



Performance Evaluation of Modified Bitumen with Replaced Percentage of Waste Cooking Oil & Tire Rubber with Bagasse Ash as Modifier

Junaid Khan ^a, Arshad Hussain ^a, Fazal Haq ^{a*}, Kamran Ahmad ^a, Kamran Mushtaq ^a

^a Department of Transportation, National Institute of Transportation, National University of Sciences and Technology, Islamabad, Pakistan.

Received 25 November 2018; Accepted 17 February 2019

Abstract

Flexible pavements are the major type of pavement use in recent days. Bitumen is the main constituent's part of flexible pavement. Bitumen is the by-produce of petroleum. The depleting reserve of petroleum led researcher to look for alternative binder. This research work explicitly aim at replacing certain percentage of bitumen with Tire Rubber powder (TR), Waste Cooking Oil (WCO) in the presence of Bagasse Ash (BA) as a modifier. Physical test were performed to determine optimum percentages of TR, WCO and BA that can be used as a percentage replacement in bitumen. Result shows that up to 20 % of bitumen can be successfully replaced without affecting performance of bitumen. Performance Tests such as Dynamic Shear Rheometer, Rotatory thin film oven, Pressure aging Vessel and Bending Beam Rheometer were performed on modified samples for its physical and rheological properties. Modified bitumen showed good resistance against rutting, skidding and low temperature cracking. The research work directly contribute in developments of alternative binder for flexible pavement which is a leading research trend these days and environmental friendly initiative.

Keywords: Bitumen; Tire Rubber Powder; Waste Cooking Oil; Bagasse Ash.

1. Introduction

Sustainability had become the most important part of the world issue highlighted by many researchers. It includes the rising global environment concern as well as socio-economic issue. The main objectives of sustainable development is to use natural resources in the most optimized way so that, environmental and socio-economic issues are minimized [1]. Road Transportation is an important tool of connecting different cities with in any country. It comprises of facilities such as bridges, highways, tunnels to ensure safe and efficient movement of people and goods within or between the countries. A good and efficient highways network directly contributes in country's economy by increasing GDP Growth [2].

Paved roads are either flexible or rigid type. During construction of flexible pavement bitumen is use as binder in asphaltic concrete. Bitumen is a complex hydrocarbon obtained as residue during the process of fractional distillation of petroleum. Petroleum is a natural resource and its reserves are depleting with the passage of time, causes increase in price which alternatively cause rise in bitumen price as well. Moreover bitumen burns at high temperature during flexible pavement construction produce fumes that are unhealthy to environment. These major issues led researchers to search for alternative binder that can replace fully or partially certain percentage of bitumen without affecting its physical and rheological properties.

* Corresponding author: fhaq.tn15@nit.nust

 <http://dx.doi.org/10.28991/cej-2019-03091270>

➤ This is an open access article under the CC-BY license (<https://creativecommons.org/licenses/by/4.0/>).

© Authors retain all copyrights.

Different research studies were conducted in this effort to look for alternative binders. M. M. A. Aziz conducted research studies on different materials and concluded that materials which are obtained from bio-oil such as waste cooking oil, polymer, plastic and rubber can be used as alternative binder in flexible pavement [3].

Waste cooking oil, tires rubber powder and bagasse ash are waste materials, obtained from restaurants, tire industries and sugar mills respectively. Proper disposal of these wastes requires expenditure and causes reduction in land filling area. Disposal in an open region causes environmental degradation. Research studies conducted by S.M. Hussain Zaidi concluded that Pakistan import 75% of its edible oil to meet its consumer demand [4]. A huge sum of money is spending on the import of cooking oil and tire rubber, results in affecting country's economy. Wasting the residue cooking oil is not economically viable for a country which spent huge amount on its import. Therefore incorporating these wastes materials into bitumen industry will not only elevate country's economy, but will also solve the waste disposal problem followed by minimizing environmental degradation. Previous studies shows that the addition of waste cooking oil into bitumen bring improvement in rheological properties such as resistance against fatigue and low temperature cracking resistance [5]. F. J. Navarro conducted research on rubber added in bitumen and concluded that rubber modified bitumen possesses high resistance against rutting, fatigue and low temperature cracking [6]. Various type of agro-waste ash such as rice hush ash and palm oil fuel ash had been used previously in bitumen. Bagasse Ash is an agro waste ash like Rice Hush Ash (RHA). It possesses similar or better properties than Rice Husk Ash. The addition of rice hush ash improves the physical and rheological properties of bitumen [7]. Based on the chemical analysis it was expected that Bagasse ash will also improve the physical and rheological properties of bitumen.

The goal of this research work is to incorporate waste materials, which includes, waste cooking oil, tire rubber powder and bagasse ash into bitumen industry in an effort to minimize the use of natural resourced material i.e. bitumen resulting in minimizing environmental degradation and positively affecting country's economy by substitution of substantial percentage of costly material i.e. bitumen with waste material. An optimum percentage of conventional bitumen will be replaced with the percentages of Waste cooking oil tire rubber powder and Bagasse ash, thus the use of bitumen will be minimized which is both economically viable and environmental friendly.

2. Research Methodology

2.1. Materials Selection

The virgin bitumen used in this research work were having penetration grade of 60-70. Waste Cooking Oil (WCO) use in this research work was obtained from different local restaurants. Collected waste cooking oil contained different impurities and suspended particles which were settled down with the help of centrifugation equipment. WCO were then passed through 12.5 cm diameter filter paper to filter all the suspended particles. WCO having low acidic value i.e. PH value, when used in bitumen shows better physical and Rheological properties [8-11]. PH test were performed on filtered WCO of different restaurants. WCO showing lowest PH value were selected for further experimentation.

Tire Rubber powder (TR) was obtained from the local shop in Rawalpindi, Pakistan In the process of conversion of tire rubber in to different shapes. The collected TR contains different sizes. Since the interaction of TR with bitumen is physical, so in order to have good physical interaction, surface area of rubber particle should be greater. Particle smaller in size has relatively greater surface area. for this purpose TR were passed through different sieves, and particle passing #200 sieve were selected for further experimentation.

Bagasse ash (BA) was obtained from sugar cane industry. Sugar cane wastes were burned at high temperature. Ash obtained as a result of burning were converted into grinded powder in ball mill, which were further passes through different sieve to obtain smaller size particle for having better interaction with bitumen. Material passing #200 sieves were collected for further experimentation. The average size of BA will be of the size of fine soil such as 0.0075um. Chemical analysis of BA was conducted with the help of XRD. XRD analysis of BA shows that it contains considerable amount of silica which is responsible for mineralogical property of BA. It is expected that BA will improve both physical and rheological property of bitumen due to its pozolanic property.

2.2. Sample Preparation

Different trials were carried out in an effort of determining an optimum percentage of WCO, TR and BA that can be used in bitumen without adversely affecting its physical property. Each trial consists of different sample having different mixing ratios. Each sample was prepared in high shear mixture. For sample preparation virgin bitumen was heated consistently for few minute in high shear reo mixture. TRP were added to virgin bitumen at varying percentage for each sample and the temperature was increased to 150 °C and heating were continued for about 30 minutes at 900 rev/min. After that WCO and BA were added and the temperature of the mix were reduced to 135 °C, so as to avoid the evaporation of WCO at high temperature.

3. Experimental Testing

Physical and Performance testing were performed on virgin bitumen PG 60-70 and modified bitumen. Modified bitumen was obtained through extensive physical testing by determining an optimum percentage of WCO, TR and BA that can replace bitumen. Results of the Physical and performance testing, which include low temperature cracking, rutting and fatigue resistance of virgin and modified bitumen were compared.

3.1. Physical Test

Physical test include penetration and softening point test. Physical test were performed to determine optimum percentages of WCO, TR and BA that can be used as a percentage replacement in bitumen.

Penetration test is important for determining Grade of bitumen, which is further used for determining suitability of bitumen used under different climatic conditions. It measures the hardness or consistency of bituminous material. A total of 75 samples were prepared for penetration testing. Each sample weight 100 gm. Samples were placed in a water bath at 25 °C for three hour. The samples were then placed in penetrometer where a needle fall down and penetrate the sample. The penetration depth was measured as penetration in the unit of 0.1 mm.

Softening point test was performed to measure temperature susceptibility of bitumen. Hot sample of bitumen was poured in two rings and placed in open air for 30 minutes. The rings are fixed in a metallic stand which is placed in water containing beaker mounted on heater. Water containing beaker is heated at a rate of 5°C/ mint. Softening point was recorded as the average temperature at which the bitumen sample flow down and touches the bottom.

3.2. Rotational Viscosity

RV test were performed in different asphalt sample in Brookfield viscometer. The sample is poured in sample chamber which is placed in thermostet and spindle is lower in it. The RV test was run for a 30 minutes for each sample. RV test were conducted on 135 °C and 160 °C.

3.3. Modified Bitumen

Results from the physical tests and RV test were used as a base to select optimum percentage of WCO, TR and BA that can be used as percentage replacement in bitumen without affecting the physical properties, we call this optimum blend of bitumen with waste material as modified bitumen. Performance tests which includes, rutting resistance test, fatigue resistance, resistance against low temperature cracking were conducted on virgin and modified bitumen and the results obtained were compared.

4. Experimental Testing

4.1. Dynamic Shear Rheometer (DSR)

DSR is used to measure the viscoelastic behavior of asphalt. It measures the complex shear modulus and the phase angle of bitumen. DSR is also used to calculate performance grade of bitumen. It can assess the performance of bitumen against rutting and fatigue. A sample of about 8 mm or 2 mm diameter is placed in DSR main unit which oscillate continuously and apply shear force which produce shearing action. The oscillation frequency range is between 0 HZ to 100 HZ. DSR test was conducted on both aged and un-aged sample.

4.2. Rotatory Thin Film Oven (RTFO)

Short term aging performance of bitumen is important. For this purpose RTFO is used to stimulate short term aging in bitumen. A sample of bitumen is placed in glass a bottle which is then placed in RTFO equipment where hot air at 163 °C temperature is applied for 80 minutes.

4.3. Pressure Aging Vessel (PAV)

PAV equipment is used to simulate long term aging of asphalt i.e. 7 to 10 years by applying heat and pressure for 20 hours. A Sample of bitumen is placed in pan which is then placed in PAV equipment where high temperature and pressure are applied to attain 7 to 10 year of asphalt aging.

RTFO and PAV aged sample were tested in DSR equipment for assessing resistance against rutting and fatigue after short term and long term aging respectively.

4.4. Bending Beam Rheometer (BBR)

BBR is a device used to measure low temperature cracking in bitumen. Sample aged in PAV is poured in a BBR mold. BBR beam formed in mold is placed in BBR assembly containing fluids. The temperature of fluid is maintained at which the low temperature cracking has to be determined.

5. Results and Discussion

5.1. Physical Test Results

Physical test were conducted in order to obtain optimum quantity of WCO, TR and BA that can be used in bitumen mix. In first trial bitumen were replaced with different percentages of WCO starting from 5 % and then increased with an increment of 5 % subsequently as shown in Table 1. The tests results shows that with the increase in percentage of WCO in bitumen softening point decreases and penetration increases, it is due to the fact that bitumen and WCO are both hydrocarbon and their bonding energy decreases in a mix.

In second trial when bitumen is replaced with WCO and TR, penetration value decreases and softening point value increases as shown in Table 2 which points to the fact that, reaction between TR and bitumen is physical and with the use of TR, bitumen mix become a little harder. An optimum value for WCO to be replaced in bitumen was selected from first and second trial which is 5 %. Because beyond 5 % increase in WCO percentage, higher penetration value and lower softening point values were obtained. BA was introduced in the third trial as additive to the mix. Since the chemical properties of BA shows that it is pozzolanic material so definitely it will improve stiffness of bitumen sample.

In third trial different percentages of BA were used as additive in a bitumen mix in which WCO and tire rubber powder were used as percentage replacement of bitumen. The results shown in Table 3 indicate that with the addition of BA, penetration of modified bitumen decreases.

Results from third trial indicate that, sample number four shows better physical test results among all the samples in which the optimum percentage of waste materials used are WCO of 5 %, TR 15 % and BA 8 %. It should be noted that only WCO and TR was used as a percentage replacement of bitumen while BA was used as additive.

Table 1. Physical Tests Results of WCO replacement in Bitumen

Type of sample (Total sample weight=200gm)	Sample Code	Bitumen Replaced (%)	Penetration (dmm)	Softening Point (°C)
Virgin Bitumen 60-70	60-70	0	68	46
60-70 Bitumen with 5 % WCO	W5	5	201	23
60-70 Bitumen with 10 % WCO	W10	10	294	20.5
60-70 Bitumen with 15 % WCO	W15	15	334	19
60-70 Bitumen with 20 % WCO	W20	20	361	18

Table 2. Physical Tests Results of WCO & TR replacement in Bitumen

Type of sample (Total sample weight=200gm)	Sample Code	Bitumen Replaced (%)	Penetration (dmm)	Softening Point (°C)
Virgin Bitumen 60-70	60-70	0	68	46
60-70 Bitumen with 5 % WCO & 5 % TR	W5TR5	10	136	31
60-70 Bitumen with 5 % WCO & 8 % TR	W5TR8	13	122	33
60-70 Bitumen with 5 % WCO & 12 % TR	W5TR12	17	114	37
60-70 Bitumen with 5 % WCO & 15 % TR	W5TR15	20	109	39
60-70 Bitumen with 5 % WCO & 18 % TR	W5TR18	23	105	41

Table 3. Physical Tests results of WCO and TR replacement in Bitumen in the presence of BA as modifier

Type of sample (Total sample weight=200gm+%BA)	Sample Code	Bitumen Replaced (%)	Penetration (dmm)	Softening Point (°C)
60-70 Bitumen with 5 % WCO, 5 % TR & 5 % BA	W5TR5B5	10	117	37
60-70 Bitumen with 5 % WCO, 8 % TR & 7 % BA	W5TR8B7	13	112	39
60-70 Bitumen with 5 % WCO, 12 % TR & 7.5 % BA	W5TR12B7.5	17	104	44
60-70 Bitumen with 5 % WCO, 15 % TR & 8 % BA	W5TR15B8	20	97	48
60-70 Bitumen with 5 % WCO, 18 % TR & 10 % BA	W5TR18B10	23	103	53



Figure 1. Softening Point Test Samples



Figure 2. Softening Point Testing Machine

5.2. Rheological Test Results

5.2.1. Rotational Viscosity

Combinations of third trial were taken further for rotational viscosity test. Table 4 Indicate that with the increase in percentage of TR and BA viscosity of modified bitumen increases.



Figure 3. Viscometer

Table 4. Viscosity of Samples from Third trial

Type of sample (Total sample weight=200gm+%BA)	Sample Code	Bitumen Replaced (%)	Viscosity(C.P)		Viscosity Ratio (135°C/160°C)
			135 °C	160 °C	
Virgin Bitumen	60-70	0	450	140	3.214
60-70 Bitumen with 5 % WCO, 5 % TR & 5 % BA	W5TR5B5	10	493	290	1.7
60-70 Bitumen with 5 % WCO, 8 % TR & 7 % BA	W5TR8B7	13	740	390	1.89
60-70 Bitumen with 5 % WCO, 12 % TR & 7.5 % BA	W5TR12B7.5	17	900	470	1.91
60-70 Bitumen with 5 % WCO, 15 % TR & 8 % BA	W5TR15B8	20	1300	490	2.653
60-70 Bitumen with 5 % WCO, 18 % TR & 10 % BA	W5TR18B10	23	1730	501	3.45

5.2.2. Dynamic Shear Rheometer (DSR)

a) Rutting Resistance

For determining resistance against rutting DSR test was performed on un-aged and RTFO aged sample of virgin and modified bitumen. Rutting resistance criteria for un-aged and RTFO aged sample at maximum temperature is $G^* / \sin \delta > 1.0$ kPa and $G^* / \sin \delta > 2.2$ kPa respectively. Figures 6 and 7 shows the comparison of complex modulus values of virgin and modified bitumen at different temperatures. Rutting resistance criteria for un-aged sample of both virgin and modified bitumen has been achieved at the temperature of 64 °C, while for aged sample, for virgin bitumen fail at 70 °C and modified bitumen fail at 75 which point to the fact that RTFO aged modified bitumen shows better resistance against rutting and the performance. The increase in rutting resistance can be attributed to the presence of high percentage of rubber and Bagasse ash in modified bitumen.



Figure 4. DSR Test Sample



Figure 5. DSR Test Machine

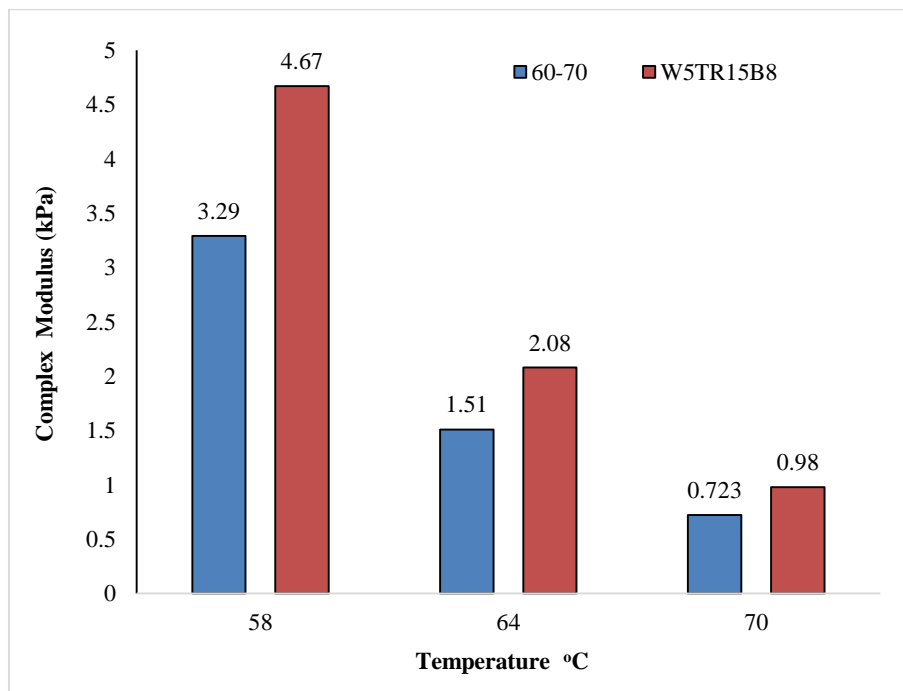


Figure 6. Comparison of Complex Modulus (kPa) of Un-aged Virgin bitumen & W5TR15BA8

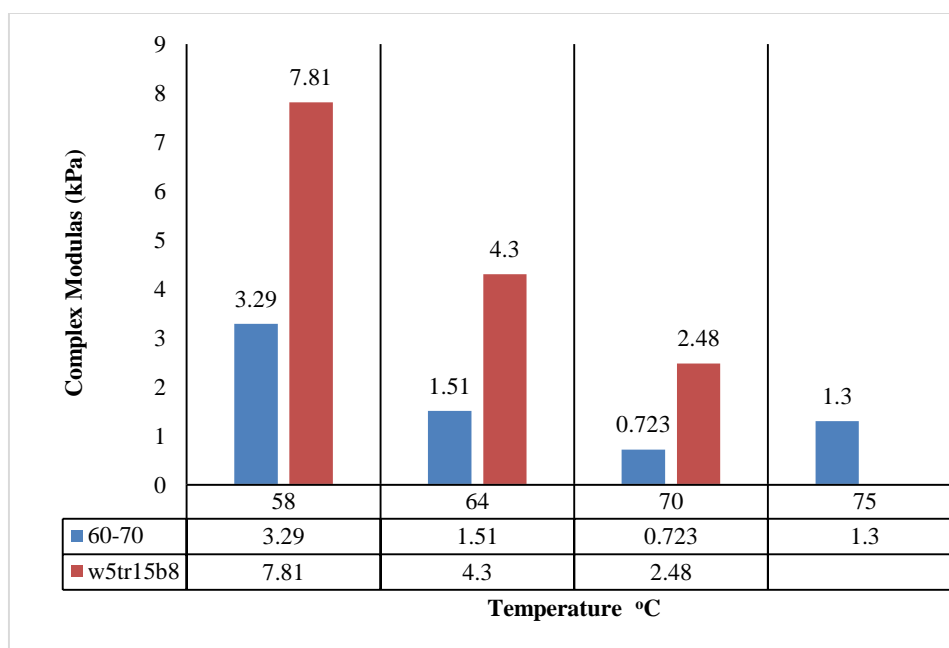


Figure 7. Comparison of complex modulus of RTFO aged virgin and W5TR15BA8

b) Fatigue Resistance

PAV aged samples of virgin and modified bitumen were tested in DSR for fatigue resistance. A criterion for fatigue resistance is that $G^* \sin \delta$ should not exceed the value of 5000 kPa at any particular temperature. Figure 8 shows comparison of value of $G^* \sin \delta$ at different temperature. It is clear from the comparison that modified bitumen can resist fatigue cracking up to temperature 10 °C an improvement in fatigue resistance can be attributed to the presence of Waste cooking oil and tire rubber powder in modified bitumen. WCO can significantly improve fatigue resistance of bitumen [9-14].

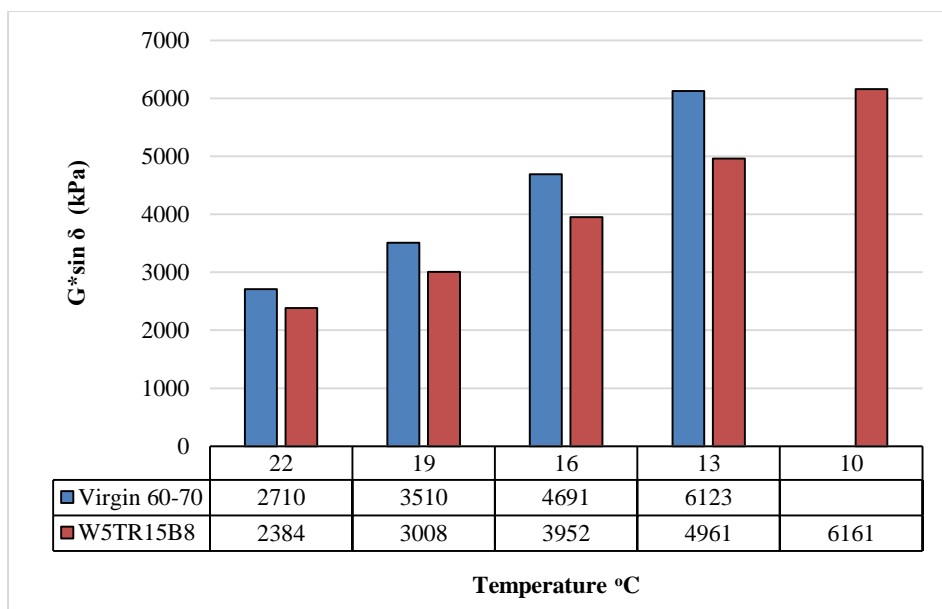


Figure 8. Comparison of $G^* \sin \delta$ (kPa) value of PAV aged virgin and W5TR15BA8 sample

5.2.3. Bending Beam Rheometer/Low Temperature Cracking

PAV aged samples of virgin and modified bitumen were placed in BBR and were tested on different temperatures of (-6, -12, -18, -22) °C to determine low temperature cracking in both the samples and the results were compared as shown in Figures 9 and 10. Virgin bitumen resists low temperature cracking up to 6 °C, while modified sample can resist low temperature cracking up to 22 °C. High low temperature cracking resistance of modified bitumen can be attributed to the presence of WCO and TR. It is evident from the literature that WCO and TR both have the potential to improve resistance against low temperature cracking.

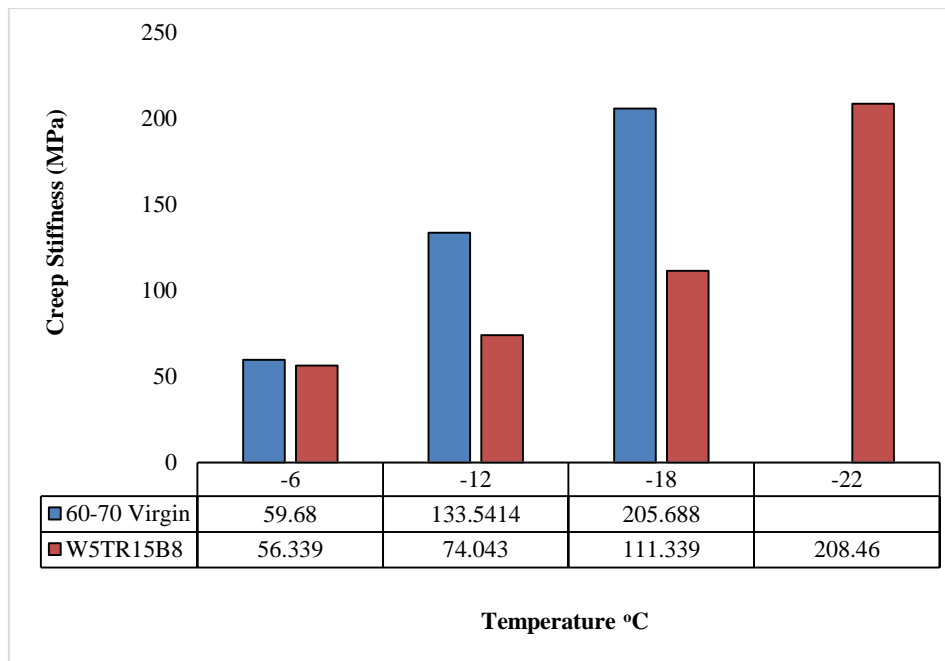


Figure 9. Comparison of Creep Stiffness (MPa) of Virgin and Modified bitumen

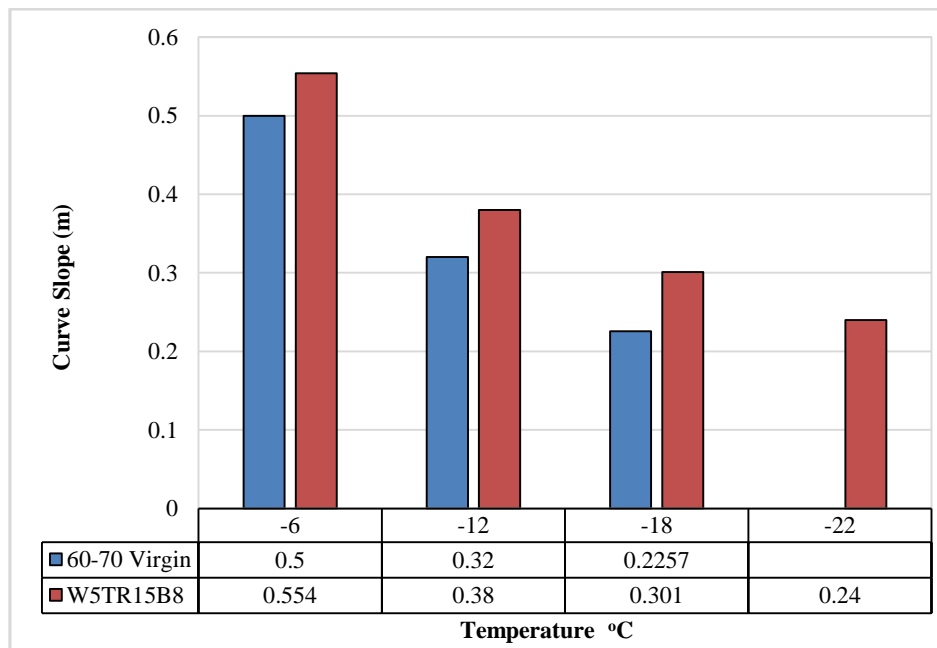


Figure 10. Comparison of curve slope of virgin bitumen and W5TR15BA8 Sample

5.2.4. Aging affect

Aging of bitumen, substantially affect asphaltic pavement durability resulting in decreasing its ability to resist traffic induced stress and strain. Excessive aging of bitumen, can lead to decrease adhesion between binder and aggregate resulting in loss of material at the surface layer and initiate weakening of asphalt mixture. Therefore it is important to assess aging of modified bitumen compare to virgin bitumen. Percentage retained penetration can be used to assess aging in bitumen. Penetration of RTFO aged sample of both virgin and modified bitumen were determined and compared with penetration value to that of un-aged, virgin and modified bitumen obtained. The following Table 5 shows retained penetration values.

Table 5. Comparison of Retained penetration of virgin and W5TR15B8 sample

Type of Sample	Sample Code	Penetration of RTFO aged Sample (mm)	Penetration of un-aged samples (mm)	Retained Penetration (%)
Virgin bitumen	60-70	46	67	68.65
Modified bitumen	W5TR15B8	72	97	74.2

As it can be clearly seen that modified bitumen shows high percentage of retained penetration after aging. Higher retained penetration shows lesser tendency of bitumen to hardening after short term aging. So it can be concluded that modified bitumen, after modification shows more resistance to hardening than virgin bitumen and so as prolong aging time.

6. Conclusion

This research work started with an aim to reduce the percentage of virgin bitumen in flexible pavement construction and maintenance, by replacing certain percentage of bitumen with wastes. Incorporating waste into bitumen will save excessive use of bitumen (Natural resourced material) and will minimize environmental degradation causes by waste disposal and excessive burning bitumen. The research work concludes the following.

- Series of physical test including penetration and softening point were done on different percentage of bitumen replaced with WCO and TR in the presence of BA as modifier, to obtain an optimum mixing ratio.
- Optimum mixing ratio contain 5 % WCO, 15% TR used as percentage replacement in bitumen in the presence of 8 % BA as modifier (additive).
- 20 % of bitumen can be successfully replaced with waste material (WCO, TR, & BA) without affecting performance of bitumen.
- Modified bitumen obtained by incorporating waste material into bitumen shows better rheological properties than virgin bitumen.
- Value of complex modulus (G^*) of modified bitumen is higher than virgin bitumen which indicate a good resistance against rutting.
- Modified bitumen shows less stiffness (S value) and more creep rate (m- value) value than virgin bitumen. It points to the fact that modified bitumen poses more resistance to low temperature cracking than virgin bitumen.
- Modified bitumen shows better resistance against rutting as compared to virgin bitumen.
- Chemical analysis of modified bitumen shows that reaction of bitumen with TR and BA is physical while WCO react chemically with bitumen.

7. Conflicts of Interest

The authors declare no conflict of interest.

8. References

- [1] Hopwood, Bill, Mary Mellor, and Geoff O'Brien. "Sustainable Development: Mapping Different Approaches." *Sustainable Development* 13, no. 1 (2005): 38–52. doi:10.1002/sd.244.
- [2] Fraumeni, Barbara. "The Contribution of Highways to GDP Growth" *The National Bureau of Economic Research*, (February 2009). doi:10.3386/w14736.
- [3] Aziz, Md Maniruzzaman A., Md Tareq Rahman, Mohd. Rosli Hainin, and Wan Azelee Wan Abu Bakar. "An Overview on Alternative Binders for Flexible Pavement." *Construction and Building Materials* 84 (June 2015): 315–319. doi:10.1016/j.conbuildmat.2015.03.068.
- [4] Zaidi, Syed Masroor Hussain. "Edible Oil Imports in Pakistan." *South Asian Journal of Management* 8, no. 1 (2014): 1-8.
- [5] Sun, Zhaojie, Junyan Yi, Yudong Huang, Decheng Feng, and Chaoyang Guo. "Properties of Asphalt Binder Modified by Bio-Oil Derived from Waste Cooking Oil." *Construction and Building Materials* 102 (January 2016): 496–504. doi:10.1016/j.conbuildmat.2015.10.173.
- [6] Navarro, F. J., P. Partal, F. Martínez-Boza, and C. Gallegos. "Influence of Crumb Rubber Concentration on the Rheological Behavior of a Crumb Rubber Modified Bitumen." *Energy & Fuels* 19, no. 5 (September 2005): 1984–1990. doi:10.1021/ef049699a.
- [7] Romastarika, Raissa, Ramadhansyah Putra Jaya, Haryati Yaacob, Fadzli Mohamed Nazri, Agussabti, Ichwana, and Dewi Sri Jayanti. "Effect of Black Rice Husk Ash on the Physical and Rheological Properties of Bitumen" (2017). doi:10.1063/1.4998383.
- [8] Azahar, Wan Nur Aifa Wan, Ramadhansyah Putra Jaya, Mohd Rosli Hainin, Mastura Bujang, and Norzita Ngadi. "Chemical Modification of Waste Cooking Oil to Improve the Physical and Rheological Properties of Asphalt Binder." *Construction and Building Materials* 126 (November 2016): 218–226. doi:10.1016/j.conbuildmat.2016.09.032.
- [9] Maharaj, Rean, Vitra Ramjattan-Harry, and Nazim Mohamed. "Rutting and Fatigue Cracking Resistance of Waste Cooking Oil Modified Trinidad Asphaltic Materials." *The Scientific World Journal* 2015 (2015): 1–7. doi:10.1155/2015/385013.

- [10] Zhang, Jiu Peng, Jian Zhong Pei, and Yan Wei Li. "Research on Interaction Between Asphalt and Filler Based on DSR Test." *Advanced Materials Research* 723 (August 2013): 480–487. doi:10.4028/www.scientific.net/amr.723.480.
- [11] Nurul Hidayah, M. K., Mohd Rosli Hainin, Norhidayah Abdul Hassan, and Mohd Ezree Abdullah. "Rutting Evaluation of Aged Binder Containing Waste Engine Oil." *Advanced Materials Research* 911 (March 2014): 405–409. doi:10.4028/www.scientific.net/amr.911.405.
- [12] Yusoff, N.I.Md., G.D. Airey, and M.R. Hainin. "Predictability of Complex Modulus Using Rheological Models." *Asian Journal of Scientific Research* 3, no. 1 (January 1, 2010): 18–30. doi:10.3923/ajsr.2010.18.30.
- [13] Fini, Ellie H., Felix Smith Buabeng, Taher Abu-Lebdeh, and Faisal Awadallah. "Effect of Introduction of Furfural on Asphalt Binder Ageing Characteristics." *Road Materials and Pavement Design* 17, no. 3 (November 3, 2015): 638–657. doi:10.1080/14680629.2015.1108219.
- [14] Katamine, N. M. "Physical and mechanical properties of bituminous mixtures containing oil shales." *Journal of Transportation Engineering* 126, no. 2 (2000): 178-184. doi: 10.1061/(ASCE)0733-947X(2000)126:2(178).