Compaction Sensitivity of Saskatchewan SPS-9A Asphalt Mixes

Aziz Salifu
Department of Civil and Geological Engineering
University of Saskatchewan
57 Campus Drive
Saskatoon, SK, S7N 5A9
306-966-7024
aziz.salifu@usask.ca

Curtis Berthelot, Ph.D., P.Eng.
Department of Civil and Geological Engineering
University of Saskatchewan
57 Campus Drive
Saskatoon, SK, S7N 5A9
306-966-7009
curtis.berthelot@usask.ca

Brent Marjerison, M.Sc., P.Eng.
Saskatchewan Ministry of Highways and Infrastructure
350 3rd Avenue North
Saskatoon, SK, S7K 2H6
306-933-7088
bmarjerison@highways.gov.sk.ca

Ania Anthony, M.Sc., P.Eng.
Saskatchewan Ministry of Highways and Infrastructure
350 3rd Avenue North
Saskatoon, SK, S7K 2H6
306-933-7088
aanthony@highways.gov.sk.ca

Paper prepared for presentation
at the Sustainability of Asphalt Mixes Session
of the 2009 Annual Conference of the
Transportation Association of Canada
Vancouver, British Columbia

ABSTRACT

Saskatchewan Ministry of Highways and Infrastructure (SMHI) currently use the Marshall compaction method for laboratory hot-mix asphalt (HMA) design and placement quality control / quality assurance. Unfortunately, Saskatchewan has witnessed premature rutting in some pavements due to significant reduction in air voids under traffic loading. As a result, it is hypothesized that laboratory compaction during the design process may not be accurately predicting in-service air voids of typical Saskatchewan asphalt mixes. This research characterized the effect of varied laboratory compaction energy on the volumetric and mechanistic mix properties of laboratory compacted hot-mix asphalt mixes. The volumetric and mechanistic mix properties of four Radisson SPS-9A asphalt mixes are summarized and presented in this paper.

One of the four asphalt mixes considered in this research is designed and constructed to meet conventional Saskatchewan Marshall Type-71 mix design protocol, two of the research mixes were designed and constructed to meet Superpave^{TM} Level I mix design criteria. One of the research mixes was designed and constructed to meet the Superpave^{TM} recycle mix design criteria.

This research found that laboratory volumetric properties are sensitive to varying Marshall and gyratory compaction energies. With regards to Saskatchewan air voids criterion, 50-blow Marshall compaction satisfied air voids criterion. However, at 75-blow Marshall compaction effort, the conventional SMHI Type-71 asphaltic mixes yielded air voids below the minimum allowable air voids. Air voids was sensitive to increased gyratory compaction energy. In terms of gyratory compaction, the conventional SMHI Type-71 mixes met air voids criterion at 1.25°, but not 2.00° and 2.75° gyratory angle.

Triaxial frequency sweep characterization of the Radisson SPS-9A mixes proved that increasing gyratory compaction energy significantly increased the mechanistic dynamic modulus mix properties of the Radisson SPS-9A mixes across deviatoric stress.

KEYWORDS: Marshall compaction, gyratory compaction, volumetric property, mechanistic property, SPS-9A test site.

INTRODUCTION

Many provincial highways are faced with the problem of permanent pavement deformation. In laboratory HMA design processes the method of compaction employed has been found to significantly influence the volumetric mix properties and mechanical behavior of the compacted asphalt mix (1, 2). Laboratory characterization of compacted samples is used for the design as well as field performance prediction of asphalt concrete mixes. As a result, it is important to produce compacted asphalt specimens in the laboratory that have similar volumetric and mechanical properties as field compacted and long term trafficked asphaltic mixes (3, 4). Saskatchewan Ministry of Highways and Infrastructure (SMHI) currently use the Marshall compaction method for laboratory hot-mix asphalt (HMA) design and placement quality control and quality assurance (5).

Typical asphalt mixes used by SMHI were obtained from the Radisson SPS-9A test sections. One of the four asphalt mixes considered in this research was designed and constructed to meet conventional Saskatchewan Marshall Type-71 mix design protocol, two of the research mixes were designed and constructed to meet Superpave^{TM} Level I mix design criteria, and one of the research mixes was designed and constructed to meet the Superpave^{TM} recycle mix design criteria. Table 1 summarizes the mix design method and asphalt binder specification for each Radisson SPS-9A asphalt mix.

This paper summarizes the effect of varied laboratory compaction energies on the volumetric and mechanical mix properties of laboratory compacted asphalt mixes. Various Marshall and gyratory compaction energies have been employed in laboratory compaction of Radisson Specific Pavement Study 9A (SPS-9A) asphalt mixes. Volumetric mix properties were obtained for the Marshall and gyratory compacted specimen. Marshall stability and flow tests were performed as per SMHI specifications (5).

Triaxial frequency sweep testing was used in characterizing mechanistic material properties of the Radisson SPS-9A asphalt mixes. The gyratory compacted specimens were tested under stresses representative of field state conditions. Rapid triaxial frequency sweep characterization has been found to be effective in determining material performance properties (6, 7, 8, 9, 10).

RESEARCH OBJECTIVE

This research attempts to identify a laboratory compaction method that produces compacted HMA which better replicate field compacted asphalt mixes used by SMHI.

VOLUMETRIC CHARACTERIZATION OF MARSHALL COMPACTED SPECIMEN

The effect of varied Marshall compaction energy on the air voids of the Radisson SPS-9A asphalt mixes were characterized by compacting Marshall specimen at 50 and 75-Marshall compaction. Voids in total mix (VTM) were obtained for each specimen.

Voids in Total Mix (VTM) after Marshall Compaction

Air voids are a physical property of asphalt concrete which is often correlated to in-field rutting performance of asphalt pavements. The stability and durability of asphalt pavements is significantly affected by the amount of air voids in the HMA mixture (11, 12). Table 2 summarizes and Figure 1 illustrates the VTM of the Radisson SPS-9A asphalt mixes across varying Marshall compaction energies. As seen in Table 2 and Figure 1, VTM was found to be lower at 75-blow Marshall compaction compared to 50-blow Marshall compaction across all the Radisson SPS-9A mixes.

SMHI conventional Marshall mix 900901 recorded lower VTM compared with Superpave^{TM} Level I mixes, indicating that the SMHI mix is more easily compacted to lower air voids due to the presence of smaller top size aggregates. VTM of SMHI conventional Marshall mix was found to be significantly different than the Superpave^{TM} Level I mixes. With regards to SMHI air voids criterion, the SMHI conventional Marshall mix is below acceptable air voids criterion at both 50-blow and 75-blow Marshall compaction while the Superpave^{TM} Level I mixes are above acceptable air voids criterion at both 50-blow and 75-blow Marshall compaction. It should however, be noted that only Superpave^{TM} Level I mix 900902, met the SMHI air voids criterion at 75-blow Marshall compaction.

VOLUMETRIC CHARACTERIZATION OF GYRATORY COMPACTOR SPECIMEN

The Strategic Highway Research Program (SHRP) adopted and modified the French gyratory compactor as part of the Superpave^{TM} Level I mix design protocol with a specified gyratory angle of 1.25° (15). In order to investigate the effect of varying compaction energy on gyratory compacted specimens, Radisson SPS-9A asphalt mixes were compacted at gyratory angles of 1.25°, 2.00° and 2.75°. The Superpave^{TM} gyratory employed in this research produces larger continuum laboratory specimen compared to the Marshall compactor and has been found to be highly sensitive to changes in asphalt mix properties and produces specimen which better replicate field compacted asphalt mix (16,17).

Voids in Total Mix (VTM) after Gyratory Compaction

The VTM of gyratory compacted specimens from the Radisson SPS-9A asphalt mixes are presented across varying angles of gyration at $N_{initial}$ (N_{ini}), N_{design} (N_{des}) and $N_{maximum}$ (N_{max}) for each mix. Table 3 summarizes and Figure 2 illustrates the VTM of the gyratory compacted specimens at N_{des} and N_{max}, respectively. As seen in Table 3 and Figure 2, VTM was found to decrease with an increase in angle of gyration at N_{ini}, N_{des} and N_{max} across all SPS-9A mixes. Increasing the angle of gyration increases the shear stress of the gyratory compactor resulting in a more consolidated HMA specimen. VTM at N_{ini} was higher than SMHI VTM criteria for all test sections across all angles of gyration as seen in Figure 2 (a).

SMHI conventional Marshall mix 900901 recorded the lowest VTM compared to the Superpave^{TM} Level I mixes at all angles of gyration. The SMHI conventional Marshall mix 900901 only met the air voids criterion at 1.25° angle of gyration at N_{des} as seen in Figure 2 (b). Only Superpave^{TM} Level I mix 900902 met the SMHI air voids criterion at N_{des} and 2.75° angle of gyration.

SMHI conventional Marshall mix 900901 recorded low VTM at N_{max} and was below acceptable SMHI air voids criterion at all angles of gyration as seen in Figure 2 (c). It should be noted that all Superpave^{TM} Level I mixes met the SMHI air voids criterion at N_{max} and 2.00° angle of gyration. However, Superpave^{TM} Level I mixes were above acceptable SMHI air voids criterion at 1.25° angle of gyration and below acceptable SMHI air voids criterion at 2.75° angle of gyration as seen in Figure 2 (c).

VTM was found to be more sensitive to change in gyratory angle from 1.25° to 2.00° compared to 2.00° to 2.75° for all mixes. VTM of Superpave^{TM} mixes were above acceptable limits of SMHI VTM criteria.

MARSHALL STABILITY AND FLOW CHARACTERIZATION

SMHI currently uses the Marshall stability and flow characterization in laboratory asphalt mix design and field quality control and quality assurance. The Marshall stability and flow characterization is empirical and does not provide fundamental visco-elastic material response properties (8). The Marshall compacted samples of the Radisson SPS-9A asphalt mixes were tested for stability and flow at a temperature of 60°C. 60°C is believed to be the optimum temperature of HMA pavements in the summer when the HMA is most susceptible to shear failure or visco-plastic flow (17).

Marshall Stability Characterization Results

Marshall stability is believed to be empirically related to the maximum load a HMA can be subjected before shear failure (8). Table 4 summarizes and Figure 3 (a) illustrates the Marshall stability of the Radisson SPS-9A asphalt mixers at 50-blow and 75-blow Marshall compaction. As seen in Table 4 and Figure 3 (a), Marshall stability is higher at 75-blow compared to 50-blow Marshall compaction for all mixes.

Marshall stability values of all mixes are within acceptable SMHI Marshall stability criterion at 50-blow Marshall compaction. However, Marshall stability at 75-blow Marshall compaction were above acceptable SMHI Marshall stability criterion for all mixes except Superpave^{TM} recycle mix 900962 with a value of 5.8 kN.

Marshall Flow Characterization Results

Marshall flow is believed to be related to the ability of HMA to resist visco-plastic deformation under applied stress. Table 4 summarizes and Figure 3 (b) illustrates the Marshall flow of the Radisson SPS-9A asphalt mixers at 50-blow and 75-blow Marshall compaction. As seen in Table 4 and Figure 3 (b), Marshall flow values met the SMHI Marshall flow criterion at 50-blow Marshall compaction for all mixes. With regards to 75-blow Marshall compaction, only Superpave^{TM} recycle mix 900962 did not meet the SMHI Marshall flow criterion with a value of 3.8 mm.

TRIAXIAL FREQUENCY SWEEP MECHANISTIC CHARACTERIZATION

This research employed the rapid triaxial frequency sweep tester to characterize fundamental constitutive relations of the Radisson SPS-9A asphalt mixes with respect to varying compaction energy across the full range of field state load rates of 10 Hz load frequency, bulk stress of 950 kPa, and deviatoric stress states of 200 kPa and 600 kPa.

Dynamic Modulus Characterization Result

Dynamic modulus is an indicator of material stiffness and is used in pavement design and structural modeling (8, 9, 10). Table 5 summarizes and Figure 4 illustrates the dynamic modulus of the Radisson SPS-9A asphalt mixes at 10 Hz load frequency and two levels of deviatoric stresses. As seen in Table 5 and Figure 4, dynamic modulus was found to increase with an increase in deviatoric stress across all mixes and all angles of gyration.

SMHI conventional Marshall mix 900901 exhibited the highest dynamic modulus at all deviatoric stresses and angles of gyration compared to the other mixes. Superpave^{TM} mix 900959 displayed the highest dynamic modulus value compared to the other Superpave^{TM} Level I mixes. Superpave^{TM} recycle mix 900962 exhibited low stiffness compared to the other mixes with the lowest dynamic modulus value across all deviatoric stress states and angles of gyrations.

Poisson's Ratio Characterization Result

Poisson's ratio is a fundamental material response property dependent on stress-strain behavior (8, 9, 10). Table 6 summarizes and Figure 5 illustrates the Poisson's ratio of the Radisson SPS-9A asphalt mixes at 10 Hz load frequency and three levels of deviatoric stresses. As seen in Table 6 and Figure 5, Poisson's ratio was not sensitive to varying deviatoric stress.

SMHI conventional Marshall mix 900901 and Superpave^{TM} recycled mix 900962, displayed the highest Poisson's ratio compared to the other test sections at 200 kPa and 600 kPa deviatoric stress. However, SMHI conventional Marshall mix 900901 recorded a low Poisson's ratio at 200 kPa deviatoric stress and1.25° angle of gyration. It should be noted that Superpave^{TM} mix 900959 recorded the lowest Poisson's ratio at all angles of gyration and deviatoric stresses.

Phase Angle Characterization Result

Phase angle is the lag between applied stress and resultant strain and is an indicator of visco-elastic material properties (8, 9, 10). Table 7 summarizes and Figure 6 illustrates the phase angle of the Radisson SPS-9A asphalt mixes at10 Hz load frequency and three levels of deviatoric stresses. As seen in Table 7 and Figure 6, phase angle was found to increase with an increase in deviatoric stress at all three angles of gyration and across all mixes.

It should be noted that the Superpave^{TM} mixes 900959 and 900902 have the lowest phase angle values at all three angles of gyration and deviatoric stresses.

Radial Microstrain Characterization Result

Recoverable radial microstrain defines the recoverable portion of strain that results from dynamic loading and is believed to be an indicator of a material's tendency for edge shear failure under traffic loading (8, 9, 10). Table 8 summarizes and Figure 7 illustrates the radial microstrain of the Radisson SPS-9A asphalt mixes at10 Hz load frequency and three levels of deviatoric stresses. As seen in Table 8 and Figure 7, radial microstrain was found to be highest at 600 kPa deviatoric stress for mixes and across all gyratory angles.

It should be noted that Superpave^{TM} recycle mix 900962 displayed the highest radial microstrain compared to the other mixes across all angles of gyration. Significantly low radial microstrain values were recorded at 200 kPa deviatoric stress compared to 600 kPa deviatoric stresses. Radial microstrain was found to be sensitive to varying deviatoric stress.

SUMMARY AND CONCLUSIONS

Saskatchewan Ministry of Highways and Infrastructure currently use the Marshall compaction method for laboratory hot-mix asphalt design and placement quality control and quality assurance. Many provincial highways are faced with the problem of permanent deformation in HMA pavements as a result of laboratory mix design and construction inadequacies. In laboratory hot-mix asphalt design process, the method of compaction employed has been found to significantly influence the volumetric mix properties and mechanical behavior of the compacted asphalt mix. This research investigated the effects of varying Marshall and gyratory compaction energies on volumetric and mechanistic properties of typical Saskatchewan Marshall and Superpave^{TM} mixes.

This research shows that volumetric properties are sensitive to varying Marshall and gyratory compaction energies. With regards to Saskatchewan air voids specification, 50-blow Marshall compaction has been found to be suitable for conventional Saskatchewan Marshall mixes. Superpave^{TM} coarse mixes however met the Saskatchewan air voids specification at 75-blow Marshall compaction. Air voids was highly sensitive to increased gyratory compaction energy. It was observed that most of the research mixes met Saskatchewan air voids specification at 2.00° angle of gyratory. An increase in Marshall compaction energy has been proved to improve Marshall stability and flow of all mixes. It can be concluded that applying increase roller compaction energy in field compaction will result in significant improvement in volumetric and mechanical mix properties of Saskatchewan asphalt mixes.

The results obtained from triaxial frequency sweep characterization show that fundamental material mechanistic properties are sensitive to varying volumetric properties. Dynamic modulus was found to increase with an increase in deviatoric stress and angle of gyration across all mixes. Phase angle also increased with an increase in deviatoric stress and angle of gyration. Radial microstrain also increased with increase deviatoric stress and angle of gyration and indicated material tendency for edge shear failure. Adopting the Superpave^{TM} gyratory compactor with 2.00° angle of gyration is expected to improve volumetric and mechanistic properties of compacted HMA. Increasing roller compaction will therefore result in improved mechanistic material properties of field compacted asphalt mixes use by SMHI.

REFERENCES

1. Ziauddin, Z. A., Al-Abdu Wahab, H.I., Asi, I., Ramadhan, R. Comparative Study of Asphalt Concrete Laboratory Compaction Methods to Simulate Field Compaction. Construction and Materials, USA, 1998, v12**:** pp.337-384.
2. Harvey, J., Eriksen, K., Sousa, J., Monismith, C.L. Effects of Laboratory Specimen Preparation on Aggregate-Asphalt Structure, Air-Void Content Measurement, and Repetitive Simple Shear Test Results. Transportation Research Board. Washington, D.C., USA, 1993, n1454**:** pp.113-122.
3. Von Quintus, H. L., Little, D.N., Consuegra, A., Burati, J. Comparative Evaluation of Laboratory Compaction Devices Based on Their Ability to Produce Mixtures with Engineering Properties similar to those produced in the Field. Transportation Research Board. Washington, D.C., USA, 1989, n1228**:** pp.80-87.
4. Sousa, J. B., Way, G., Harvey, J.T., Hines, M. Comparison of Mix Design Concepts. Transportation Research Board. Washington, D.C., USA, 1995, n1492**:** pp.151-160.
5. SMHI. Standard Test Procedure for Marshall Mix Design Method. Saskatchewan Ministry of Highway and Infrastructure, Saskatchewan, Canada, 2001, STP-204-10.
6. Anthony, A. and Berthelot, C. Effect of Manufactured Fines on Physical and Mechanistic Properties of Fine Dense Graded Hot Mix Asphalt Pavement Mixes in Saskatchewan. Canadian Technical Asphalt Association Annual Conference, Montreal, Canada, 2004, pp.377-397.
7. Anthony, A. Effect of Manufactured Fine Aggregate on Physical and Mechanistic Properties of Saskatchewan Asphalt Concrete Mixes. MSc. Thesis, University of Saskatchewan, Department of Civil and Geological Engineering, Canada, 2007.
8. Berthelot, C. F., Crockford, B., Lytton, R. Comparison of Alternative Test Methods for Predicting Asphalt Concrete Rut Performance. Canadian Technical Asphalt Association Proceedings, Canada, 1999, vXLVL**:** pp.405-434.
9. Berthelot, C. F. Mechanistic Modeling of Saskatchewan SPS-9A Asphalt Concrete Pavements. Ph.D. Dissertation, Texas A&M University, Department of Civil Engineering, USA, 1999.
10. Crockford, W. W., Berthelot, C.F., Tritt, B., Sinadinos, C. Triaxial Frequency Sweep Test. Association of Asphalt Paving Technologists, USA, 2002, v71**:** pp.712-724.
11. Huber, G. A., and Herman, G.H. Effect of Asphalt Concrete Parameters on Rutting Performance: A Field Investigation. Association of Asphalt Paving Technologists, USA, 1987, v56**:** pp.33-61.
12. Brown, E. R., and Cross, S. A Study of In-Place Rutting of Asphalt Pavements. Association of Asphalt Paving Technologists, USA, 1989, v58**.**
13. Chadbourn, B. A., Eugene, L.S.Jr., Crow, B.L., Spindler, S. Effect of Voids in Mineral Aggregates (VMA) on Hot-Mix Asphalt Pavement. M. D. o. Transportation. Minnesota Department of Transportation, USA, 2000.
14. Aschenbrener T., M., C. Factors that Affect the Voids in the Mineral Aggregate of Hot-Mix Asphalt. Transportation Research Board. Washington, D.C., USA, 1994, n1416**:** pp.1-8.
15. SHRP-A-408. Level One Mix Design: Materials Selection, Compaction, and Conditioning. Strategic Highway Research Program, USA, 1994.
16. Harman, T. P., D'Angelo, J., Bukowski, J.R. Evaluation of Superpave^{TM} Gyratory Compactor in the Field Management of Asphalt Mixes: Four Simulation Studies. Transportation Research Board. Washington, D.C., USA, 1995, n1513**:** pp.1-8
17. Button, J. W., Little, D.N., Jagadam, V., Pendleton, O.J. Correlation of Selected Laboratory Compaction Methods with Field Compaction. Transportation Research Board. Washington, D.C., USA, 1994, n1454**:** pp.193-204.

LIST OF TABLES

Table 1 Asphalt Binder and Mix Design Method across Radisson SPS-9A Mixes

Test Section Number	Specified Asphalt Binder	Mix Design Method
900901	PG 52-28 (AC 150/200)	SMHI Marshall Mix Design
900959	PG 52-28 (AC 150/200)	Superpave^{TM} Mix Design
900902	PG 52-40	Superpave^{TM} Mix Design
900962	PG 52-40	Superpave^{TM} Recycled Mix Design

Table 2 Average Voids in Total Mix at 50 and 75-Blow Marshall Compaction

Test Section Number	50-Blow Marshall (%)	Coefficient of Variation (%)	75-Blow Marshall (%)	Coefficient of Variation (%)
900901	2.9	3.9	2.7	20.2
900959	6.2	10.3	5.3	5.3
900902	5.5	7.5	4.3	43.0
900962	5.5	8.7	5.3	1.6

Table 3 Gyratory Compacted Voids in Total Mix at $N_{initial}$, N_{design} and $N_{maximum}$

Test Section Number	1.25° Angle of Gyration	Coefficient of Variation (%)	2.00° Angle of Gyration	Coefficient of Variation (%)	2.75° Angle of Gyration	Coefficient of Variation (%)
$N_{initial}$						
900901	10.9	4.8	9.8	4.3	9.1	5.9
900959	17.7	4.8	16.5	3.2	15.7	4.0
900902	15.6	11.3	15.5	4.7	12.4	7.4
900962	17.0	0.9	15.8	2.2	15.6	3.9
N_{design}						
900901	3.6	15.8	2.8	18.1	2.4	27.8
900959	8.3	11.0	6.3	6.3	5.6	13.9
900902	6.7	28.1	6.3	7.3	4.4	14.4
900962	7.2	5.4	5.8	5.8	5.6	4.7
$N_{maximum}$						
900901	1.8	5.7	0.8	18.0	0.4	31.9
900959	6.0	5.0	4.0	10.2	2.9	17.8
900902	5.1	8.0	4.0	15.8	2.1	18.3
900962	5.2	6.9	3.7	13.5	3.1	3.3

Table 4 Marshall Stability and Flow at 50-Blow and 75-Blow Marshall

Test Section Number	Marshall Stability 50-Blow (kN)	Marshall Stability 75-Blow (kN)	Marshall Flow 50-Blow (mm)	Marshall Flow 75-Blow (mm)
900901	2.92	2.73	2.92	2.73
900959	3.37	2.95	3.37	2.95
900902	2.92	3.49	2.92	3.49
900962	3.11	3.81	3.11	3.81

Table 5 Dynamic Modulus across Deviatoric Stress States at 1.25° Angle of Gyration

Test Section Number	Deviatoric Stress (kPa)	Dynamic Modulus @ 1.25°	Dynamic Modulus @ 2.00°	Dynamic Modulus @ 2.75°
900901	200	3722	3788	3975
	600	3305	3317	3517
900959	200	3216	3557	3184
	600	2714	3075	2922
900902	200	2840	2848	3182
	600	2172	2189	2676
900962	200	2224	2657	2954
	600	1618	1935	2183

Table 6 Poisson's Ratio across Deviatoric Stress States at 1.25° Angle of Gyration

Test Section Number	Deviatoric Stress (kPa)	Poisson's Ratio @ 1.25°	Poisson's Ratio @ 2.00°	Poisson's Ratio @ 2.75°
900901	200	0.28	0.36	0.39
	600	0.32	0.33	0.37
900959	200	0.29	0.27	0.25
	600	0.28	0.29	0.27
900902	200	0.26	0.27	0.28
	600	0.27	0.28	0.28
900962	200	0.31	0.32	0.37
	600	0.32	0.33	0.36

Table 7 Phase Angle across Deviatoric Stress States at 1.25° Angle of Gyration

Test Section Number	Deviatoric Stress (kPa)	Phase Angle @ 1.25°	Phase Angle @ 2.00°	Phase Angle @ 2.75°
900901	200	19.5	23.0	23.0
	600	21.0	22.8	23.3
900959	200	19.4	18.0	16.9
	600	21.0	19.1	18.3
900902	200	18.6	18.6	17.5
	600	21.9	21.8	20.0
900962	200	19.4	19.8	20.9
	600	23.1	23.1	23.4

Table 8 Radial Microstrain across Deviatoric Stress States at 1.25° Angle of Gyration

Test Section Number	Deviatoric Stress (kPa)	Radial Microstrain @ 1.25°	Radial Microstrain @ 2.00°	Radial Microstrain @ 2.75°
900901	200	14.7	17.0	19.3
	600	58.7	58.5	60.7
900959	200	17.9	15.2	14.2
	600	60.7	54.6	53.5
900902	200	16.1	17.7	14.9
	600	68.9	74.2	61.6
900962	200	27.1	24.0	24.7
	600	113.7	100.7	95.2

LIST OF FIGURES

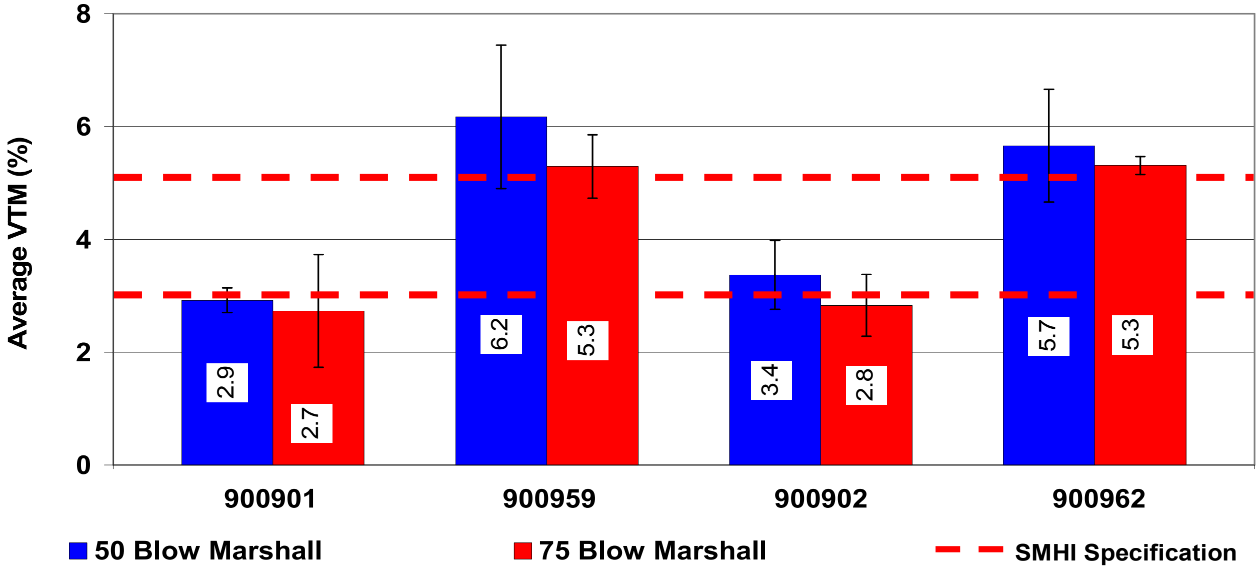
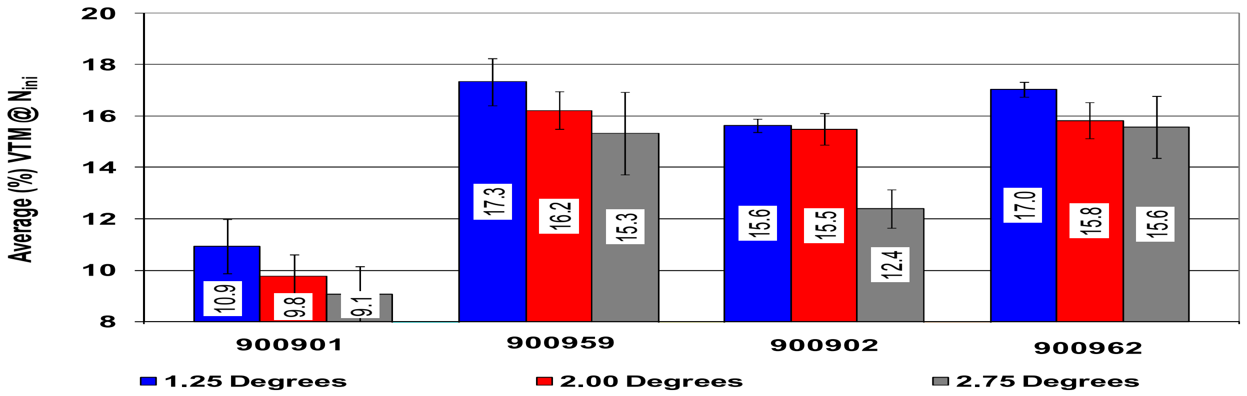
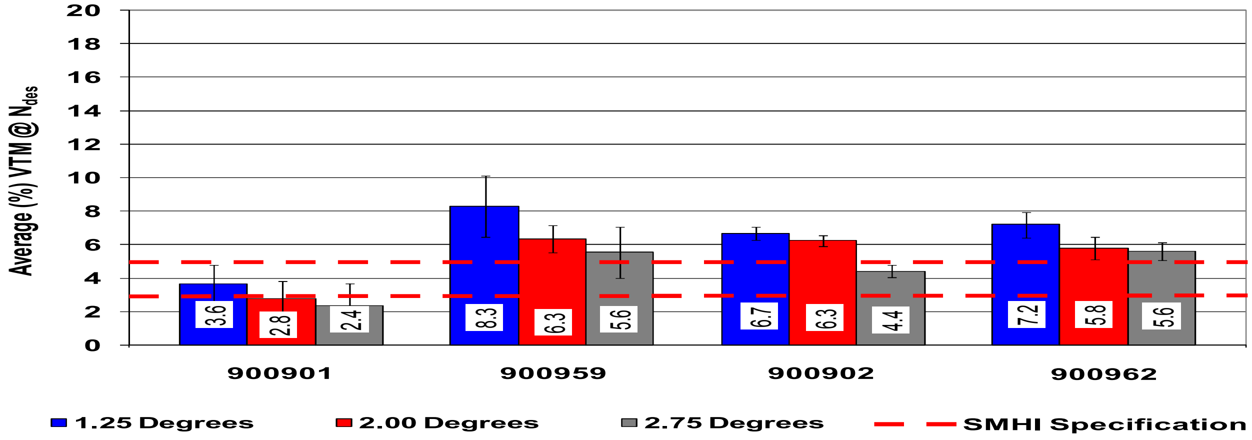


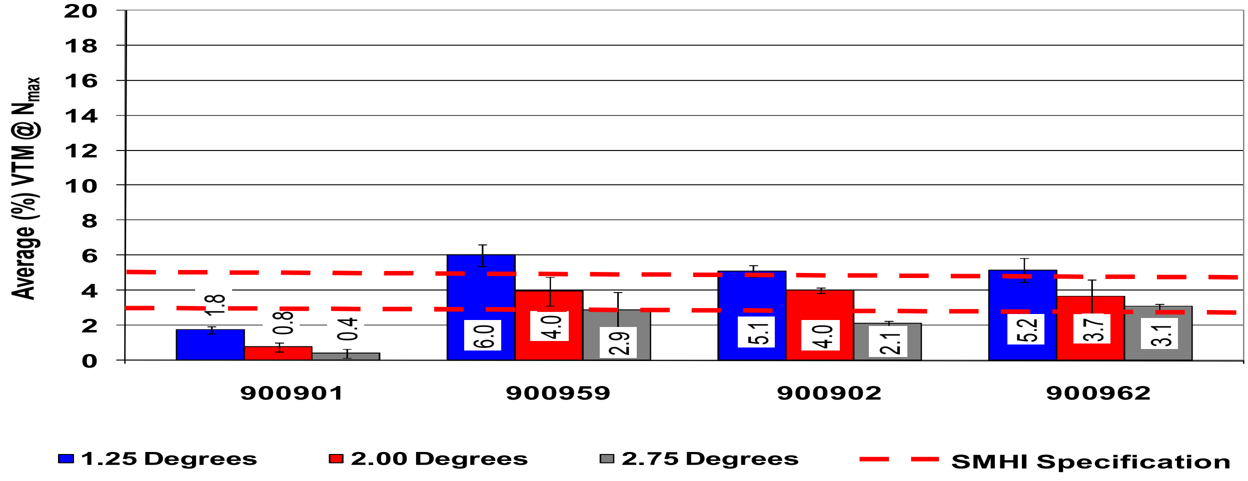
Figure 1 Voids in Total Mix of Marshall Compacted Samples at 50-Blow and 75-Blow Marshall



(a) Voids in Total Mix at N_{ini}

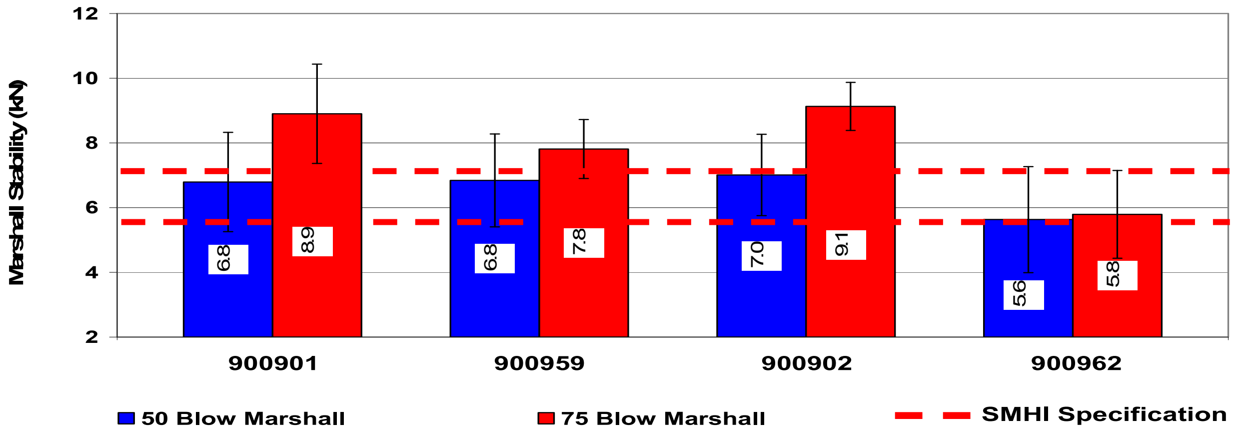


(b) Voids in Total Mix at N_{des}

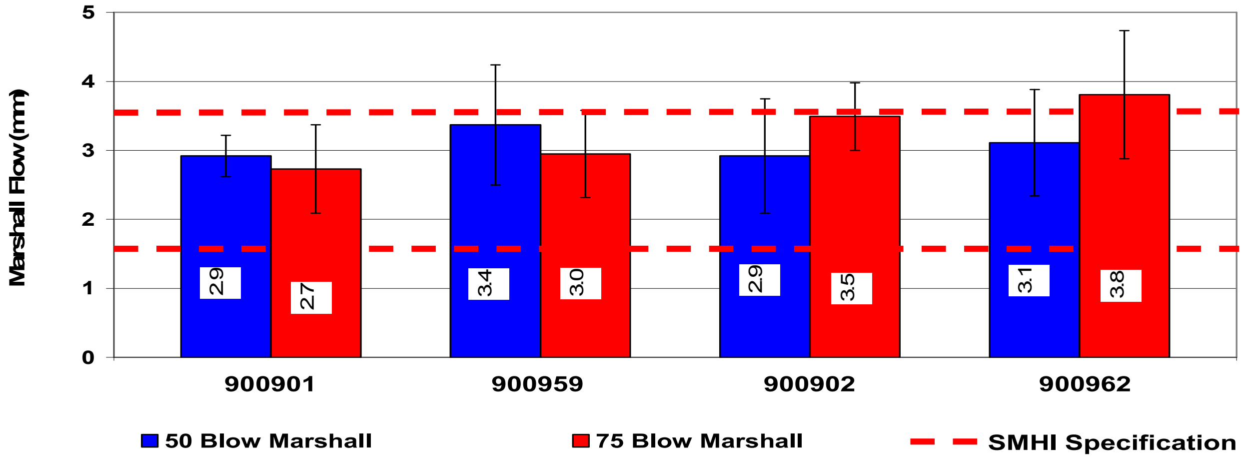


(c) Voids in Total Mix at N_{max}

Figure 2 Voids in Total Mix of Gyratory Compacted Samples

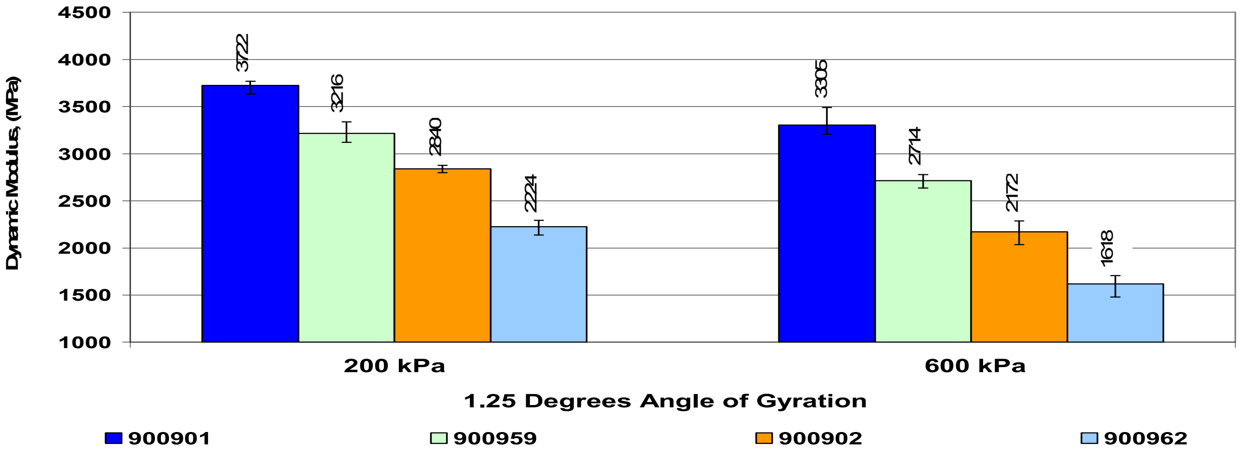


(a) Marshall Stability

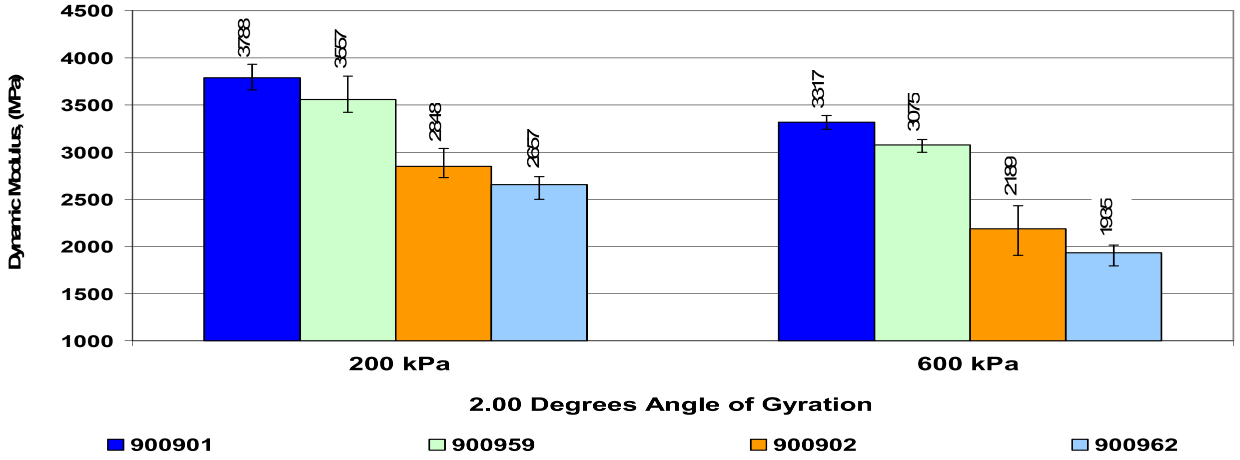


(b) Marshall Flow

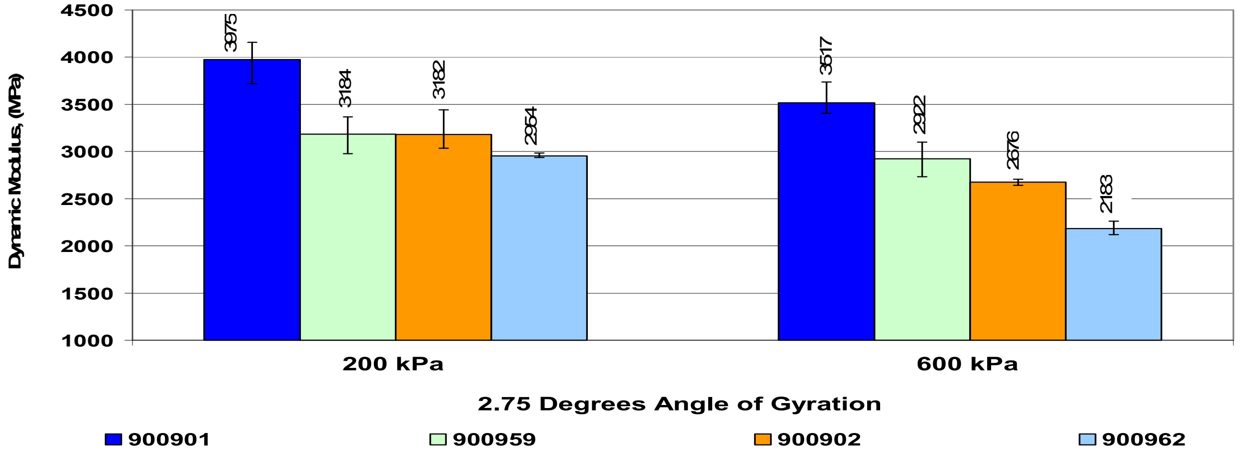
Figure 3 Marshall Stability and Flow across 50-Blow and 75-Blow Marshall Compaction



(a) Dynamic Modulus at 1.25°

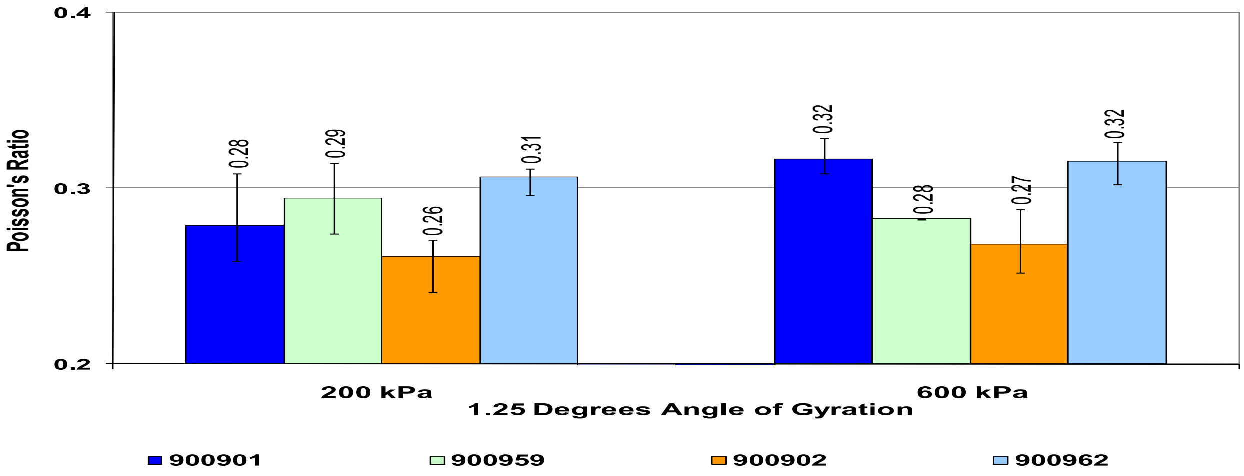


(b) Dynamic Modulus at 2.00°

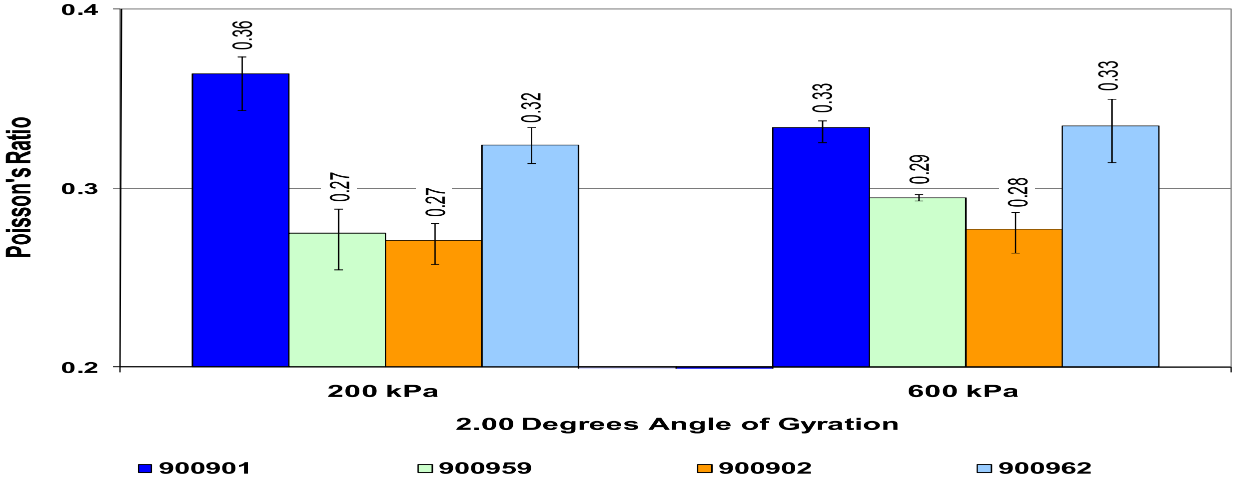


(c) Dynamic Modulus at 2.75°

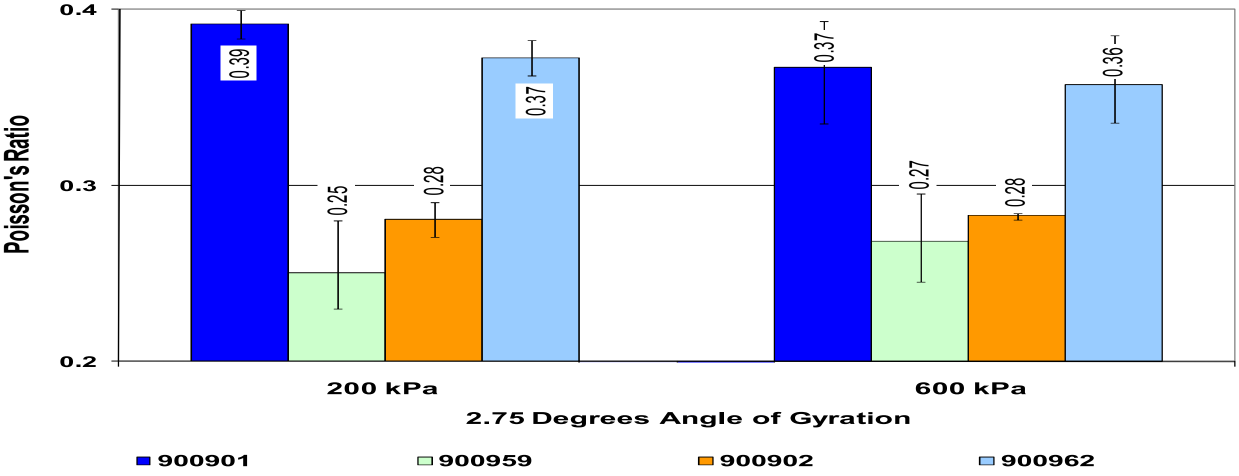
Figure 4 Dynamic Modulus across Deviatoric Stress States and Angle of Gyration



(a) Poisson's Ratio at 1.25°

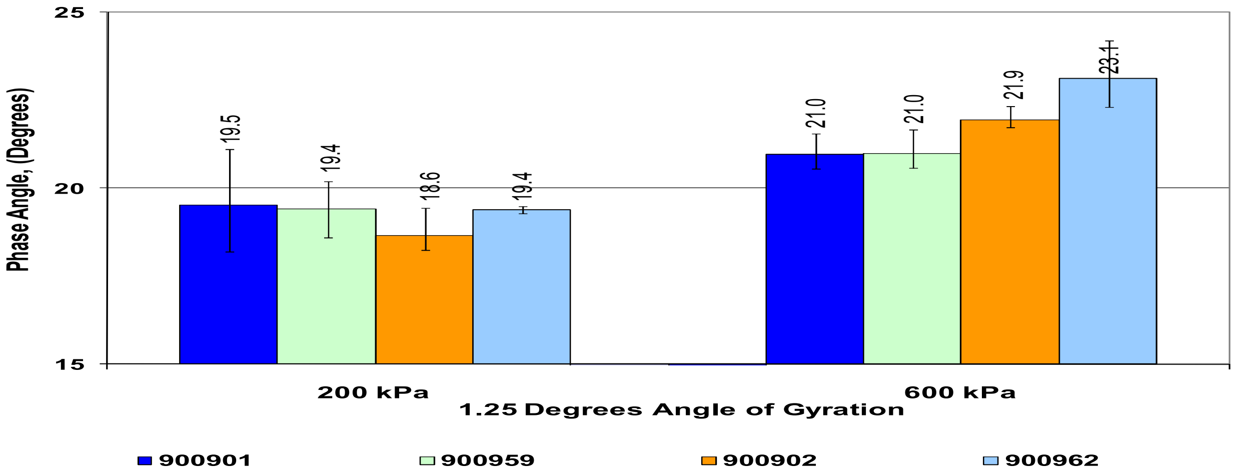


(b) Poisson's Ratio at 2.00°

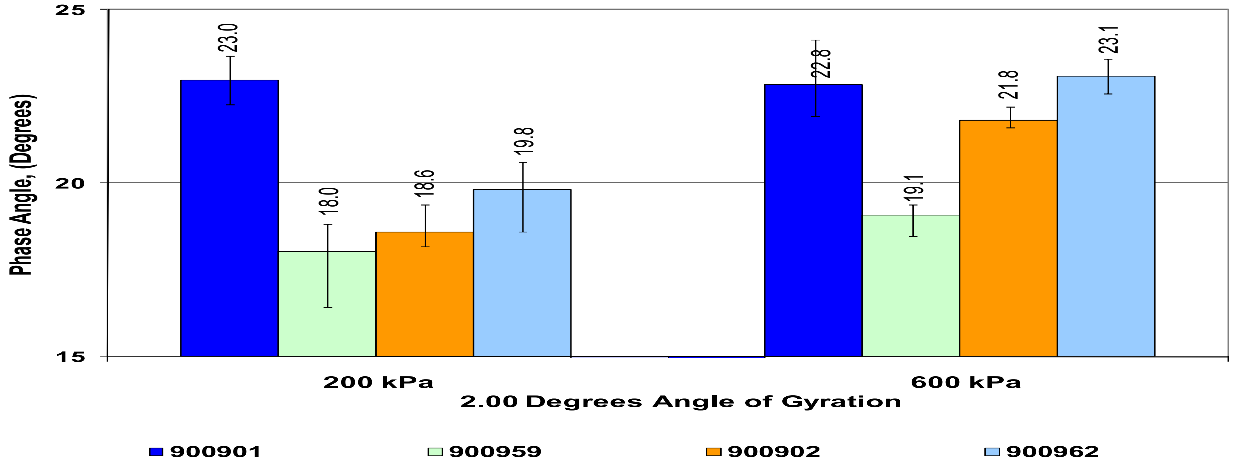


(c) Poisson's Ratio at 2.75°

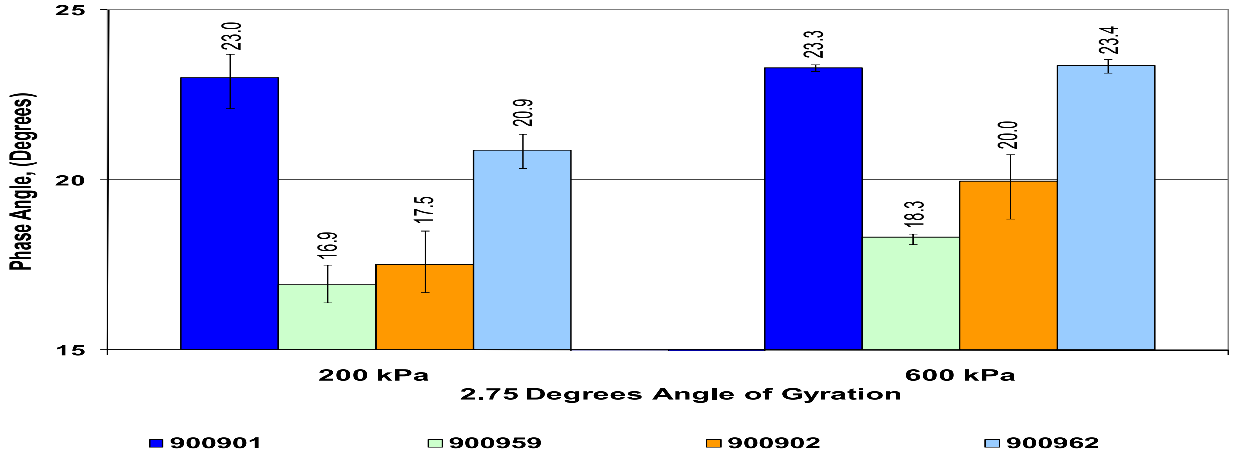
Figure 5 Poisson's Ratio across Deviatoric Stress States and Angle of Gyration



(a) Phase Angle at 1.25°

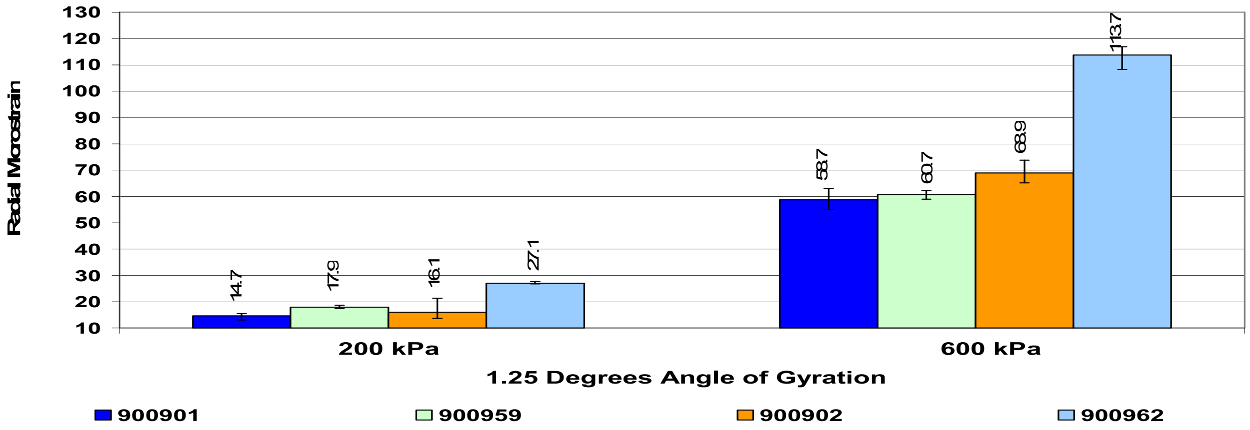


(b) Phase Angle at 2.00°

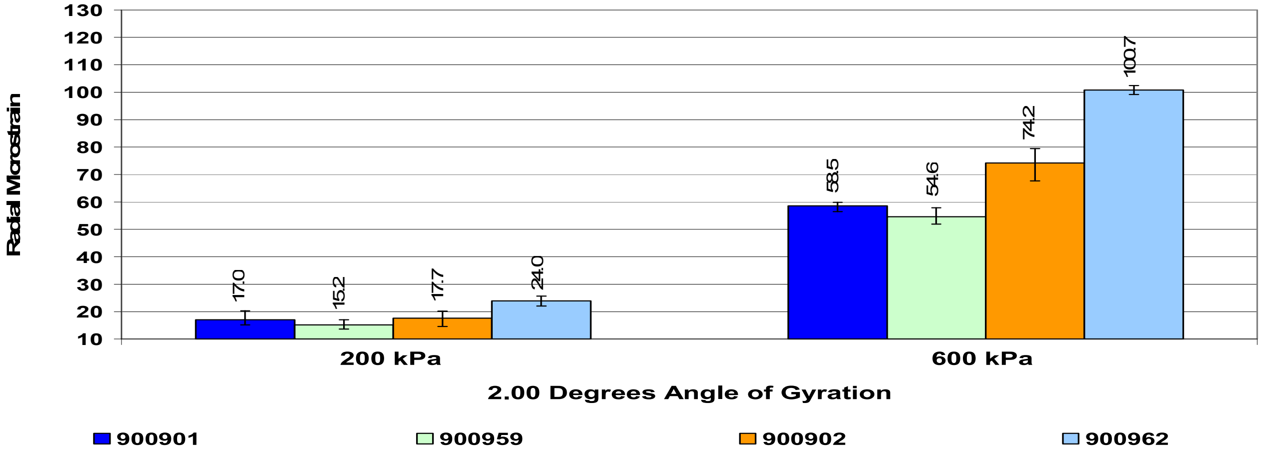


(c) Phase Angle at 2.75°

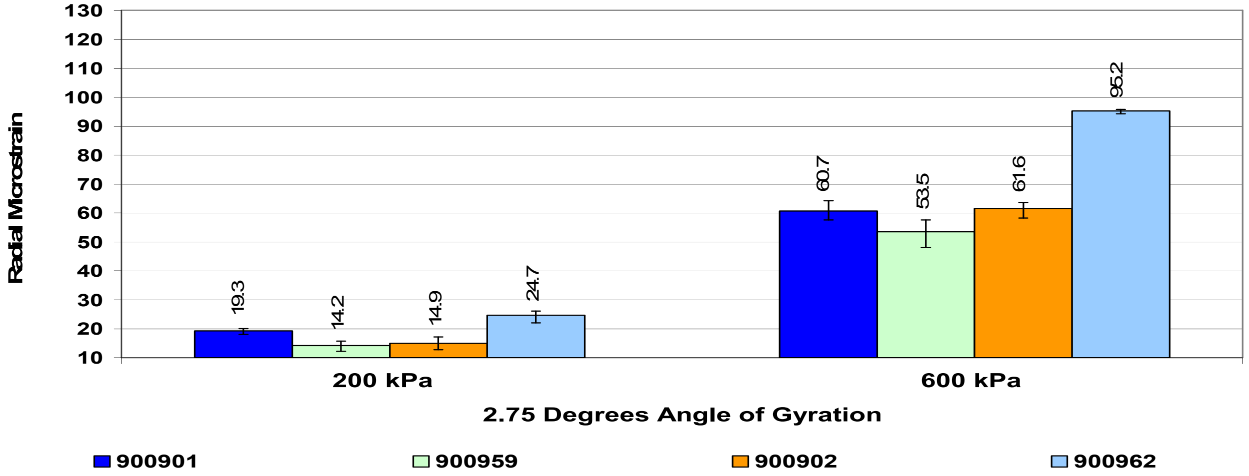
Figure 6 Phase Angle across Deviatoric Stress States and Angle of Gyration



(a) Radial Microstrain at 1.25°



(b) Radial Microstrain at 2.00°



(c) Radial Microstrain at 2.75°

Figure 7 Radial Microstrain across Deviatoric Stress States and Angle of Gyration