max}} \textit{ (unit-less)}$$

Normalized Shear Index (NSI) – Normalized Shear Index (NSI) represents the area under the Normalized Shear curve from N=2 to N_{92} and in analogous to a normalized CFI measure.[9] **Error! Reference source not found.**

$$NSI = \sum_{N=2}^{N_{92}} \frac{S_g}{S_{g\,max}} \textit{ (unit-less)}$$

Gyratory Compactibility Index (GCI) – The ratio of the height at 60 gyrations ($h_{n=60}$) to the height at 30 gyrations ($h_{n=30}$) as described in ASTM D3387.[1]

$$GCI = \frac{h_{n=60}}{h_{n=30}} \textit{(unit-less)}$$

III. Loading Data into the Workbook

3.1 SGC Data Files

The workbook requires the *.dat data file from the AFG2AS Superpave Gyratory Compactor to be retained in the format as saved by the compactor. Saving the data into another file format will make the data incompatible with the PineShear+™ workbook data loading utility. The *.dat file may be opened and saved in alternate file formats but should be renamed with an appropriate extension such as *.txt or *.xls, etc.

Replicate specimens should be loaded into the workbook as groups of specimens representing the same material and compacted at the same temperature (replicates). Groups can be renamed to meaningful identity such as material, temperature, binder, etc. Renaming the *.dat file with specimen identification and compaction temperature is good practice to help with archiving data and this name will be loaded into the workbook (6).

3.2 Load Data File

1. Select the "Height" worksheet in a PineShear+ workbook. See Figure 1.
2. Select the column to place the data. Use different groups for different materials.
3. Select PineShear+ from the menu ribbon.
4. Select Load Data File. Navigate and select the appropriate *.dat file. Rename the *.dat data file to the specimen ID to help keep thing better identified in the workbook. This name will be loaded in row 2.
5. Identify Groups with Material Identification.
6. Rename Specimen if desired (default is file name).
7. Enter compaction temperature in degree C.

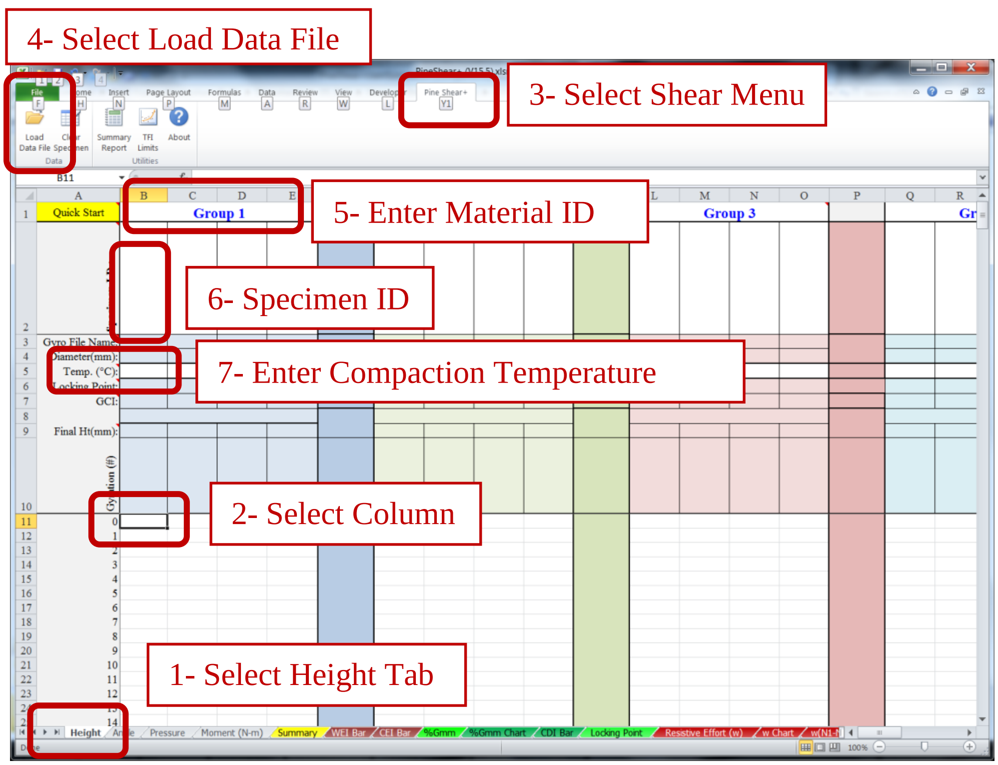

Figure 1: Height Worksheet

8. Select the "%G_{mm}" worksheet. See Figure 2
9. Enter the G_{mb} and G_{mm} for each specimen in rows 7 and 8.

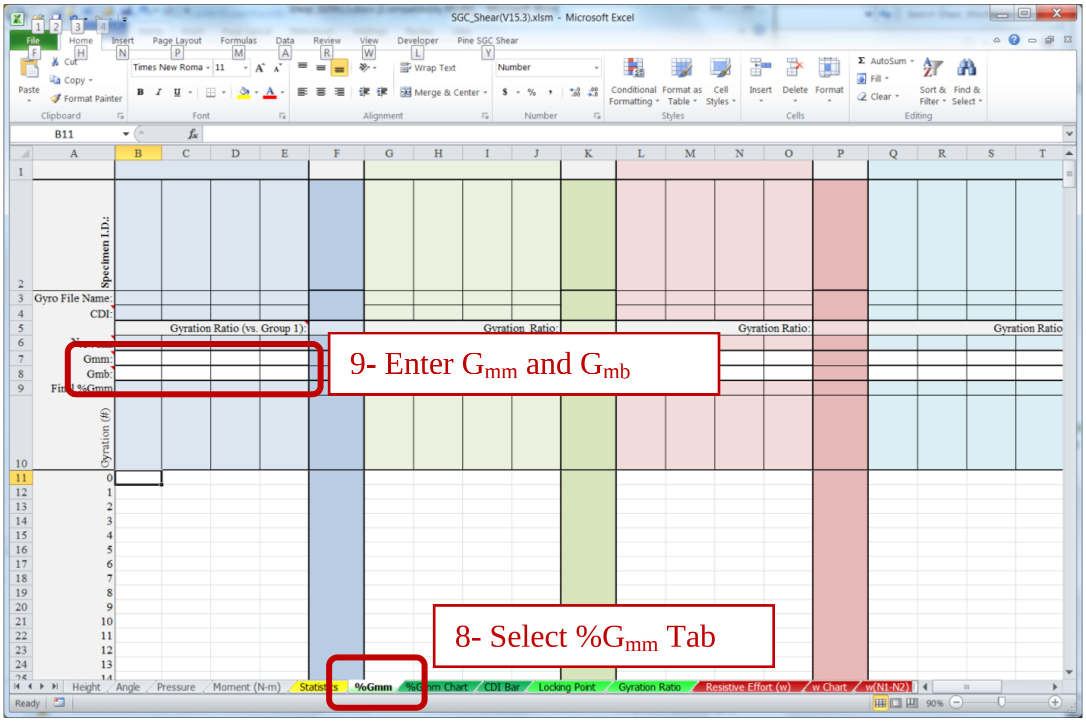

Figure 2: %Gmm Worksheet

IV. Worksheets

4.1 SGC Raw Data Worksheets

The following worksheets contain the data from the SGC *.dat file for each gyration.

4.1.1 Height (mm)

This worksheet contains the specimen height data from the SGC compaction file.

4.1.2 Angle (degree)

This worksheet contains the angle data from the SGC compaction file, typically 1.16° for Superpave gyratory compaction.

4.1.3 Pressure (kPa)

This worksheet contains the applied pressure data from the SGC compaction file, typically 600kPa for Superpave gyratory compaction.

4.1.4 Moment (N-m)

Contains the tilting moment data from the SGC compaction file. The tilting moment is the resistive force of the mix to gyratory motion as measured by the shear instrumentation.

4.2 Summary

This worksheet provides summary tables of the compaction metrics for each group.

4.2.1 Summary Report

The Summary Report ribbon button makes a copy of this worksheet with values (without formulas) making the data easily transferred to other programs for further analysis. Once the report is created it will not be updated when changes are made. To update the Summary Report after a change is made, delete the worksheet then recreate.

4.3 %G_{mm}

The specimen bulk specific gravity (G_{mb}) and mixture maximum specific gravity (G_{mm}) must be entered in rows 7 and 8 of the %G_{mm} worksheet. The relative density (%G_{mm}) at each gyration is calculated from the G_{mb}, G_{mm}, final height, and the height at each gyration. See Figure 2.

N_{92} is the gyration which 92% G_{mm} is obtained. The Final %G_{mm} is of the compacted specimen.

The bulk specific gravity (G_{mb}) of each specimen and the associated mixture maximum specific gravity (G_{mm}) must be entered in rows 7 and 8 of the %G_{mm} worksheet for most calculations in this workbook to be completed.

4.3.1 %G_{mm} Chart

This worksheet is a chart of the average %G_{mm} versus gyrations for each group.

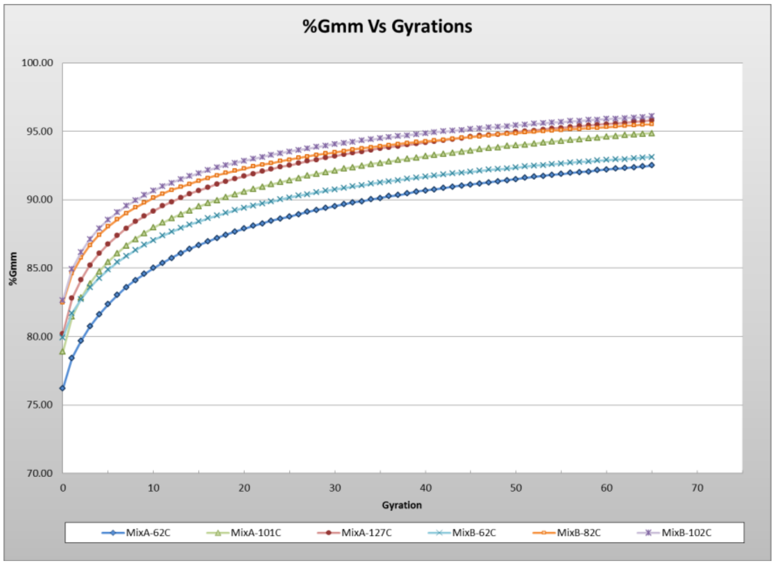

Figure 3: %G_{mm} vs. Gyration Chart

4.4 CDI Bar

This worksheet is a bar chart of the average Construction Densification Index (CDI) for each group. Error bars are one standard deviation (±σ).

> "The construction densification index (CDI), which is the value of the area under the densification curve from density at 8 gyrations to density of 92% G_{mm}, represents the work done during the construction period to achieve 8 % air voids."[5]

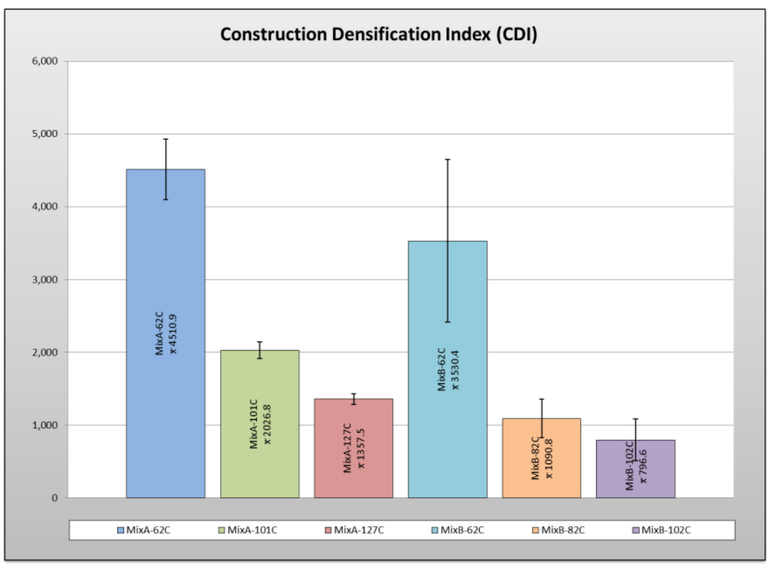

Figure 4: CDI Bar Chart

4.5 Locking Point

This worksheet is a bar chart of the average locking point for each group.

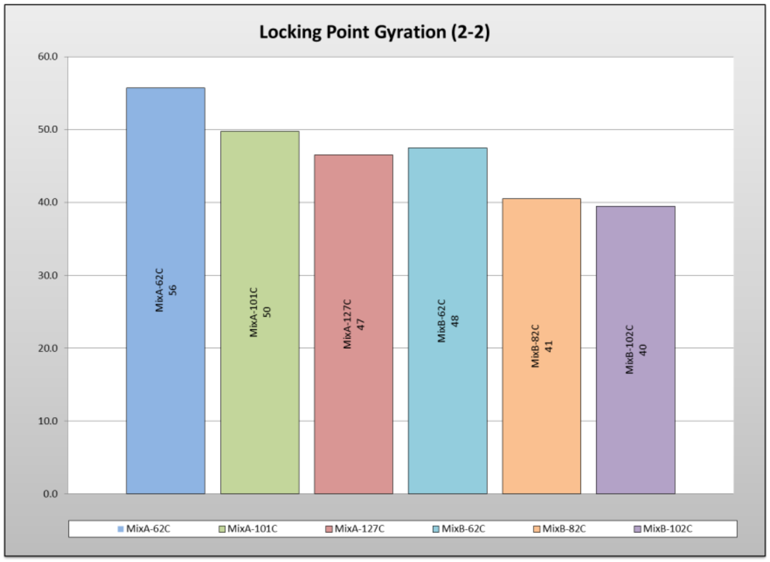

Figure 5: Locking Point Bar Chart

4.6 WEI Bar

This worksheet is a bar chart of the average *Workability Energy Index (WEI)*[8] for each group. Specimens must have reached a minimum of 92% G_{mm} to have a *WEI* value.

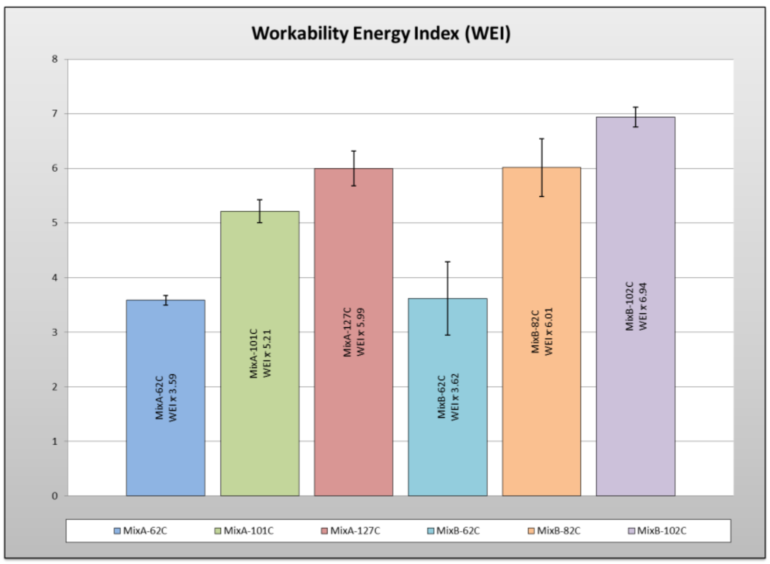

Figure 6: WEI Bar Chart

4.7 CEI Bar

This worksheet is a bar chart of the average *Compactability Energy Index (CEI)*[8] for each group. Specimens must have reached a minimum of 96%G_{mm} to obtain a *CEI* result.

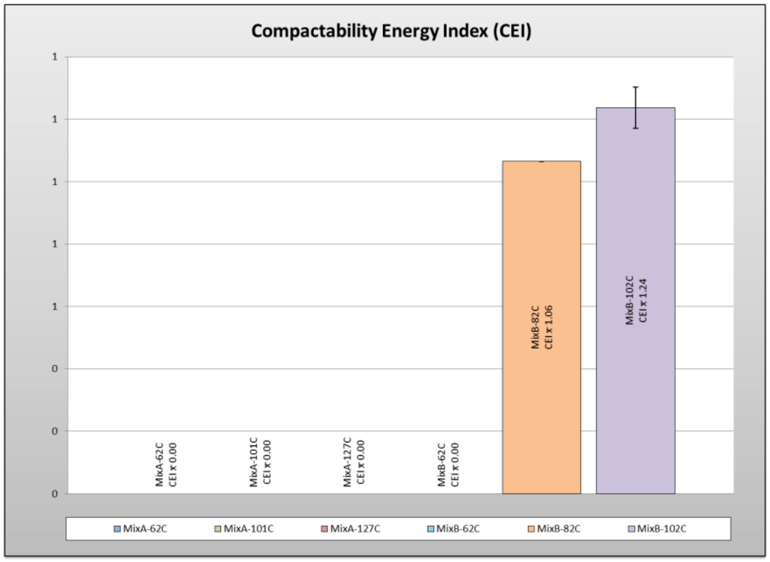

Figure 7: CEI Bar Chart

4.8 Resistive Effort (w)

The *Resistive Effort (w)*[5] worksheet contains the calculations associated with determining w.

4.8.1 W Chart

This worksheet is a bar chart of the Resistive Effort (*w*) for each group.

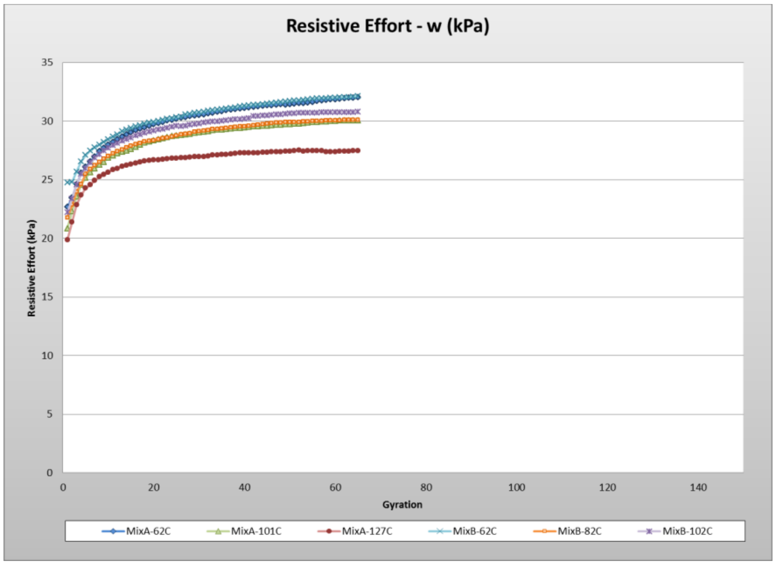

Figure 8: Resistive Effort (W) vs. Gyration Chart

4.8.2 w(∑N1-N2) Bar

This worksheet is a bar chart of the sum of the *Resistive Effort* (*w*)[5] from gyration N1 to gyration N2 for each group where N1 and N2 are user defined. User defined gyration N1 and N2 permit the investigation of the Resistive Effort over compaction ranges other than the CFI (N=2 to N_{92}) and TFI (N_{92} to N_{98}) defined ranges.

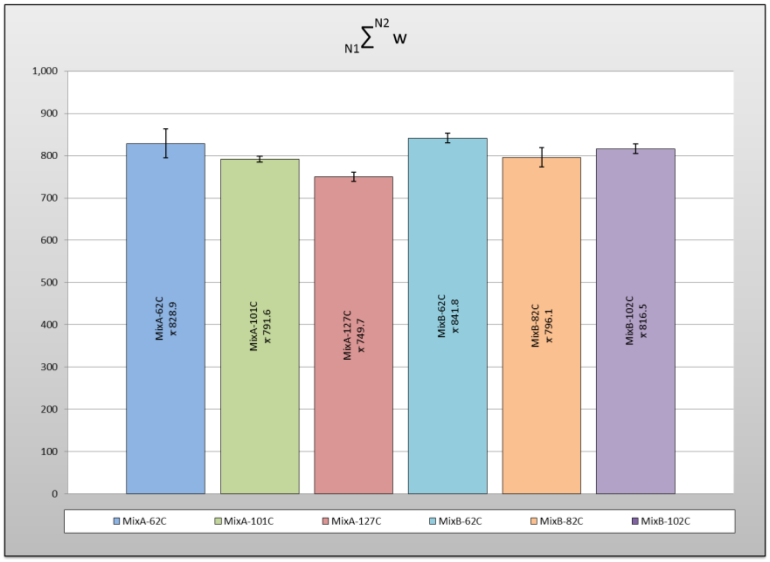

Figure 9: *w* (∑N1 to N2) Bar Chart

4.8.3 CFI Bar

This worksheet is a bar chart *Construction Force Index (CFI)*[5] for each group which is the sum of the Resistive Effort (*w*) from gyration N=2 to N_{92}. Specimens must have reached a minimum of $92\%G_{mm}$ to obtain a CFI result.

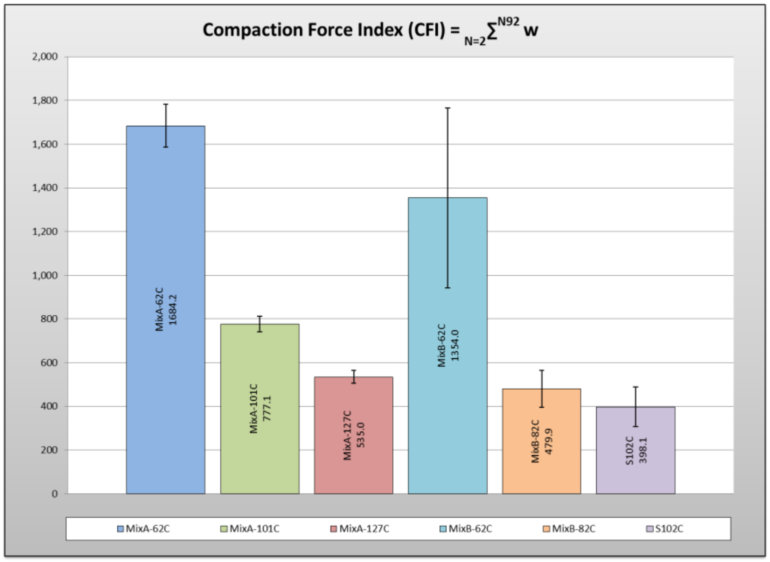

Figure 10: CFI Bar Chart

4.8.4 TFI Bar

This worksheet is a bar chart of the *Traffic Force Index (TFI)*[5] for each group which is the sum of the Resistive Effort (*w*) from gyration N_{92} to N_{98}. Specimens must have reached a minimum of 98%G_{mm} to obtain a TFI result.

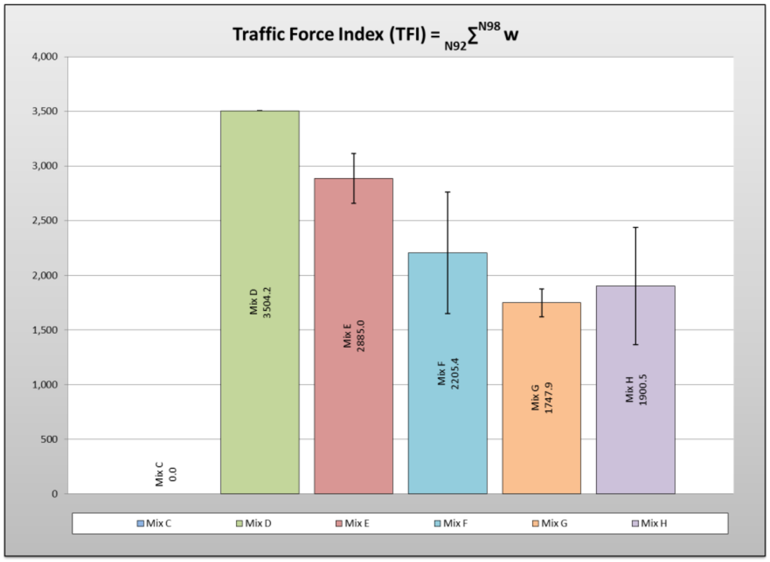

Figure 11: TFI Bar Chart

4.9 S_g (kPa)

The S_g (kPa) worksheet contains the calculations associated with determining gyratory shear. Gyratory Shear (S_g) [1] is charted several ways within the workbook.

4.9.1 S_g Chart

This worksheet is a chart of the average Gyratory Shear (S_g) versus gyration for each group. A mixture with a defined maximum then a significant reduction may indicate a mixture that should be examined in more detail. See Figure 12.

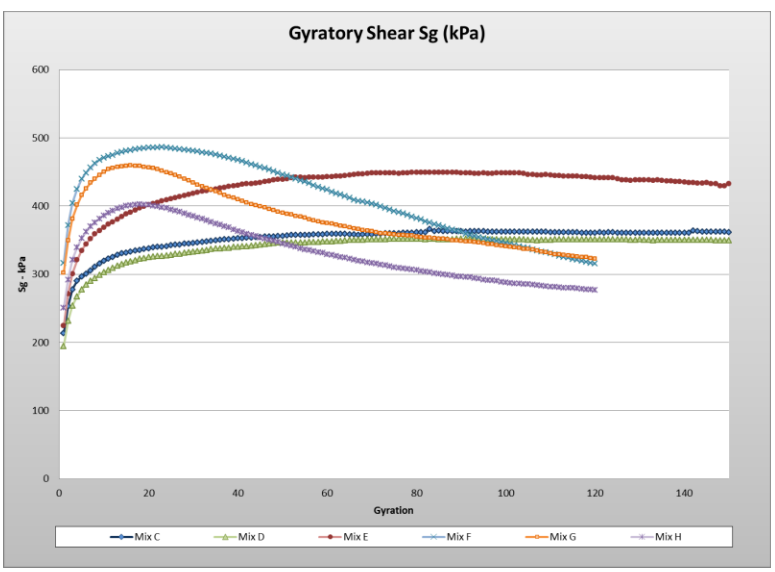

Figure 12: Gyratory Shear (S_g) vs. Gyration Chart

4.9.2 Sg Chart (%G_{mm})

This worksheet is a chart of the average Gyratory Shear (S_g) versus relative density for each group. Some quality mixes exhibit a minor drop in S_g near a relative density of 98%G_{mm} (i.e.: Mix E). However, a significant drop in gyratory shear at densities less than 98%G_{mm} may suggest an unstable mix (i.e.: Mix H). See Figure 13

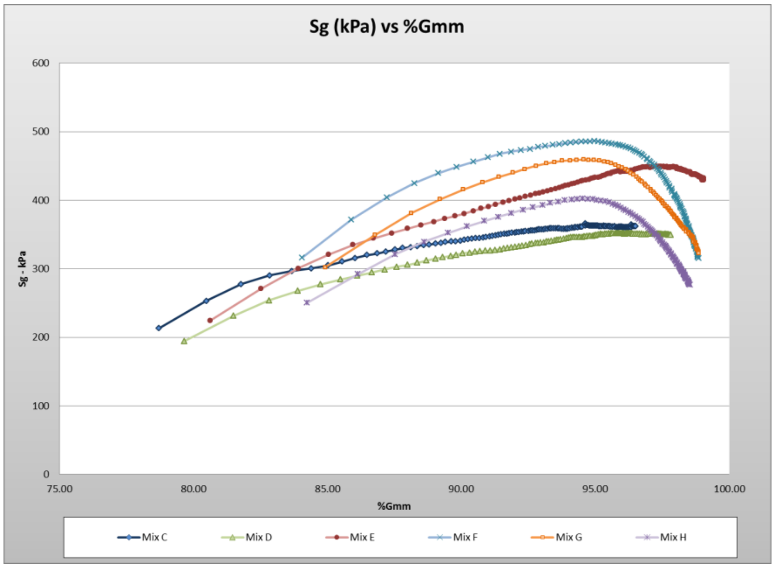

Figure 13: Gyratory Shear (S_g) vs. %G_{mm} Chart

4.10 Normalized S_g

The $S_{g\text{-norm}}$ represents the S_g as a percentage of its maximum. Butcher: "Shear stress results are, however, more illustrative when presented as the percentage of maximum shear stress and when compared against percentage voids rather than cycles."[3] The Normalized S_g worksheet contains the calculations associated with this concept.

4.10.1 NSI Bar

This worksheet is a bar chart of the Normalized Shear Index (NSI)[9] for each group which is the sum of the Normalized Shear from gyration N=2 to N_{92}. Specimens must have reached a minimum of $92\%G_{mm}$ to have an NSI value.

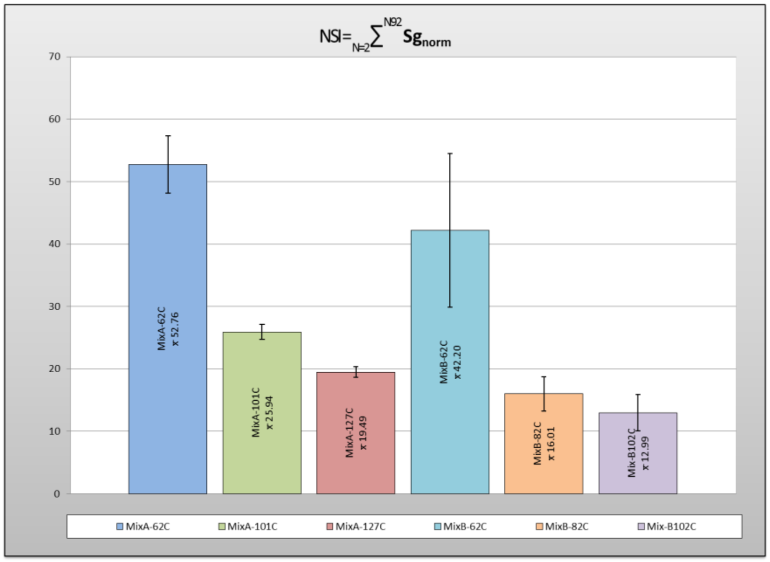

Figure 14: NSI Bar Chart

4.10.2 Norm S_g Chart

This worksheet is a chart of the Normalized Shear value for each group versus gyrations plotted on a log scale. A severe drop in the Normalized Shear value (i.e: Mix F, G, H) indicates a reduction in the resistance of the material to the gyratory action during compaction in the SGC. See Figure 15.

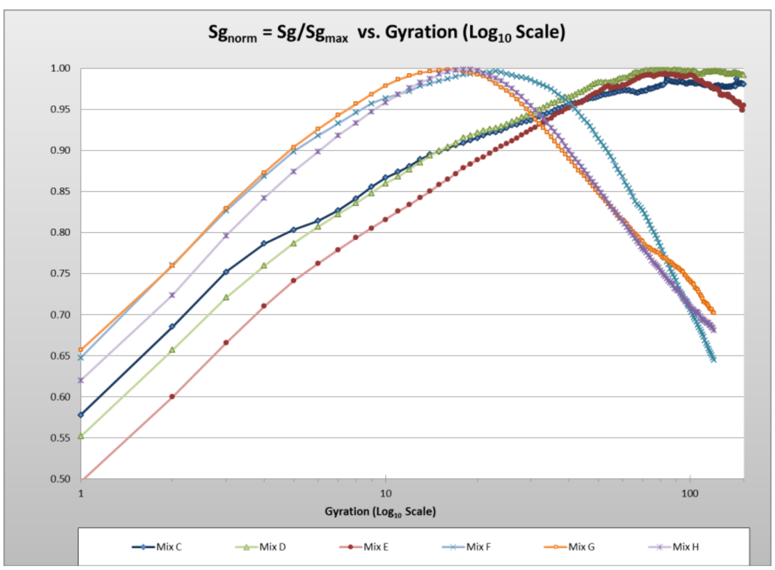

Figure 15: Normalized S_g vs. Gyration Chart

4.10.3 Norm S_g (%G_{mm}) Chart

This chart plots the group average of the Normalized Shear $S_{g\text{-}norm}$ with respect to the percent of maximum theoretical density (%G_{mm}). Butcher discusses the shear curve shape:

> *"An explanation for the behavior is suggested in that most of the first stage is purely mechanical where the coated particles are pushed together and generate increasing resistance until a point is reached where the lubrication aspects of the mastic are able to increase their influence. The mastic influence continues to increase until finally a position is reached where the binder actually begins to migrate to the outsides of the specimen."*[3]

> *"The maximum shear stress is achieved within a tight percentage voids band for all dense mixes and is independent of angle and vertical stress. The rate of change of percentage voids at the maximum shear stress position is a characteristic of the mix gradation and is independent of angle and vertical stress."*[3]

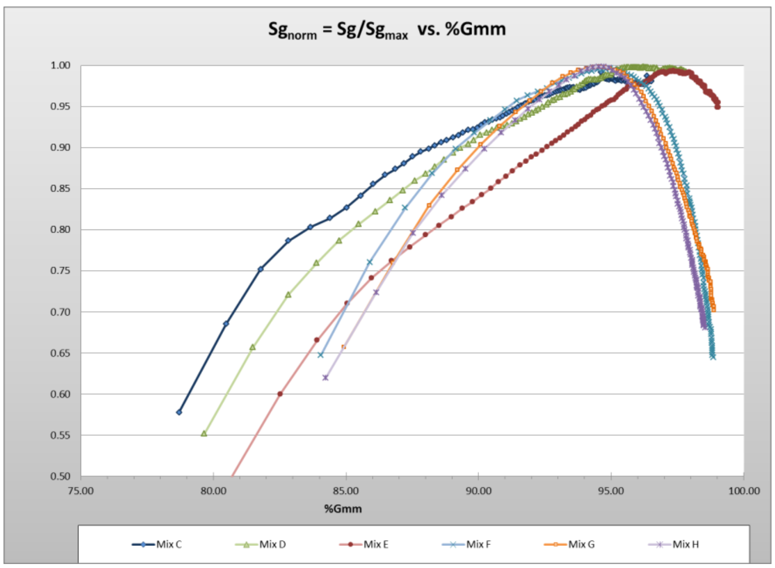

Figure 16: Normalized S_g vs. %G_{mm} Chart

4.10.4 Norm Sg Chart - Group1-6

These charts plot the Normalized Shear $S_{g\text{-}norm}$ with respect to the percent of maximum theoretical density ($\%G_{mm}$) for all specimens within each group.

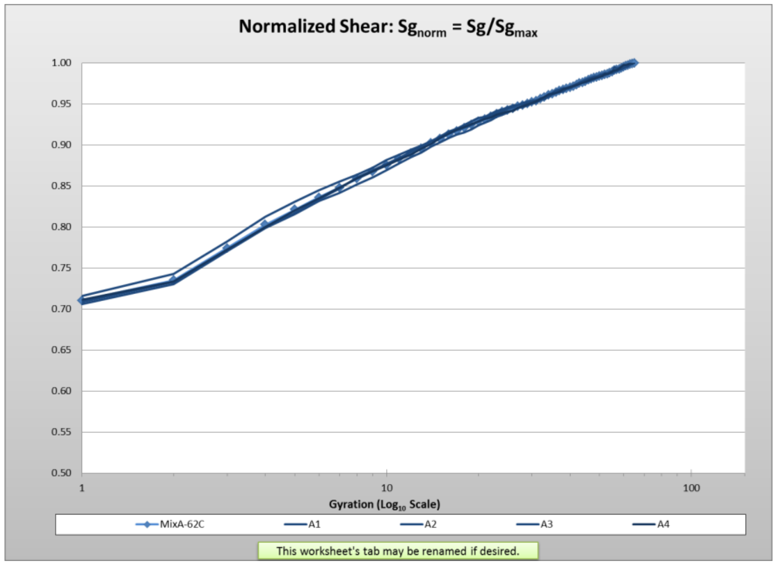

Figure 17: Normalized S_g Chart - Groups

4.10.5 N@ %Norm S_g Bar

Gyration N at which the user selected $\%S_g$ max (i.e.: 100%) occurs.

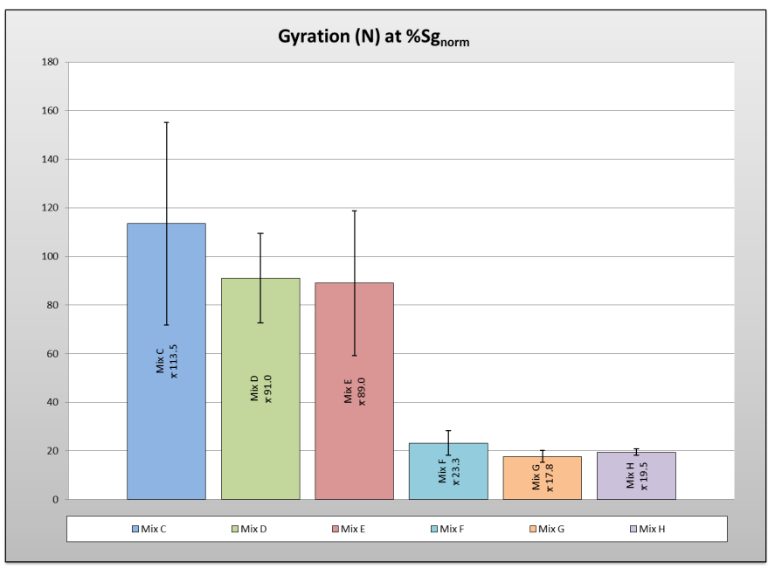

Figure 18: N @%Sg Norm Gyration Bar Chart

4.11 Sg (kPa) Fit

This worksheet and associated graphs fit a second order polynomial function to the gyratory shear data and determines the gyration N at the maximum value of the fit curve[4]. The number of gyrations at maximum shear ratio is analogous to (N-SR_{max}) reported in NCHRP Project 9-16 (Report 478)[4].

4.11.1 N@ Sg(kPa) Fit Bar

This worksheet presents a bar chart of the group average gyration N at the maximum value of the S_g 2nd order polynomial curve fit.

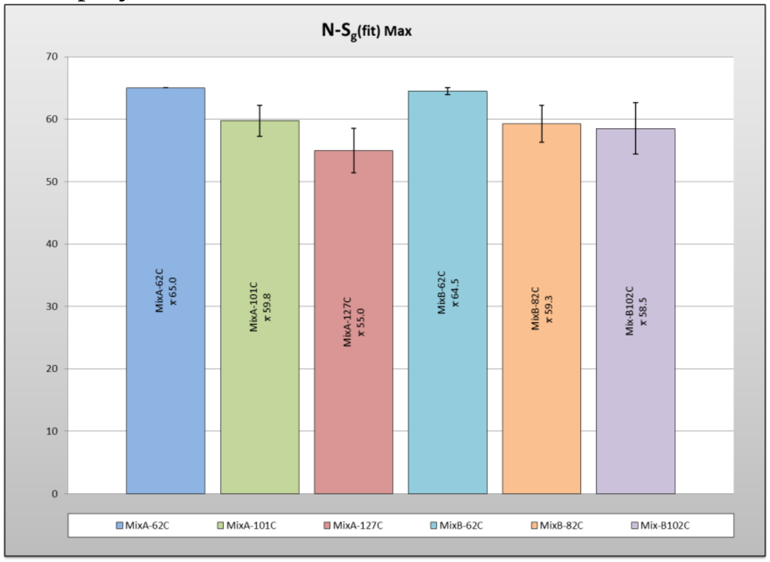

Figure 19: Sg Fit Bar Chart

4.11.2 S_g (kPa) Fit Chart

This chart shows the group average of the 2nd order polynomial data fit and the gyration N at the maximum value of the S_g fit curve.

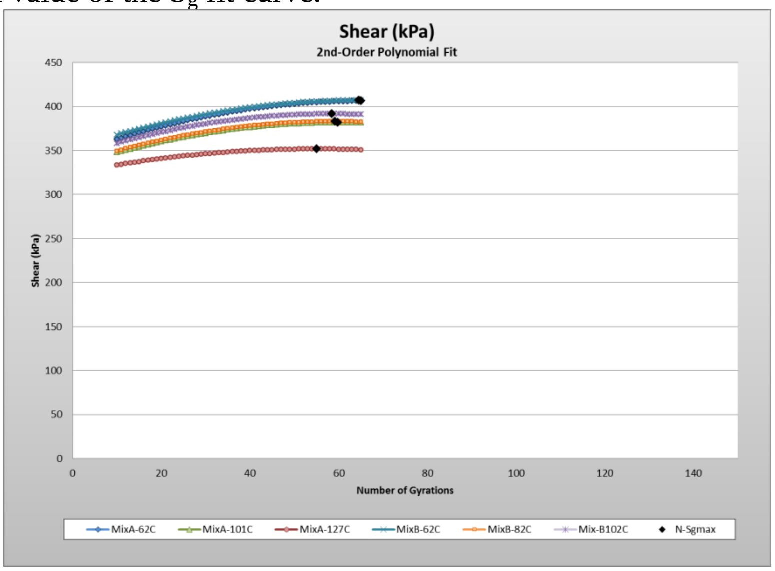

Figure 20: S_g Polynomial Fit Chart

4.12 Revisions

The Revisions worksheet lists the changes made to the workbook.

V. References

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