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Effect of Nanoclay on Rutting Resistance of HMA Mixes

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***Abstract*— Even though engineers are interested in the material properties at the macro- and mesoscales, the phenomena at nano- and micro-scales provide fundamental insight for the underlying interactions defining the physio-chemical behavior of materials. Nanomaterials possess extraordinary potential for improving the performance of asphalt mixtures. The rutting resistance of a nanoclay modified mixture may be improved due to the change in binder microstructure. The main objective of this study is to investigate the effect of nanoclay content on the rutting resistance of hot mix asphalt (HMA) mixes. Four different binder grades (PG 58-28, PG 58-34, PG 64-28, and PG 64-34) and nanoclay contents (0%, 1%, 3%, and 5%) have been considered. A gyratory compactor was used to compact 48 specimens. The rutting resistance of the specimens was tested using an Asphalt Pavement Analyzer (APA) under dry conditions. An independent t-test was used to determine statistically significant differences in the rutting resistance of the different mixes. Nanoclay content has the most and no significant effect in increasing rutting resistance of PG 58-28 and PG 64-34 based mixes, respectively. The higher the nanoclay content, the lower the rate of progression of rutting. There is no significant difference between the rutting resistance of all the mixes with 0% (control) and 1% nanoclay content at all numbers of passes. There is no significant difference between the rutting resistances of mixes with the different binder grades at 5% nanoclay content.**

Keywords*— *Nanoclay, Rutting Resistance, Hot Mix Asphalt, Asphalt Pavement Analyzer.

I. INTRODUCTION

Birgisson [1] suggested that nanotechnology studies are needed to develop safe and sustainable pavement infrastructure. In the mid- to long-term, nanotechnology development will lead to revolutionary approaches to the design and production of materials with improved energy efficiency, sustainability, and adaptability to changing environment [2]. Steyn [3] indicated that the major current needs in pavement engineering, where nanotechnology can potentially play a role, lie in the improved use of existing and available materials and the processing of these materials to enable them to fulfill the required specifications of perpetual pavement structures. Some researchers have introduced nanotechnology in pavement engineering [3,4].

Even though engineers are interested in the material properties at the macro- and meso- scales, the phenomena at nano- and micro- scales provide fundamental insight for the underlying interactions defining the physio-chemical behavior of materials. Additives, such as nanoparticles (e.g., nanoclay) and microfibers (e.g., carbon microfiber), have been found to have the potential to improve material strength while enhancing ductility and other durability properties of engineering materials [5-7].

Nanomaterials possess extraordinary potential for improving the performance of asphalt mixtures. It is anticipated that these may enhance or modify the properties of asphalt pavement. The rutting resistance of nanoclay-modified asphalt binder and mixture may be improved through changing the binder microstructure [7]. Some researchers have found that nanoclay can improve rutting performance of asphalt mixtures [8-12].

A. Objectives of the Study

The main objective of this study is to investigate the effect of nanoclay on the rutting resistance of hot mix asphalt (HMA) mixes with four different types of performance grade (PG) binders. Statistical analysis has been conducted to determine any significant difference between rutting resistances of HMA mixes with different binder grades and nanoclay contents.

II. MATERIALS AND METHODS

A. Specimen Preparation

The mixes were designed following the Superpave mix design method. Four different binder grades (PG 58-28, PG 58-34, PG 64-28, and PG 64-34) that are commonly used in North Dakota have been used in this study. Four nanoclay contents (0%, 1%, 3%, and 5% by weight of the binders) have been used. The size of the nanoclay used in this study varied from 10-30 nm. The target binder content, including nanoclay, was 6%. Three specimens were compacted using a Gyratory compactor for each nanoclay content and binder grade. The total number of specimens prepared was 48 (4 nanoclay contents, 4 types of binder grades, and 3 specimens). The target height for each specimen was 75 mm, which is the height needed for Asphalt Pavement Analyzer (APA) rut resistance testing [13]. The diameter of the specimens was 300 mm. The specimens were cured and the bulk specific gravities were determined before testing.

B. Rutting Resistance Testing Using APA

The utilization of APA to evaluate rutting resistance of asphalt mixtures has been fast, cost-effective, and practical (Suleiman and Mandal 2013). The AASHTO designation (T 340-10) was used to determine rutting resistance of dry conditioned specimens after the application of 8,000 cycles. Prior to APA dry condition testing, the specimens were heated to a temperature matching the high temperature of the PG grade of the binder for 6 hours (24 specimens at 58oC and 24 specimens at 64oC). The temperatures were also maintained during the actual APA dry condition testing.

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All the specimens were set to 8,000 loading cycles at 690 kPa pressure [14]. There were nine runs. There were six specimens in each run except the first (two specimens) and the last (four specimens). All of the specimens in the same run had the same high temperature PG grade. None of the specimens failed in rutting, where the failure criterion was 12.5 mm rut depth. The relative performances of the mixes were examined based on APA rut values at 2000, 4000, 6000, and 8000 passes.

III. RESULTS AND DISCUSSIONS

Rut depths at four different number of APA passes (2000, 4000, 6000, and 8000) were considered to investigate the effect of nanoclay on the progression of rutting. The effect of binder grade on rutting resistance was considered as well. Rutting progression and statistical analysis results have been discussed.

A. Effect of Nanoclay Content on Rutting Resistance

The effect of nanoclay on rutting resistance of HMA mixes for each binder grade has been discussed separately and then summarized in a table. Fig. 1 shows the effect of nanoclay on the progression of rutting in mixes with PG 58-28. The higher the nanoclay content, the lower the rut depth. As the nanoclay content and number of passes increase, the rate of increase in rut depth decreases.

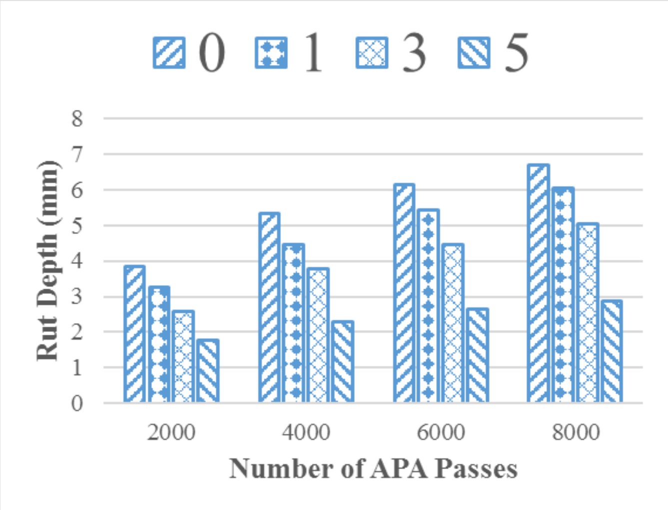

Fig.1. Effect of nanoclay on rutting resistance of mixes with PG 58-28

Fig. 2 shows that the rut depth of the mix with 1% nanoclay content is slightly higher than the control (0% nanoclay), which implies that nanoclay addition has a negative effect on the rutting resistance of the mixes with PG 58-34 at a lower number of passes (2000 and 4000). However, the trend changes as the number of passes increases. Nanoclay contents of 3% and 5% reduce the rut depth at all number of passes. The higher the nanoclay content, the lower the rate of progression of rutting as the number of passes increases. This shows that nanoclay has a significant effect in reducing long-term rutting progression.

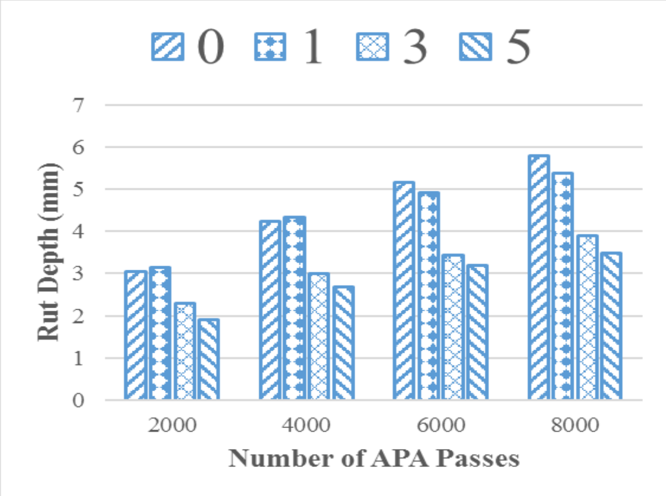

Fig.2. Effect of nanoclay on rutting resistance of mixes with PG 58-34

A mix with PG 64-28 that contains 1% nanoclay content shows a slightly higher rut depth than the control (0% nanoclay content) at 2000 passes, as shown in Fig. 3, but the trend changes as the number of passes increases. The higher the nanoclay content, the lower the rate of progression in rutting. The difference between rut depth at 3% and 5% nanoclay content increases as the number of passes increases.

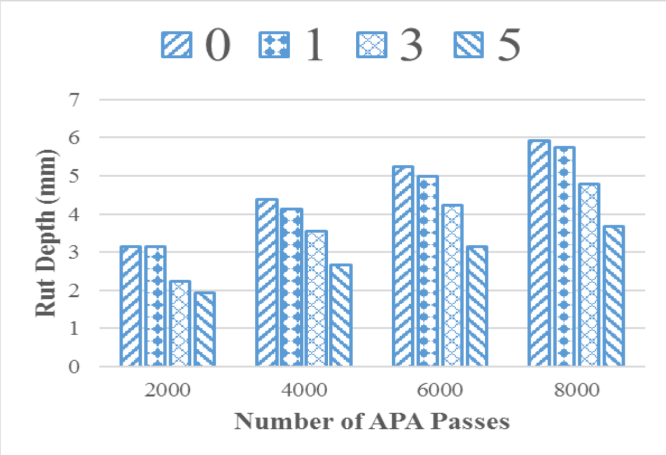

Fig.3. Effect of nanoclay on rutting resistance of mixes with PG 64-28

Nanoclay has no to a slightly higher negative effect (higher rut depth) on the rutting resistance of the mix with PG 64-34 at 2000 passes as shown in Fig. 4, but nanoclay has a positive effect (lower rut depth) on rutting resistance at all other numbers of passes. Increasing nanoclay content has no to a slightly higher negative effect on the rutting resistance of the PG 64-34 based mixes.

B. Effect of Binder Grade on Rutting Resistance

The effect of binder grade on rutting resistance has been investigated at four different APA passes (2000, 4000, 6000, and 8000) separately. Fig. 5 shows that a control mix (0% nanoclay content) with PG 58-34 is slightly more rut resistant than the mix with PG 64-28 at 2000 passes. Nanoclay content does not have significant effect on rutting resistance of PG 64-34 based mixes. There is a significant increase in rutting resistance with an increase in nanoclay content for the mixes with PG 58-28 at 2000 passes.

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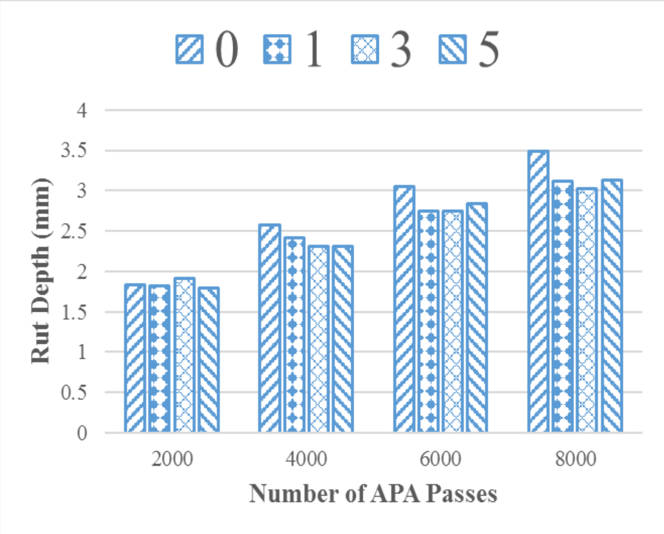

Fig.4. Effect of nanoclay on rutting resistance of mixes with PG 64-34

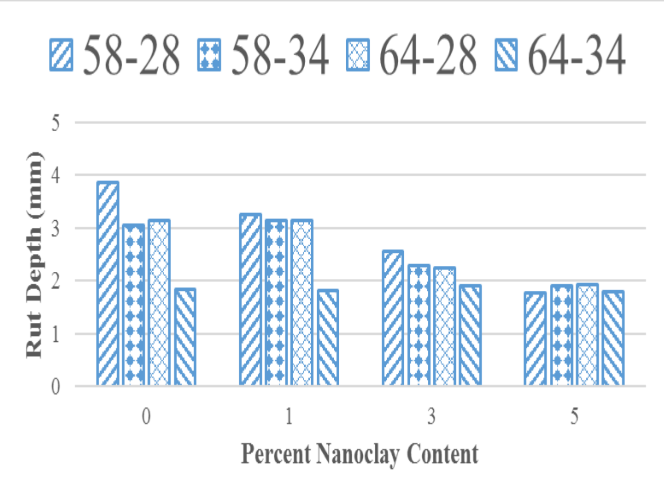

Fig.5. Effect of binder grade on rutting resistance at 2000 APT passes

Nanoclay content has the most and least significant effect at 4000 passes in increasing rutting resistance of the mix with PG 58-28 and PG 64-34, respectively, as shown in Fig. 6. Rut depths of the different mixes are close at 5% nanoclay content.

The mixes with PG 58-34 are more rut resistant at 6000 passes than the mixes with PG 64-28 at all nanoclay contents, except at 5% nanoclay content, as shown in Fig. 7. Nanoclay content has the most and least significant effect in increasing rutting resistance of the mix with PG 58-28 and PG 64-34, respectively.

Mixes with binder grades PG 58-28, PG 64-28, PG 58-34, and PG 64-34 show rut depths at 8,000 passes in descending order at all nanoclay contents, except at 5% nanoclay content, as shown in Fig. 8. This indicates that mixes with PG 58-34 are more rut resistant than mixes with PG 64-28. Nanoclay content has the most and least significant effect at 8000 passes in increasing rutting resistance of the mix with PG 58-28 and PG 64-34, respectively.

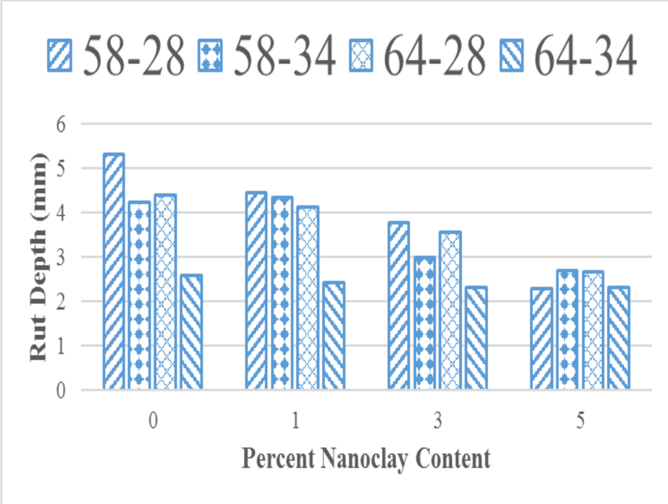

Fig.6. Effect of binder grade on rutting resistance at 4000 APT passes

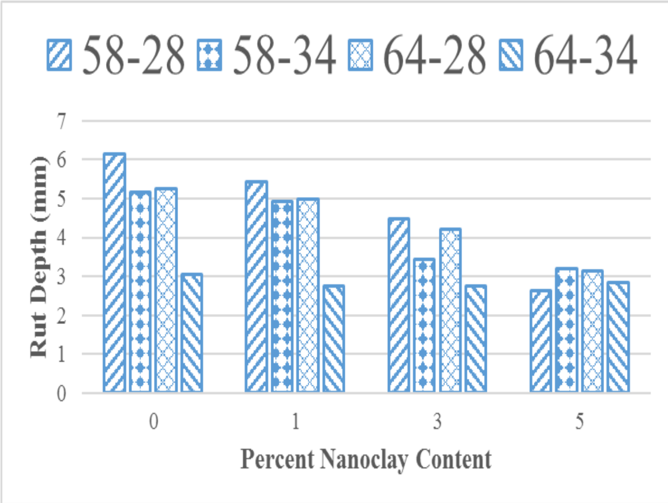

Fig.7. Effect of binder grade on rutting resistance at 6000 APT passes

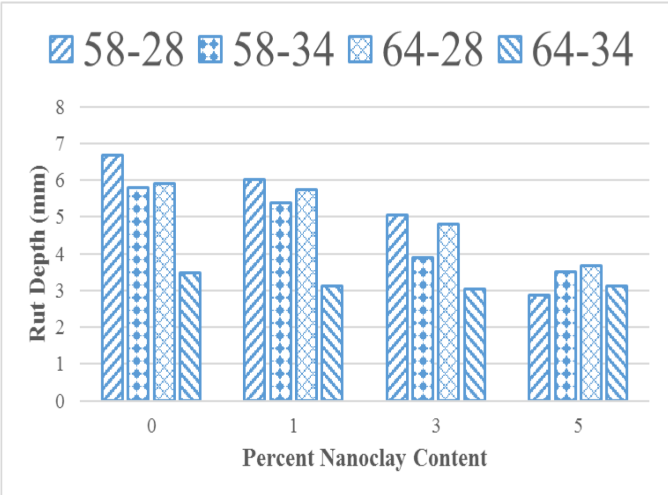

Fig.8. Effect of binder grade on rutting resistance at 8000 APT passes

C. Effect of Nanoclay Content on Rate of Progression of Rutting

Table 1 shows the progression of rut depth with an increase in nanoclay content and number of passes for the different mixes. The percent increase in rut depth has been calculated as 100 times the difference between the rut depth at the higher number of passes and the lower number of passes divided by the rut depth at the lower number of passes. Percent increase in rut depth due to the increase in the number of passes from 2000 to 4000 and 6000 to 8000 is the highest and lowest, respectively, for all the mixes. As nanoclay content increases, there is a decrease in the rate of progression of rutting in general.

TABLE 1. EFFECT OF NANOCLAY ON PROGRESSION OF RUTTING

Binder Grade	% NC	Increase in Rut Depth (mm)			% Increase in Rut Depth		
		2k to 4k	4k to 6k	6k to 8k	2k to 4k	4k to 6k	6k to 8k
58-28	0	1.46	0.82	0.55	37.91	15.50	8.90
	1	1.21	0.96	0.62	37.29	21.58	11.37
	3	1.20	0.70	0.57	46.86	18.57	12.85
	5	0.51	0.34	0.25	28.81	15.03	9.61
58-34	0	1.19	0.94	0.62	39.18	22.14	11.91
	1	1.18	0.60	0.47	37.65	13.82	9.45
	3	0.71	0.45	0.46	30.91	15.07	13.44
	5	0.77	0.50	0.31	40.56	18.61	9.72
64-28	0	1.25	0.85	0.67	39.72	19.31	12.84
	1	0.99	0.85	0.77	31.42	20.65	15.46
	3	1.31	0.67	0.57	58.31	18.92	13.58
	5	0.72	0.48	0.53	37.22	17.97	17.00
64-34	0	0.74	0.48	0.43	40.34	18.63	14.20
	1	0.59	0.33	0.38	32.30	13.67	13.68
	3	0.39	0.45	0.27	20.44	19.33	9.98
	5	0.51	0.54	0.29	28.66	23.23	10.13

D. Effect of Relative Increase in Nanoclay Content on Rutting Resistance at 8000 Passes

The effect of the relative increase in nanoclay content on the reduction in rut depth has been calculated as the difference between the rut depth at the lower and the higher nanoclay content at 8000 passes. Increasing nanoclay content from 0% to 1% (1% range) has the highest and lowest effect on the reduction in rut depth for mixes with PG 64-34 and PG 64-28, respectively, as shown in Table 2. Increasing nanoclay content from 3% to 5% (2% range) has a higher impact on rutting resistance than increasing nanoclay content from 1% to 3% (2% range) for mixes containing PG 58-28 and PG 64-28 and vice versa for mixes containing PG 58-34 and PG 64-34. Increasing nanoclay content from 3% to 5% has a negative effect on rutting resistance of the mix with PG 64-34, since there is an increase in rut depth. Increasing nanoclay content from 0% to 3% (3% range) has the lowest and highest effect on rutting resistance of the mixes containing PG 64-34 and PG 58-34, respectively. Increasing nanoclay content from 1% to 5% (4% range) has the highest positive effect on rutting resistance on mixes with PG 58-28 and has a negative effect (higher rut depth) on rutting resistance of the mixes with PG 64-34. Increasing nanoclay content from 0% to 5% (5% range) has the highest and lowest effect on rutting resistance of the mixes with PG 58-28 and PG 64-34, respectively. In summary, the relative increase in nanoclay has the highest and lowest effect on rutting resistance of mixes with PG 58-28 and PG 64-34, respectively.

TABLE 2. EFFECT OF NANOCLAY CONTENT ON REDUCTION IN RUT DEPTH AT 8000 APT PASSES

% Range in NC	Inter-val	58-28		58-34		64-28		64-34	
		Red. in Rut (mm)	% Red.	Red. in Rut (mm	% Red.	Red. in Rut (mm)	% Red.	Red. in Rut (mm)	% Red.
1	0 to 1	-0.7	-10	-0.4	-7	-0.2	-3	-0.4	-11
2	1 to 3	-1.0	-16	-1.5	-28	-1.0	-17	-0.1	-3
	3 to 5	-2.2	-43	-0.4	-11	-1.1	-23	0.1	4
3	0 to 3	-1.7	-25	-1.9	-33	-1.1	-19	-0.5	-13
4	1 to 5	-3.2	-52	-1.9	-35	-2.1	-36	0.0	0
5	0 to 5	-3.8	-57	-2.3	-40	-2.2	-38	-0.4	-10

E. Significant Difference Test

An independent t-test was used to determine any significant difference between rutting resistance of mixes with different nanoclay contents at 5% significance level. There is no significant difference between the rutting resistance of all the mixes with 0% and 1% nanoclay content at all number of passes, as shown in Table 3. There is no significant difference between the rutting resistance of PG 58-28 mixes with 1% and 3% nanoclay content at all numbers of passes. The rutting resistance of PG 64-28 mixes containing 5% nanoclay is significantly different from mixes with any other nanoclay contents. The rutting resistance of the control (0% nanoclay) is significantly different from rutting resistance of mixes containing 5% nanoclay for all binder grades and at all numbers of passes except PG 64-34 mixes. Nanoclay content does not have any significant effect on the mixes with PG 64-34 at all number of passes. The effect of the number of passes on the significant difference test is not clear.

The effect of binder grade on rutting resistance has been investigated in greater detail at 8000 passes as well. The rutting resistance of PG 64-34 mixes is significantly different from mixes with other binder grades at 0%, 1%, and 3% nanoclay contents, as shown in Table 4. There is a significant difference between rutting resistance of the different mixes at 3% nanoclay content except mixes with PG 58-28 and PG 64-28. There is no significant difference between rutting resistance of mixes with the different binder grades at 5% nanoclay content. The mean rut depth difference between PG 58-28 mixes and all other mixes is negative at all nanoclay contents except at 5% nanoclay content, which shows 5% nanoclay has the highest effect in increasing rutting resistance on PG 58-28 mixes. Mean rut depth difference between PG 58-34 and PG 64-28 mixes is positive, which implies that PG 58-34 mixes are more rut resistant than PG 64-28 mixes. This implies increasing high temperature PG grade by one grade (58ºC to 64ºC) has a lesser effect on rutting resistance than decreasing low temperature PG grade by one grade (-28ºC to -34ºC).

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TABLE 3. EFFECT OF NANOCLAY ON DIFFERENT BINDER GRADES

Passes		PG 58-28				PG 58-34			
		0	1	3	5	0	1	3	5
2000	0	x	N	Y	Y	x	N	Y	Y
	1		x	N	Y		x	Y	Y
	3			x	N			x	N
	5				x				x
4000	0	x	N	N	Y	x	N	Y	Y
	1		x	N	Y		x	Y	Y
	3			x	Y			x	N
	5				x				x
6000	0	x	N	N	Y	x	N	Y	Y
	1		x	N	Y		x	Y	Y
	3			x	Y			x	N
	5				x				x
8000	0	x	N	N	Y	x	N	Y	Y
	1		x	N	Y		x	Y	Y
	3			x	Y			x	N
	5				x				x
Passes		PG 58-28				PG 58-34			
		0	1	3	5	0	1	3	5
2000	0	x	N	Y	Y	x	N	Y	Y
	1		x	N	Y		x	Y	Y
	3			x	N			x	N
	5				x				x
4000	0	x	N	N	Y	x	N	Y	Y
	1		x	N	Y		x	Y	Y
	3			x	Y			x	N
	5				x				x
6000	0	x	N	N	Y	x	N	Y	Y
	1		x	N	Y		x	Y	Y
	3			x	Y			x	N
	5				x				x
8000	0	x	N	N	Y	x	N	Y	Y
	1		x	N	Y		x	Y	Y
	3			x	Y			x	N
	5				x				x

Note: "Y"-yes, there is a significant difference and "N"-no, there is no significant difference.

IV. CONCLUSIONS

Based on this study, the following conclusions can be drawn:

- Nanoclay content has the most significant effect in increasing rutting resistance of PG 58-28 based mix, but it does not have any significant effect on the rutting resistance of the mixes with PG 64-34 at all numbers of passes.
- The higher the nanoclay content, the lower the rate of progression of rutting as the number of passes increases. This shows that nanoclay has a significant effect in reducing long-term rutting progression.
- Increasing nanoclay content from 3% to 5% (a 2% range) has a higher impact on rutting resistance than increasing nanoclay content from 1% to 3% (a 2% range) for mixes containing PG 58-28 and PG 64-28 and vice versa for mixes containing PG 58-34 and PG 64-34. This implies that low-temperature binder grade also has an effect on rutting resistance of the mixes, even though the main purpose of low-temperature grade is for cracking resistance.
- There is no significant difference between the rutting resistance of all the mixes with 0% and 1% nanoclay content at all number of passes. This shows 1% nanoclay is not enough to significantly increase rutting resistance of the mixes.
- There is no significant difference between rutting resistance of mixes with the different binder grades at 5% nanoclay content. This shows 5% nanoclay content is too high for the binder grade to have an effect on rutting resistance.
- The effect of the number of passes on the significant difference test is not clear.

TABLE 4. EFFECT OF BINDER GRADE ON RUT DEPTH AT 8000 PASSES

% Nanoclay			PG 58-34	PG 64-28	PG 64-34
0	PG 58-28	Sign. Diff.?	N	N	Y
		Mean Diff. (mm)	-0.90	-0.78	-3.20
	PG 58-34	Sign. Diff.?		N	Y
		Mean Diff. (mm)		0.12	-2.30
	PG 64-28	Sign. Diff.?			Y
		Mean Diff. (mm)			-2.42
1	PG 58-28	Sign. Diff.?	N	N	Y
		Mean Diff. (mm)	-0.64	-0.28	-2.91
	PG 58-34	Sign. Diff.?		N	Y
		Mean Diff. (mm)		0.36	-2.27
	PG 64-28	Sign. Diff.?			Y
		Mean Diff. (mm)			-2.63
3	PG 58-28	Sign. Diff.?	Y	N	Y
		Mean Diff. (mm)	-1.14	-0.24	-2.01
	PG 58-34	Sign. Diff.?		Y	Y
		Mean Diff. (mm)		0.90	-0.87
	PG 64-28	Sign. Diff.?			Y
		Mean Diff. (mm)			-1.77
5	PG 58-28	Sign. Diff.?	N	N	N
		Mean Diff. (mm)	0.61	0.79	0.25
	PG 58-34	Sign. Diff.?		N	N
		Mean Diff. (mm)		0.18	-0.36
	PG 64-28	Sign. Diff.?			N
		Mean Diff. (mm)			-0.54

Note: "Y"-yes, there is significant difference and "N"-no, there is no significant difference.

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