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Investigation of Effect of Bakelite on Mechanical Properties of Hot Mix Asphalt Mixes - A Full Factorial Design Experiment

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ABSTRACT

In Pakistan, mostly flexible pavements are constructed which have a higher susceptibility to rutting, moisture damage and stripping. Under current economic conditions, one such solution to overcome this is the addition of economical and locally available additives in the bitumen being produced by our refineries. This study investigates the effects of bakelite as an additive on various mechanical properties. Bakelite is a high-density plastic, cost-effective and locally available material. The modified Hot Mix Asphalt (HMA) specimens were prepared with (2%,4%,6%,8%,10%,12%) Bakelite by weight of optimum binder content found using Marshall Mix design. Performance tests, including Marshall Stability and flow. Retained stability and Resilient Modulus tests were performed to check the performance of modified mixes. The test results revealed that a modified mix containing 6% Bakelite by weight of optimum bitumen content provides the best resistance against moisture damage, rutting and enhancing the HMA mix's stability than the other modifier percentages. The Marshall stability and quotient values of the modified mix increased by almost 22% and 44% respectively. The results showed an increase of 3.5% in the tensile strength ratio indicating an increase in the capability of HMA to resist moisture-induced damage and strength retention. The resilient modulus test was then performed under different conditions, i.e., bakelite (0% & 6%), temperature (25˚C &40˚C) and load duration (100 ms & 300 ms) and analyzed by full factorial design experiment. The factorial analysis showed that Bakelite content is the most significant factor affecting the MR and, ultimately, the strength of the HMA mix. The Resilient modulus test results showed a 20% increase for the modified mix containing 6% Bakelite as compared to the conventional mix. Therefore, it is concluded that the addition of bakelite as an additive in hot mix asphalt mixes gives better results regarding pavement performance.

Keywords: Hot mix asphalt; pavements; bakelite; rutting; bitumen

INTRODUCTION

Pavements in severe climates experience stripping, moisture damage and rutting. In recent decades, countries that are more vulnerable to climate change have faced a major challenge in road failure: rutting (Ahmad et al. 2019). In China, one of the neighboring countries of Pakistan, rutting is the most common type of asphalt distress observed (Zou et al. 2017). Similarly, in Pakistan, pavements undergo such conditions due to the prevailing traffic conditions and climatic changes, including very high temperatures in the summer season. To overcome these issues, the use of high-quality asphalt is indispensable. In general, the pavements are constructed using 60-70 or 80-100 penetration grade bitumen that does not perform well under extreme loading and temperature conditions. The pavement structure fails prematurely mainly due to cracking at low temperatures, while plastic deformation occurs at high temperatures. This is because the bitumen contains a high amount of wax, which imparts softening when the temperature is high and reduces stability, adhesion and consequently, strength (Al-Hadidy and Yi-qiu, 2010).

Therefore, it is essential to shift either to the Super-Pave method of mix design or enhance the conventional asphalt properties (Institute 1996).

The most common reason of rutting is material mixing and gradation, or in other words, rutting is highly dependent on the materials and quality. Therefore, to improve the pavement structure, different asphaltic materials modification is usually observed. Using locally available, environment-friendly and economical additives, we can enhance the HMA mix properties. Past research on additives indicated that polymers proved to be the most significant to enhance the HMA mix Properties (Lu et al. 1999). The benefits include reduced rutting potential, increased useful life and reduction in thickness of the pavement layer (Al-Hadidy and Tan 2009). The polymer family is subdivided into many types, but only two basic types are used to modify HMA for pavement applications (Lu, Isacsson, and Ekblad 1999). These include plastomers and elastomers. Plastomers decrease the elasticity and low-temperature flexibility of bitumen while they increase the strength at higher temperatures due to the increase in the stiffness and decrease in penetration of bitumen (Lu and Isacsson 2000, Gorkem and Sengoz 2009). Phenols are the oldest family of polymers. This polymer family has ring structure alcohol named phenol. The main process to obtain phenols is from petroleum distillates. The first commercial phenol-formaldehyde polymer was produced in the early part of the 20th century under the trade name Bakelite. Bakelite was used mainly for compression-molded electrical parts. Phenols are still being used largely for this purpose because they are characterized by their good properties like low moisture absorption, high resistance to temperature, high compressive strength, creep resistance, less brittle nature and cost effective as compared to most of thermosetting polymers (Baron 2012). Bakelite, a high-density plastic, is classified as plastomers. This study investigates the effects of bakelite as a modifier based on performance parameters, including marshall properties (stability, flow, quotient), resilient modulus and moisture susceptibility of HMA mixes.

LITERATURE REVIEW

Different studies have been carried out to investigate the effect of bakelite on pavement performance in different ways. Yousaf conclusively discussed that the bakelite improves the rutting resistance of asphalt up to 29 and 38% for class A and class B hot mix asphalt (HMA), respectively (Yousaf, 2014). Bakelite waste products in powder form are used in asphalt pavement as an alternative, previously. Saha and Suman investigated the effect of phenol-formaldehyde—a thermosetting type of plastic on the mechanical behavior of asphalt. Polytetrafluoroethylene type of polymer was found to increase the viscosity of the bitumen. It is observed in one of the previous studies that bitumen modified with 2% bakelite found increased complex modulus, decreased phase angle, and improved rutting. Furthermore, it was also observed that the marshall stability of the asphalt mixtures is decreased (Saha and Suman 2017). Cubuk et al. also concluded that the phenol-formaldehyde improves the rheological properties of bitumen such as bleeding, the formation of rutting, stripping, and cracking in bitumen (Cubuk, Guru, and Cubuk 2011). Currently, AASHTO T283 is the most widely used test procedure to determine the potential of moisture-induced damage to the HMA pavements (Hwang et al. 2008).

Stability can be defined as the measure of the ability of asphalt concrete to rut resistance under heavy loads (Kuloglu et al. 1999). The flow, on the other hand, is the ability to adjust to gradual deformations without any cracking. Thus, it is the opposite of stability (Kuloglu et al. 1999). Marshall Quotient is stability to flow ratio and therefore is an indication of material's resilience to deformation (Shell 2003). Indirect Tensile Strength Test is a measure of the tensile strength of HMA mixes, which influences its cracking behavior (Tayfur et al. 2005).

The temperature greatly influences the MR of the HMA mix and the performance of pavement is directly related to temperature variations. Above 20oC, the resilient modulus reduces rapidly and reaches impractically low values at 400C; therefore, this temperature limit is crucial for the asphalt layer (Per Ullidtz 1987). Stroup et al. (1997) carried out extensive research on the effect of load duration and temperature on the resilient modulus (M_R). The loading ranges of 0.1 and 1.0 seconds at the temperatures of -18, 1, 25, and 40°C were investigated. It was observed that increasing the load duration decreased the resilient modulus for all temperatures except for -18°C. At – 18°C, it was found that the resilient modulus had slightly increased, but at a higher temperature, the resilient modulus decreased. Ziari et al. (2005) concluded in their research that increasing temperature decreases the resilient modulus. This is due to the decrease in stiffness of the bitumen at higher temperatures. Consequently, it is evident from the literature that the use of polymer to alter asphalt pavement has the potential to reduce rutting and improve stability (Ahmad and Ayob, 2015).

The Design of Experiment is a technique used to study many variables at a time rather than conducting a separate study for every variable present, thus increasing efficiency and reducing testing time (Barrentine 1999). Therefore; to consider various factors, the best method is to conduct the Design of Experiment (Montgomery 2001). The Design of the Experiment is the sole way of knowing whether the relationships are present among the factors or not (Montgomery 2003). The Pareto chart allows one to detect the factor effect as well as the interaction effect that is very important to the process (Antony 2003). The Main Effect is the variation in the mean response between the low and high levels of a factor (Tamhane 2009).

Literature review reveals that polymer modification of bitumen is an effective way to reduce the rutting potential and thickness of the pavement as well as increases the pavement life (Al-Hadidy and Yi-qiu 2009, Gorkem and Sengoz 2009, Lu, Isacsson, and Ekblad 1999, Lu and Isacsson 2000, Saha and Suman 2017, Cubuk, Guru, and Cubuk 2011, Çubuk et al. 2014). Moreover, the polymer addition usually results in a higher degree of stiffness in asphalt accompanied by the enhancement in temperature and moisture susceptibility, which, in turn, increased rut resistance.

The past studies have conclusively discussed the effect of bakelite on pavement performance. However, further research is required to investigate the effect of different types and percentages of bakelite on the mechanical and rheological performance of asphalt mixtures. In this research, we investigated the influence of bakelite on asphaltic concrete.

RESEARCH OBJECTIVES

1. To evaluate the compatibility of bakelite as a modifier.
2. To identify the optimum Bakelite content for modified asphalt concrete.
3. To investigate the individual and joint effects of different factors, including Bakelite content on the Resilient Modulus by factorial analysis.

EXPERIMENTAL PROGRAM

The research methodology is shown in Figure 1. Class B mix under the envelope of National Highway Authority of Pakistan (NHA) gradation for wearing courses was selected. This specification is most frequently used by highway agencies for wearing courses in Pakistan. The Bakelite used in the study was obtained from Ismail Industries Gujranwala in grinded form. The Bakelite was sieved and the portion of Bakelite passing #100 sieve was then used. The results are presented in Table 1.

TABLE 1. Properties of Bakelite

Properties of Bakelite	Results
Specific gravity	1.36
Melting point range	150-165°C
Decomposition temp. range	270-350°C
Sieve analysis	Passing sieve # 100

The first step was finding the optimum bitumen content (OBC) by Marshall mix design (ASTM D6926), which was then used in the preparation of both control and modified specimens. The modified asphalt concrete specimens were prepared by a wet process using 60/70 penetration grade bitumen and bakelite (2,4,6,8,10 and 12% by weight of OBC). Modifiers can be added either by dry process or by wet process (for details please see (Hung et al. 2014)). In the dry process, the aggregate is mixed with the modifier prior to the addition of the binder to the mixture while in the wet process, the modifier is added to the binder and heated together and then this modified binder is added to the aggregate. (Abtahi et al. 2010). The wet process was adopted for the present study to ensure proper blending and mixing of Bakelite with bitumen and ultimately achieving uniform mixing. Bakelite and bitumen were mixed (thorough hand mixing for 15 minutes) and heated (150-165˚C) first before mixing with aggregates. Heated aggregate (165˚C) and bitumen were transferred to the mechanical mixer which was pre-heated to 165˚C. The mix was given 1000 cycles at 100rpm. The second step was the performance tests, including Marshall Stability, flow, Quotient (ASTM D6926) and retained stability (AASHTO T283) on control and modified specimens to compare their performance and find the optimum Bakelite percentage, which showed better strength, flow and resistance to moisture-induced damages. The stability and flow tests are performed using a compression testing machine. The stability of the mix measures the maximum load that is supported by the test specimen at the constant loading rate of about 2-inch/minute. Basically, the load is increased until it reaches the maximum. When the load just starts to decrease, the loading is stopped and the maximum load is recorded. During the loading, an attached dial gauge to the machine measures the specimen's flow as a result of the loading. The flow value is recorded in 0.01-inch increments at the same time the load is recorded. The Marshall quotient was calculated by taking the ratio of stability to the flow for each specimen.

In the end, resilient modulus (ASTM D4123) test was performed under variable bakelite (0% & 6%), temperature (25˚C & 40˚C) and load (100 ms& 300 ms) duration and the experimental investigation of these conditions and their interaction were analyzed by full factorial design experiment by MINITAB-16 software. 2K full factorial design of experiment is also known as two-level full factorial design of experiment. The 2 denotes two levels of the experiment i.e. high and low level and K represent the number of factors involved in the factorial design of the experiment. Factorial design is widely used in experiments involving several factors where it is necessary to study the joint effect of these factors on a response (Montgomery 2010). The full factorial design of the experiment consists of all the possible combinations of levels for all the factors (Antony 2003).

Optimum bitumen content was calculated from the Marshall mix design method at 4% air voids which came out to be 4.3% by weight of the mix. All other volumetric properties were determined about the 4.3% binder content. All the results were within the design limits of NHA design specifications. The results are tabulated in Table 2.

TABLE 2. Volumetric Properties at OBC and NHA Specifications

Properties Investigated	Test Results	NHA Specifications
Binder Content (%)	4.3	3.5 (Minimum)
Stability (kg)	1111 kg	1000 (Minimum)
Flow (mm)	2.94	2 - 3.5
Air Voids (VA) (%)	4	3 - 5
Voids in Mineral Aggregate (VMA) (%)	15.53	15 - 16
Voids Filled with Bitumen (VFB) (%)	68	65 - 75

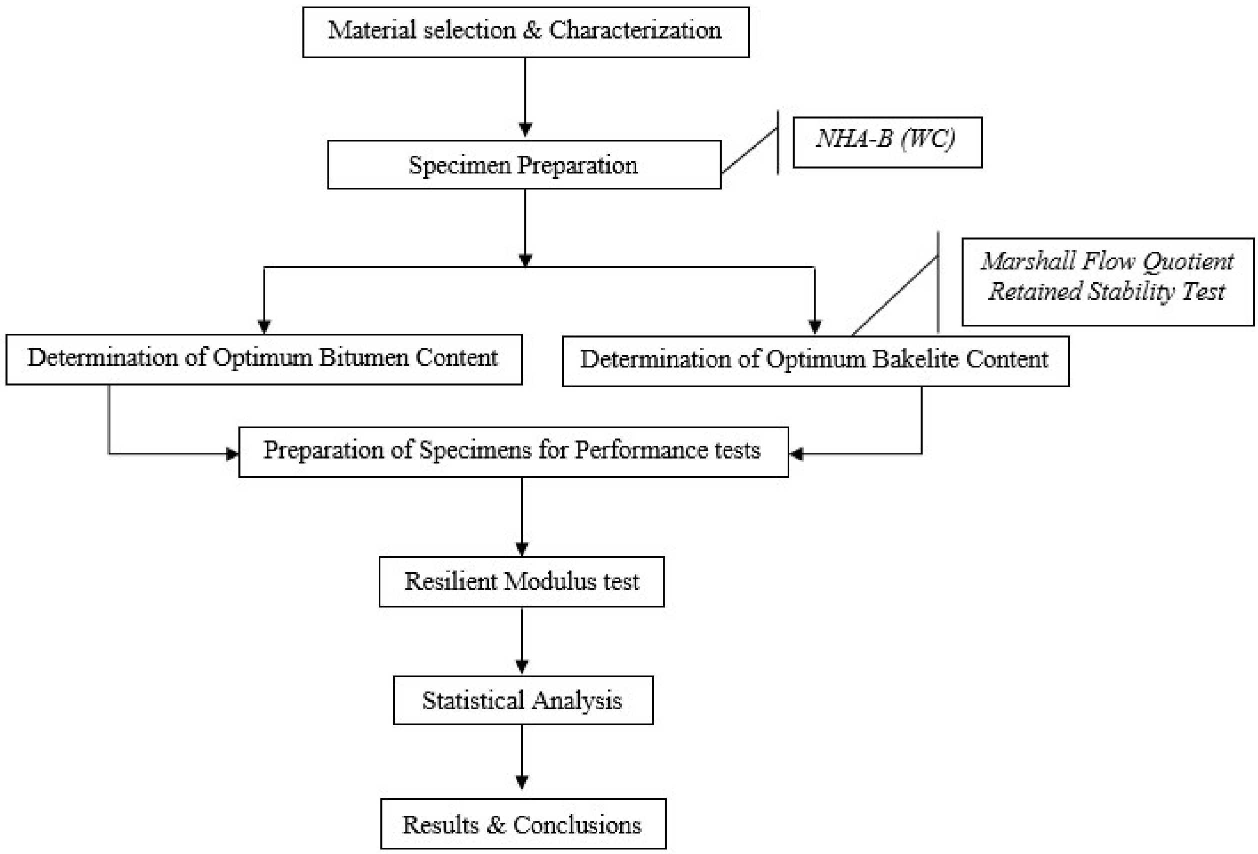

Figure 1. Flow Chart of Research Methodology

RESULTS AND DISCUSSIONS

MARSHALL STABILITY, FLOW AND QUOTIENT TESTS

Marshall Stability, Flow, Quotient, Resilient Modulus and Tensile Strength Ratio (TSR) tests were performed to analyze the comparative analysis of both control (60-70 PG at OBC) and modified asphalt specimens with Bakelite content of 2,4,6,8,10 and 12% by weight of optimum bitumen content. A total of 21 specimens (3 replicates of each) were prepared, tested and the average value of each is tabulated in Table 3. It can be seen that the Marshall Stability of modified mixes is higher as compared to conventional mixes. The stability increases with increasing Bakelite content until it reaches 6%, which is almost 22%

greater than a conventional mix. The increase in stability with polymer addition is due to the increase in adhesion between the mix (Awwad and Shbeeb 2007, Khan and Sharma 2011). However, a further increase in Bakelite content (8-12%) results in a decrease in stability, which is probably due to the decrease in the adhesion between the mix components. Therefore, the optimum Bakelite content came out to be 6% by weight of bitumen. Flow values for the conventional and modified mixes at various Bakelite percentages decrease initially until 6% but increases from 8% to 12%. This decrease in flow is due to an increase in stiffness of the mix. However, further increase causes fatigue cracking due to which the flow increases (Ahmadinia et al. 2012, Ahmadinia et al. 2011). Marshall quotient, which is a measure of resistance to permanent deformation, shear stress and rutting(Ahmadinia et al. 2011, Tayfur, Ozen, and Aksoy 2007). It can be seen that the addition of 6% Bakelite content in the mix produced optimum value (543). Moreover, this value is 19% higher as compared to the conventional mix.

TABLE 3. Marshall Test Results for Conventional and Modified Mixes

Properties Tested	Bakelite percentage by weight of Optimum binder content						
	0%	2%	4%	6%	8%	10%	12%
Marshall Stability (KN)	10.89	11.95	12.60	13.26	12.80	12.486	12.09
Flow (mm)	2.94	2.81	2.64	2.49	2.79	3.04	3.29
Marshall Quotient	378	434	486	543	468	419	375

TENSILE STRENGTH RATIO (TSR) TEST

The tensile strength ratio (TSR) test was conducted according to AASHTO T283 to test the resistance of compacted asphalt concrete specimens to moisture-induced damage. The 21 (3 replicates each) conditioned and unconditioned Marshally compacted sample (4-in dia) were tested for splitting indirect tensile strength at room temperature and applied load at a constant rate of 2 inches per minute until the specimen splits. ITS was calculated using equation 1.

$$ITS = \frac{2Pmax}{\pi td} \ldots\ldots\ldots\ldots\ldots\ldots \quad (1)$$

P_{max}= Maximum load (kg), t = thickness of the specimen (cm), d = diameter of the specimen (cm)

TSR was calculated by taking the ratio of ITS of conditioned (60˚C, 24h) to unconditioned specimens (dry) given by equation 2.

$$TSR = \frac{ITS\ (Conditioned)}{ITS(Dry)} \ldots\ldots\ldots\ldots\ldots \quad (2)$$

Figure 2. Splitting Tensile Test Set up

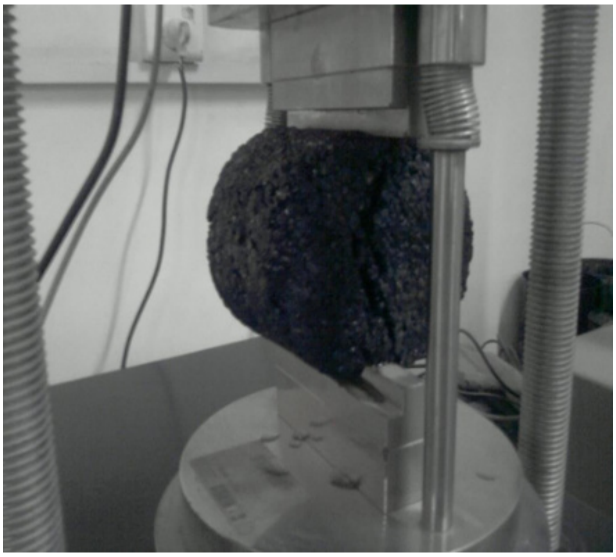

Figure 3. Specimen Starting to Split under the Load

The results of the ITS test and TSR are given in Table 4. Higher the TSR value the better the asphalt mixture resistance against moisture damage. The results illustrate that the modified specimens show better results as compared to the control mix. ITS (dry) value obtained at 25˚C for conventional mix was 9.98 kg/cm2 while it is 12.15 kg/cm² for 6% Bakelite modified mix. This implies that the bakelite modified mix can withstand much larger tensile strain before cracking and thus they are less susceptible to moisture-induced damages as compared to control mixes. Results indicate that 6% modified asphalt concrete retained 95% of its strength as compared to control which retained 91.5% thus indicating an increase of about 3.5% in the capability of the HMA to resist moisture-induced damages and retain its strength as compared to control mix. This indicates that modified mixes have high moisture-resistant capabilities as compared to the control mixes.

TABLE 4. ITS and TSR Results for Dry and Wet Specimens (average)

Properties Tested	Bakelite percentage by weight of Optimum binder content						
	0%	2%	4%	6%	8%	10%	12%
ITS(DRY), (kg/cm²)	9.98	10.95	11.60	12.15	11.73	11.44	11.08
ITS(WET), (kg/cm²)	9.13	10.11	10.69	11.55	11.12	10.75	10.33
TSR (%)	91.5	92.3	92.6	95	94.8	94	93.6

RESILIENT MODULUS TEST

Resilient modulus is the ratio of applied stress to the recoverable strain after the removal of applied stress. The current pavement performance prediction models also employ it as a vital material parameter (Al-Hadidy and Yi-qiu 2010). This test (ASTM D4123) was performed to predict the performance of both control and modified asphalt mixes under different temperature and loading conditions using a Universal testing machine (UTM-25) at 20% of ITS peak force value obtained from stress-strain test software developed by IPC global. Both control and modified specimens (16 each) were tested in a group of four at two different temperatures (25˚C & 40˚C) and loading (100 ms& 300 ms) conditions. The results of the resilient modulus test are enlisted in Table 5.

TABLE 5. Resilient Modulus Results for Conventional and Modified Mixes

Bakelite (%)	Load duration (ms)	Temp (°C)	Resilient modulus (MPa)			
			1	2	3	4
0	100	40	5619	6012	5274	6190
0	300	40	4170	4567	4480	4355
0	100	25	7331	7562	7291	7583
0	300	25	6308	6311	6519	6405
6	100	40	8718	8507	8998	8683
6	300	40	7746	7604	7856	7623
6	100	25	9633	9782	9678	9814
6	300	25	8236	8468	8172	8327

It was observed that MR decreased with increasing temperature. This increase in temperature makes the bitumen soft which decreases the stiffness of the mix and ultimately decreases the elastic modulus of the mix (Ziari and Khabiri 2005). The decrement in resilient modulus due to increased loading duration is expected because the more significant the time of loading, the more significant will be the amount of strain produced, reducing the resilient modulus (Saleh and Jian 2006). The addition of bakelite increases the resilient modulus as it increases the stiffness of the mix thus increasing its strength and reducing the strain produced in the mix. The data were statistically analyzed for the quantification of bakelite's performance.

STATISTICAL ANALYSIS FOR RESILIENT MODULUS

2^3full factorial design experiment was carried out using MINITAB-16 software by taking three factors (Bakelite content, test temperature and loading duration). Inputting these three factors in software resulted in eight combinations. In order to achieve a realistic estimation of errors, each combination was simulated four times; thus, a total of 32 tests were performed.

The effects and coefficient values calculated by using MINITAB-16 for the significant effects are shown in Table 6. The factors and interaction of factors with high (positive or negative) values of Effect and Coefficient indicate that they have a large impact on the resilient modulus of bituminous paving mixes. The individual factors or interaction of factors with p-value > significant level indicate that these factors and interactions are statistically significant at a 5% significance level. Therefore, bakelite content (BC), load duration (LD), temperature (T), 2-way interaction of BC and temperature and 3-way interaction of BC, LD and temperature are significant with a p-value of 0.000. A similar conclusion can be drawn from a t-value with any value (positive or negative) greater than the critical value of t-statistics (tcritical= 2.06) indicates that the main effects and interactions are significant.

TABLE 6. Effects and Coefficients for Resilient Modulus

Term	Effects	Coefficient	SE coefficient	t-test	p-value
Constant		7306.9	34.77	210.16	0.00
Bakelite Content	2616.7	1308.4	34.77	37.63	0.000
Load Duration	-1220.5	-610.3	34.77	-17.55	0.000
Temperature	-1313.6	-656.8	34.77	-18.89	0.000
Bakelite - Load Duration	-2.1	-1.1	34.77	-0.03	0.976
Bakelite Content-Temperature	516.8	258.4	34.77	7.43	0.000
Load Duration-Temperature	20.5	10.3	34.77	0.29	0.771
Bakelite-Load Duration-Temp	182.9	91.4	34.77	2.63	0.015

Figure 4 shows the Pareto plot of the standardized effects. The Pareto chart allows one to detect the factor effect as well as the interaction effect that is very important to the process (Antony 2003). It shows the relative importance of the effect. It is the standardized effect of each term i.e. factor or combination of factors for the mean response and draws a reference line on the chart which represents the critical-t value. The bars for the terms that extend past the reference line indicate that they are significant. It also gives information about the significance of main factors or interactions. The 2-way interaction of Bakelite content and temperature is well beyond the critical point, which shows that both these factors are critical at a 5 percent significance level and influence the MR of bituminous paving mixtures. The Bakelite content alone has the most significant impact on a bituminous mix's resilient modulus when its level changes from 0% to 6%. However, its 2-way interaction with load duration has no significant impact on resilient modulus. This may be since the addition of bakelite makes the HMA stiffer, thus reducing the elasticity and increasing its potential for cracking under increasing load durations. It is interesting to note that the 3-way interaction of Bakelite content, load duration, and temperature is significant as compared to 2-way interactions of load duration with temperature. Thus, the addition of bakelite enhances the interaction of load duration and temperature and makes it significant for resilient modulus. The standardized effects and their interactions were obtained from Normal probability plots whose significance was measured based on their distance from the reference line. The greater the distance, the greater the significance at the 5% significance level.

The effects of individual factors are shown with the main effect plots, 2-way interaction with interaction matrix and 3-way interaction with the cubic plot. It is clear from figure 6 that the resilient modulus is much lower for 40°C as compared to 25°C temperatures. The plot for the load duration confirms the previous observation that the longer the duration of loading, the lesser the resilient modulus. The reason for this observation is that the bitumen is viscoelastic and dependent on the condition and time of loading. Thus, the slow-moving vehicle has more adverse consequences for the bituminous pavements results in excessive rutting and destruction of the pavement structure. The Bakelite content plot shows a very steep slope as compared to load duration and temperature plots which shows that it is the most significant effect. This plot also confirms the previous observation that the addition of bakelite increases the resilient modulus. Therefore, the effect of Bakelite content is most significant as compared to other factors.

Figure 7 shows the interaction plot of different factors. It is clear from the plot that the only 2-way interaction between Bakelite content and temperature, represented by non-parallel lines, is significant. The variation in the resilient modulus for 6% Bakelite specimens is high as compared to 0% specimen when the temperature changes from 25 to 40 . Similarly, substantial variation in resilient modulus occurs from 100 ms to 300ms at the temperature of 25 as compared to the test temperature of 40. Thus, indicating that Bakelite content and temperature are the most significant factors influencing the MR of HMA mixes.

Figure 8 shows the 3-way interaction between the bakelite, load duration and temperature. It is interesting to note that the 2-way interaction of load duration and temperature were insignificant, but their 3-way interaction with bakelite is significant, which indicates that amount of bakelite incorporated in the HMA mix has a significant effect on the performance of the mix. It is clear that the highest resilient modulus value is observed at 25 , 100 ms load duration and 6% Bakelite content. This could be the result of very small deformations that occur during this condition and hence it results in the highest resilient modulus. The lowest resilient modulus occurred when the Bakelite content, temperature, and load duration were at 0%, 40^{o}C and 300 ms, respectively. This again could be due to the high value of strains that lead to the reduction of resilient modulus.

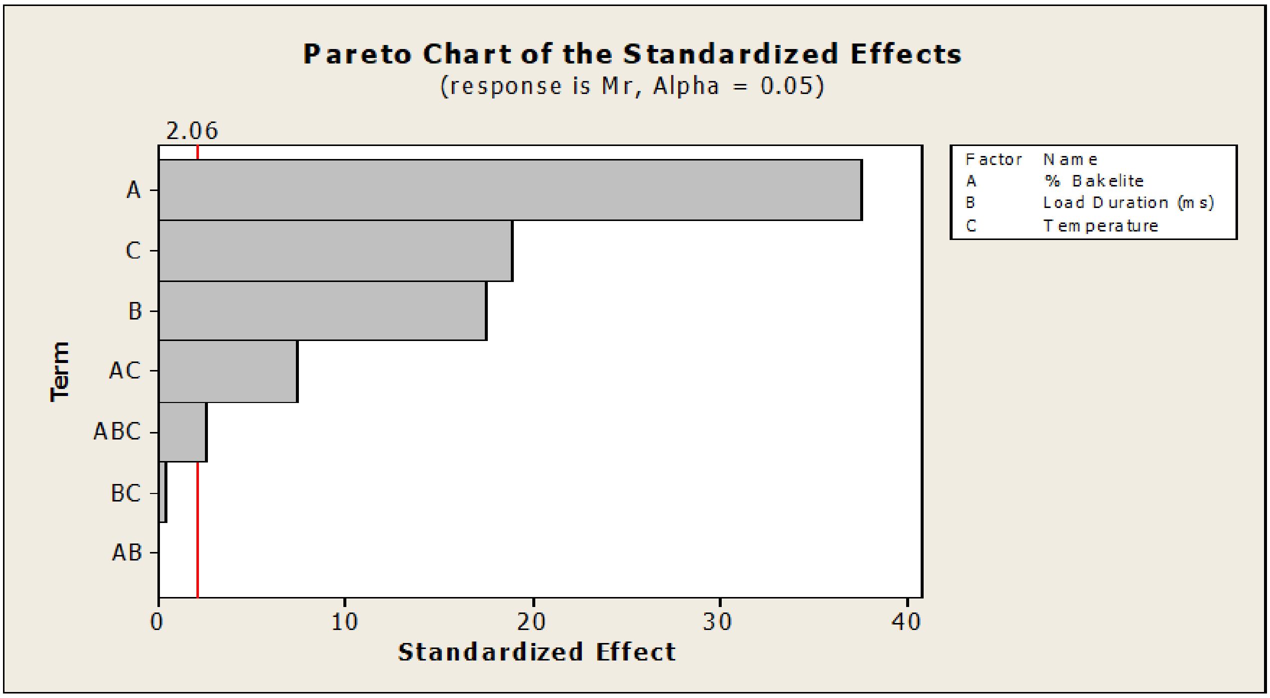

Figure 4 Pareto Chart of the Standardized Effect

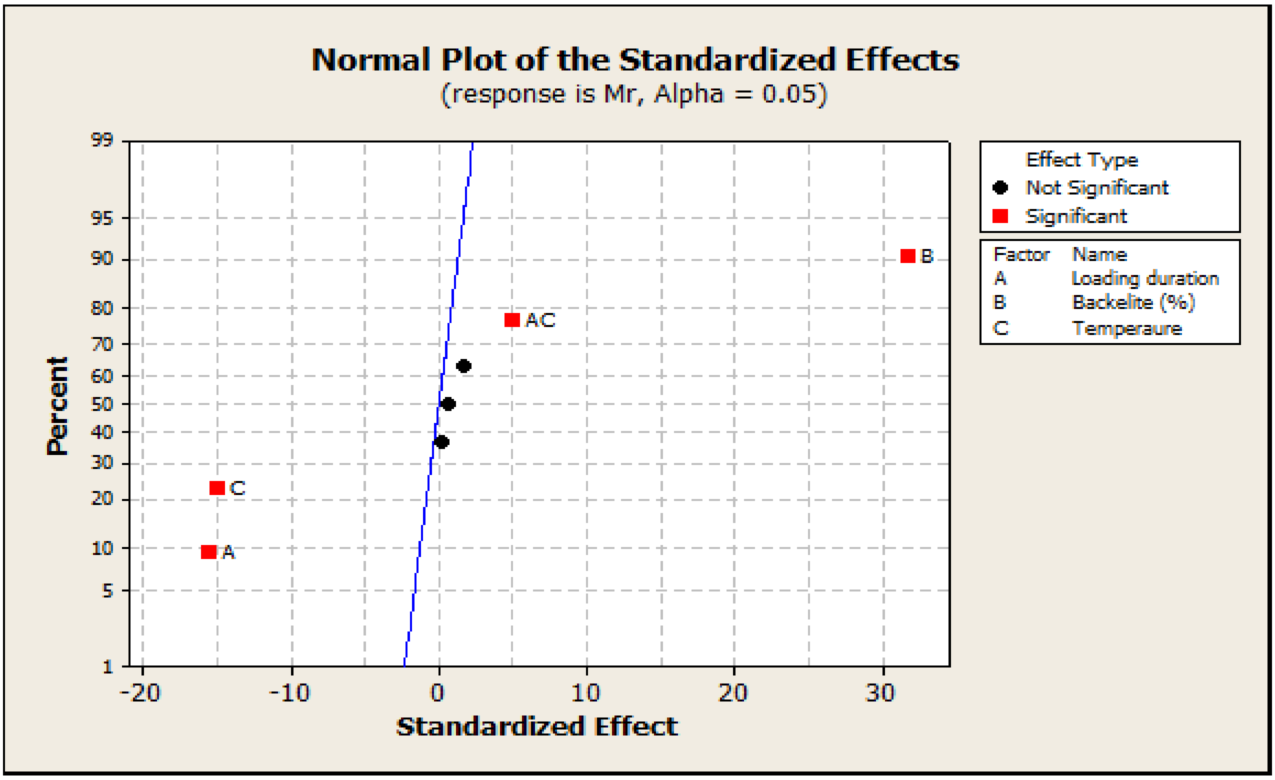

Figure 5 Normal Plot of the Standardized Effect

ANALYSIS OF VARIANCE (ANOVA)

The Analysis of Variance was evaluated by forming four F-tests and probability values are given as shown in Table 7. The P-value < 0.05 specifies that these tests are satisfied, and they are significant in accessing the resilient modulus of the HMA mixes. The lack of fit test is used to access the model for errors.

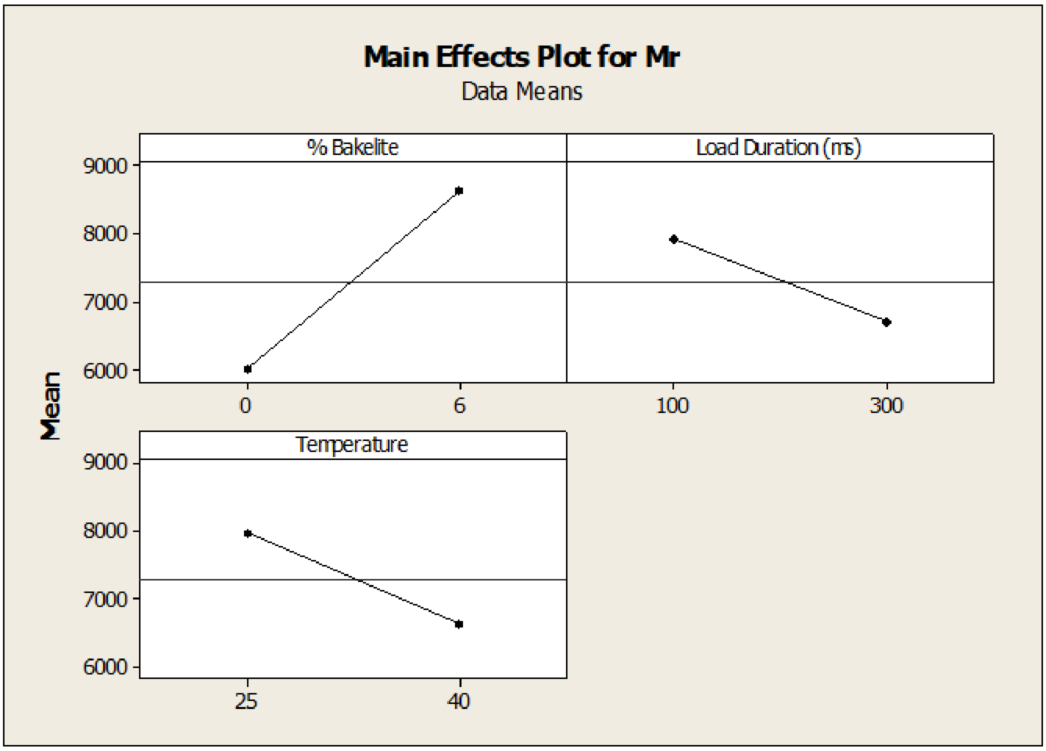

Figure 6 Main Effect Plots

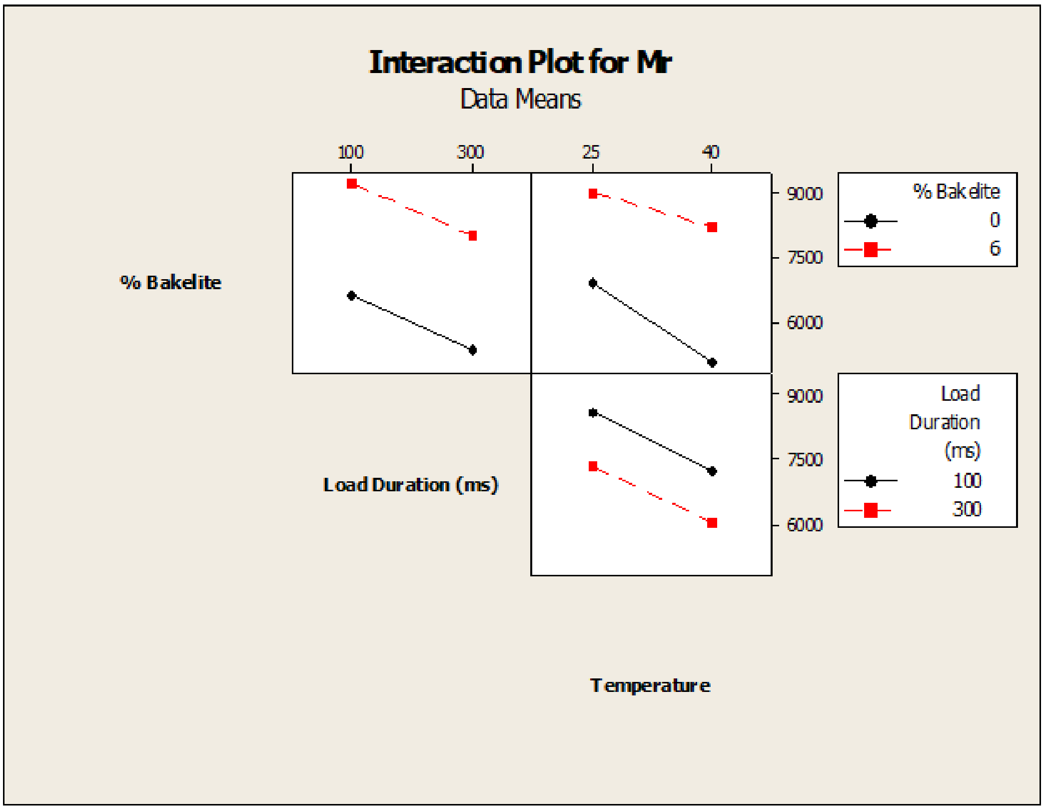

Figure 7 Interaction Plots

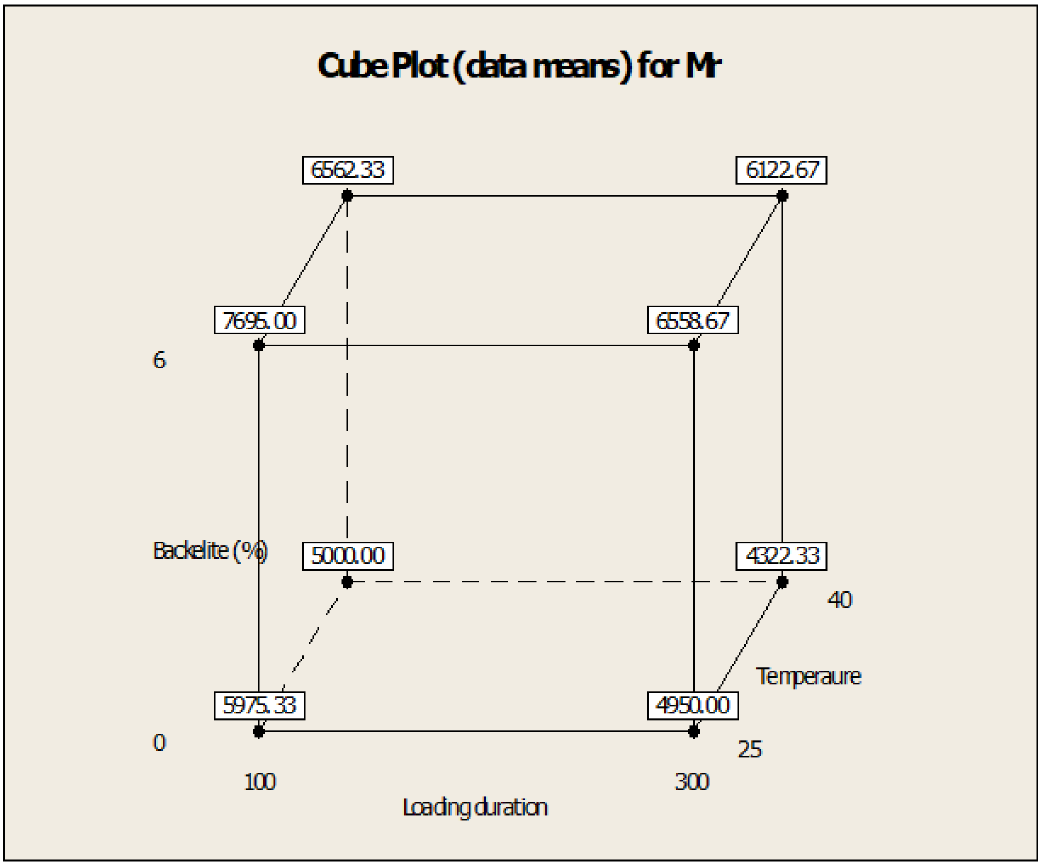

Figure 8 Cube Plot

TABLE 7. Analysis of Variance for Resilient Modulus

Source	DF	SS	MSS	F-Test	P-value
Main Effects	3	49185593	32790395	693.67	0.000
2-Way Interaction	3	415477	138492	18.44	0.000
3-Way Interaction	1	45675	45675	6.92	0.015
Residual Errors	24	12804304	261312		
Lack of Fit	1	385331	385331	1.49	0.976
Total	31	187124621			

DIAGNOSTIC CHECKING

The diagnostic checking is applied to the residuals to check the accuracy of the model based on 23 factorial design matrices by using the residual analysis tool. The residual (e) is the difference between the dependent variable (y) and the predicted value ($\hat{y}$). Firstly, the normality assumption is checked by plotting histograms as shown in figure 9. It reveals that the assumption is more or less satisfied since the plot looks like a normal distribution that is centered at zero. There is a slight skewness from normality, which is not significant, so the assumption is not violated. Normality assumptions are also checked by plotting Normal Probability shown in Figure 9. The straight line showed that errors are distributed normally distributed, and the assumption is satisfied.

Secondly, the constant variance assumption is also plotted for checking the variance of Residual vs. Fitted values. It is clear that the residuals are structureless and randomly distributed around zero with neither megaphone nor funnel-shaped patterns. This shows that the constant variance assumption is also fulfilled and the model is valid. This assumption is cross-checked by plotting the residuals in order of data collection sequence i.e., observation order. A cyclic trend of residuals with alternating positive and negative values indicates that the correlation exists between them and the implication is that the assumption of independence of residuals is violated. The proper randomization of the experiment and remembering the order of data collection is important to obtain independence. Figure 9 shows that the residuals are not correlated and they are independent.

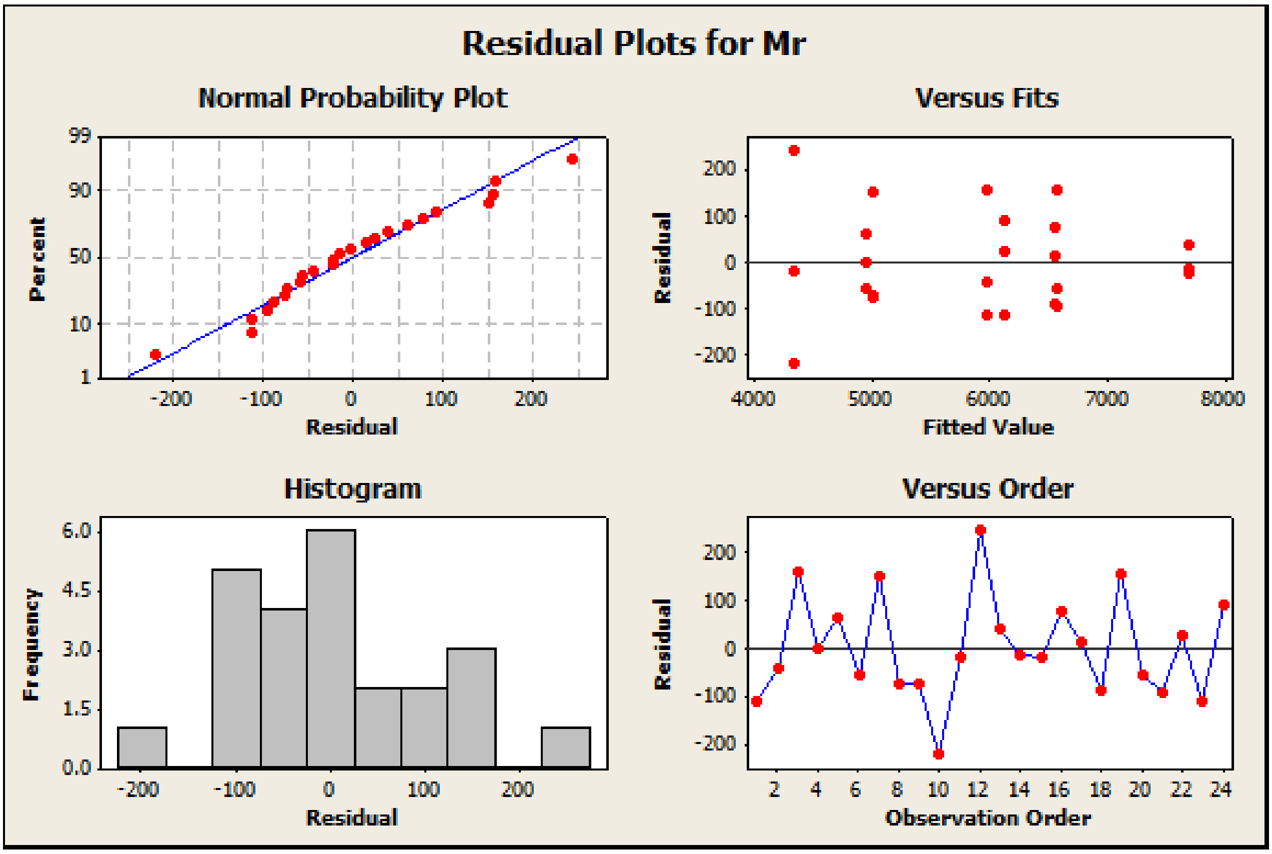

Figure 9 Residual plots

CONCLUSIONS

Based on the results obtained from the Marshall Stability, flow, quotient, retained stability and resilient modulus testing of both conventional and modified asphalt concrete samples and analysis of experimental results, the following conclusions have been drawn

The Bakelite enhanced various mechanical properties of asphalt concrete mixes like Marshall Stability, flow, quotient, retained stability and resilient modulus thus it can be used as an additive.

1. Optimum bitumen content (OBC) found by Marshall Mix design criteria (ASTM D6926) came out to be 4.3% by weight of aggregates.
2. Marshall Stability, flow, Marshall Quotient and retained stability test results showed that optimum Bakelite content for asphalt concrete mixes is 6% by weight of OBC.
3. Marshall Stability, flow, Marshall Quotient test results showed that up to 6% Bakelite content, strength and flow of the mixes increased.
4. Retained stability test showed that with the addition of Bakelite, the moisture susceptibility of asphalt concrete decreased thus making it more resistant to moisture damage as compared to conventional mix. The test showed 6% Bakelite content to be the optimum modifier content.
5. Factorial design revealed that Bakelite content was the most significant factor influencing the resilient modulus and, ultimately, the asphalt concrete mix's strength.
6. The addition of bakelite, as an additive, in hot mix asphalt mixes gives better results regarding pavement performance and can be used by the highway industry of Pakistan.

RECOMMENDATIONS FOR FUTURE WORK

For future study, other properties, such as rutting potential, dynamic creep and flexural stiffness can be tested for bitumen modified specimens. In this research, the Bakelite alone was used as a modifier. Furthermore, it can be mixed with other modifiers such as crumb rubber, fibers and other types of plastics.

This study compared the properties of modified and conventional 60/70 penetration grade bitumen. For future study, one must compare the results obtained by testing both 60/70 & 80/100 specimens against performance grade specimens. The field performance of Bakelite modified mixes should be evaluated.

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DECLARATION OF COMPETING INTEREST

None

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