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Modification of the dry method for mixing crumb rubber modifier with aggregate and asphalt based on the binder mix design

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HIGHLIGHTS

- The crumb rubber modifier dry process was modified and named the complex process.
- Mechanical characteristics of asphalt mixtures significantly enhanced by utilising CRM complex method.
- In a complex process, bitumen and aggregates were mixed, then the CRM was added.
- CRM complex process provides the homogeneous mixtures and better results.
- A complex method has a function of improving asphalt mixtures better than dry and wet methods.

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ABSTRACT

Mechanical characteristics of the asphalt binders and mixtures were enhanced by utilising modifiers. The crumb rubber modifier has been introduced to the asphalt modification as an environmentally friendly procedure of scrap tires, to improve the mechanical characteristics of the asphalt. This study aims to modify the dry method for mixing crumb rubber modifier with asphalt and aggregate based on the binder mix design. To achieve this goal crumb rubber modified asphalt mixtures were prepared and tested by applying various tests such as Marshall Stability test, indirect tensile strength test, and wheel tracking test. Three mixing methods of CRM were studied regarding evaluating the stability, rutting, and moisture susceptibility. The crumb rubber modifier dry mixing method was modified and named the complex process. Better results were achieved for enhancing mechanical properties.

1. Introduction

To reduce the environmental effects of roads building and maintenance, necessary to find solutions capable of increasing the performance of the pavement while decreasing the negative impacts. In this context, the utilisation of recycled materials appropriate for other re-uses must be progressed and enhanced [1,2]. The fields of application of CRM in road constructions are miscellaneous. The previous researchers validate them are as numerous as the number of positive results achieved in recycling this material [1].

The usage of the recycled rubber from the End of Life Tires into the bitumen concretes was began in the 1960s. The technology that has spread more is the so-called Asphalt Rubber (AR) one. AR binders produced with the manufacturing process innovated by Charles McDonald, and that is at the foundation of the wet process. This method began with the mix of the end of life tire ground rubber with the asphalt binders utilising mechanical stirring systems, operating at temperatures ranging between 190 and 218 °C, for a time interval of 45–60 min [3–6].

The McDonald blend was the asphalt Rubber blend produced in the mixing reservoir by blending the CRM and the asphalt binder [6]. In 1975 several experimental tests carried out by Caltrans on asphalt rubber chips which led to the construction of first rubberised asphalt pavement [6,7]. In recent years, the use of CR as modifier or additive within asphalt concretes has permitted getting mixtures capable of binding the high performances to restoration and reuse of neglected tires. To date, the common technologies that permit the reuse of rubber powder are the wet, dry, dry-hybrid technology, terminal blend, and reacted and activated rubber [5,8]. There are two popular methods for processing binders to incorporate the crumb rubber modifier in hot mix asphalt (HMA): wet and dry processes [9].

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The production of field and terminal blending processes are named: “asphalt rubber binder” and “tire rubber modified binder,” respectively. The crumb rubber content and properties, kinds of extenders, and the digestible process vary considerably between the two methods. Consequently, the features of the rubberised binders produced by the two processes are also very different and therefore require different approaches to define the binder properties [10]. Two technologies which utilise the wet method are the McDonald (batch) technology and the continuous mixing technology [6].

Two technologies which use dry processes are the Plus Ride technology and the generic dry technology. In the wet process, the CRM is blended with the bitumen cement before mixing the CRM modified asphalt binder with the aggregate. In McDonald technology, the crumb rubber modifier is mixed in a blending tank and reacted in a holding reservoir prior to the introducing into the mix. In continued blending technology, the CRM and the bitumen cement could be mixed just before the binder is added into the mix or it can be mixed and placed in a storage tank for use later. In the dry process, the crumb rubber materials were mixed with the aggregate before the addition of the asphalt cement to the blended mixture [11].

In the Previous study performed by Kocak and Kutay concluded that there were three fundamental methods utilised to produce the crumb rubber modified asphalt pavements. These methods are a dry process, terminal blend and wet process. While the CRM dry process substitutes the portion of fine aggregate in the asphalt mixture with the crumb rubber particles, crumb rubber modifier wet process integrates the crumb rubber modifier particles into hot liquid asphalt before mixing with aggregates. CRM terminal blend is known as a particular type of CRM wet process where the CRM is blended with asphalt binder at the asphalt terminal. Also, they concluded that it is possible to raise the quantity of the CRM in the mixture by using the CRHY method, without negatively influencing the performance of the mixture [12,13]. Currently, there are two distinct forms of wet-process crumb rubber modified asphalt such as Asphalt Rubber (known as Wet-Process, high viscosity) and Rubber Modified Binder (known as Wet-Process, no agitation and terminal blend) [6,7].

The Rubber Modified Binder process utilises a more finely-ground crumb rubber than Asphalt Rubber, and there is more extended and more thorough mixing, yielding a material with more continuous and homogeneous properties and which does not require agitation to prohibit separation. CRM types are different, their sources are vast, and their components are diverse, so their modified influence on asphalt binder will not be the same [14].

The aim of this study was to modify the dry method for mixing crumb rubber modifier with asphalt and aggregate based on the binder mix design. In this study, the use of the crumb rubber modifier in the flexible pavement was investigated to modify the dry method of crumb rubber with bitumen and aggregates. The mechanical properties, especially the rutting resistance and moisture susceptibility as well as the stability were assessed by applying various tests on CRM-modified asphalt blends with various CRM concentrations.

2. Materials and methods

2.1. Materials

Used materials include asphalt penetration grade 60/70, coarse and fine aggregate, mineral filler, and crumb rubber modifier. All materials were obtained from “Jiangsu Yi Nuo Road and Bridge Engineering and testing material Co., Ltd/China”.

2.1.1. Asphalt

The unmodified asphalt binder used in this study is asphalt 60/70 penetration grade. The asphalt mixtures used in this

Table 2
The components and properties of the crumb rubber modifier.

Component	Content (%)
Ash content	5
Acetone extract	11
Natural rubber Content	25.8
Rubber Hydrocarbon Content	37
Carbon Black Content	21.2
Relative density	1.2
Particle size range (μm)	163–149

Fig. 1. The sample of the crumb rubber modifier.

Table 1
Physical properties of base asphalt.

Test	Method	Quantity	Specification limits
Penetration at (25 °C,100 g, 5 s), 0.1 mm	ASTM D5	64	60–70
Ductility (25 °C, 5 cm/min), (cm)	ASTM D113	149	Min 100
Kinematic Viscosity at 135 °C (Pa.s)	ASTM D2170	0.421	–
Softening point (Ring & ball method) (°C)	ASTM D36	49	Min 46.0
Flash point (°C)	ASTM D92	316	–
Fire point (°C)	ASTM D92	330	–
Specific gravity at 25 °C (g/cm^3)	ASTM D70	1.05	–
Loss on heat (%)	ASTM D-6	0.05	–
Dynamic Viscosity at 60 °C (Pa. s)	ASTM D2171	0.411	–

research are the asphalt concrete (AC), and the optimum asphalt content (OAC) was 4.6% by mixture weight. The physical properties of the asphalt illustrated in Table 1.

2.1.2. Crumb rubber modifier

The CRM was obtained by the cryogenic grinding method. To guarantee that the uniformity of the CRM maintained throughout the study, only one batch of crumb rubber used. The tire rubber powder size utilised in the current research was passed through a sieve No. 90# (163 µm) and retained on a No. 100# (149 µm). Table 2 illustrated the components and properties of the crumb rubber modifier, and Fig. 1 shows the sample of used CRM.

2.1.3. Aggregates

The crushed basalt aggregate utilised in samples preparation is a mixture of the coarse aggregates, fine aggregates, and filler. The aggregation curve of the blending ratio of the aggregates is showing in Fig. 2 and the physical properties of the used aggregate illustrated in Table 3. The mineral filler used in the current study is the limestone filler, and its characteristics were shown in Table 4.

2.2. Methods

2.2.1. Sample preparation

Marshall Stability test, wheel tracking test (WTT), and indirect tensile strength test (IDST) were conducted following the standard test methods showed in Table 5.

To prepare the samples for the Marshall test coarse aggregates, fine aggregate, and mineral filler were proportioned to fulfil the requirement of the relevant standards. The required quantity of the aggregates, limestone filler, and bitumen were preheated to a temperature of 175–190 °C and thoroughly mixed at a temperature of 175–190 °C (control mixture). Mixing was performed utilising a high-power mechanical mixer. CRM-modified asphalt heated to 180–190 °C; then the preheated aggregates and CRM-modified bitumen were thoroughly mixed at a temperature of 180–190 °C (wet process). The preheated aggregates and preheated CRM were thoroughly mixed at a temperature of 180–190 °C then the heated bitumen was added and thoroughly mixed at a temperature of 180–190 °C (dry process). For preparing the CRM-modified asphalt mixture specimen by the complex process, aggregates were preheated and mixed for 60 s by using a mixer to ensure the homogeneity. After that, the preheated bitumen was added to the aggregates according to ASTM-D1559 specification and thoroughly mixed for 30 s at a temperature of 180–190 °C, then the mineral fillers (limestone filler) were added to aggregates and asphalt binder and mixed for 30 s at a temperature of 180–190 °C. CRM was heated to a temperature of 180–190 °C and then progressively added to the mixture. Aggregates, bitumen, and the CRM were thoroughly mixed for 60 s at a temperature of 180–190 °C. Table 6 explained the mechanism of preparing CRM-modified bitumen mixtures used in this study. The blend is placed in a preheated mould and compacted by a rammer with 50 blows per face at a temperature of 170–175 °C. The dimensions of the compacted specimen were 63.5 ± 3 mm thickness and 101.6 mm diameter. The optimum asphalt content was 4.6% by the mixture weight. Six samples were prepared for each crumb rubber contents (e.g., 6%, 12%, 18%, and 24% by weight of asphalt) for each process (wet, dry, and complex). The number of the CRM-modified asphalt specimens was 72 and six specimens for control (unmodified).

The IDTS test has been considered as an index of the strength and adhesion against the temperature cracking, and the rutting. A total of 144 of the Marshall test samples of CRM-modified mixtures with different modifier concentrations 6%, 12%, 18%, and 24% were prepared by utilising the three methods (wet, dry, and complex process). Forty-eight specimens were prepared for each method (12 samples have been made for each percentage and divided into two groups six samples each). The first group was conditioned specimens (the specimens were immersed in the water bath at a temperature of 60 °C for 24 h). The second set of samples which were unconditioned samples were kept at a temperature of 25 °C for 24 h. As well, a total of 12 specimens of control were prepared and divided into two groups (6 samples each), and one group is conditioned.

Wheel tracking test (WTT) specimens were manufactured with dimensions 300 × 300 × 50 mm using a roller compactor. Thirteen samples were prepared (4 samples each method and one sample for unmodified bitumen) and allowed to cool at a temperature of 25 °C for about 24 h.

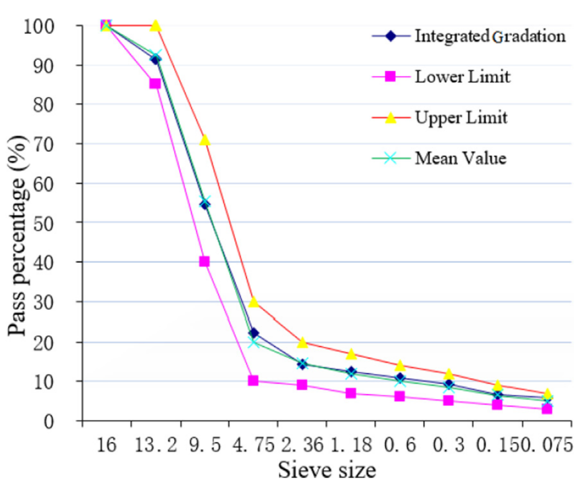

Fig. 2. The aggregate gradation curve.

Table 3
The characteristics of the natural aggregate.

Test	Method	Quantity	Specification limits
Stone crushing value (%)	IS: 2386 part-IV	14.1	30
Los Angeles abrasion loss (%)	ASTM C535	18	30
Apparent relative density (%)	ASTM C127	2.51	2.6
Water absorption (%)	ASTM C1585-13	1.2	2.0

Table 4
The characteristics of limestone filler.

Test	Method	Quantity	Specification limits
Hygroscopic moisture content (%)	ASTM C535	0.009	<30
Apparent relative density (%)	ASTM C128	2.6	≥2.5
Ignition Loss (%)	ASTM C618	42.8	–
Specific Gravity (g/cm^3)	ASTM C128-88	2.746	

2.2.2. Testing procedure

In conducting the Marshall stability test, the prepared samples were immersed in a water bath at a temperature of 60 °C ± 1 °C for 2 h. Then the sample placed in the Marshall stability testing machine and loaded at a constant deformation rate of 51 mm/minute until failure. The total maximum load in kN (that causes failure of the specimen) was taken as Marshall Stability. The stability value so obtained was corrected for volume.

Tensile characteristics of the unmodified and CRM-modified asphalt mixtures were measured by loading the Marshall specimen

Table 5
Testing methods for evaluating the characteristics of CRM-modified asphalt mixtures.

Compaction method	Evaluated properties	Specimen dimension (mm)	Method of sampling	Testing methods	Number of sample
Marshall	Marshall stability, plastic flow, air voids content,	Diameter: 101.6, height: 63.5	ASTM D1559	ASTM D6927	78
	indirect tensile strength Tensile Strength Ratio (TSR)			ASTM D6931	156
Roller Sector Compactor	Rut depth, and dynamic stability (DS)	300 × 300 × 50	AASHTO T 324	AASHTO T 324	13

Table 6
Mechanism of mixing CRM with aggregates and asphalt.

Method	First mix	Second mix
Dry process	Aggregates + CRM = α	α + Asphalt
Wet process	Asphalt + CRM = β	β + aggregates
Complex process	Aggregates + Asphalt = γ	γ + CRM

along a diametric plane with the compressive load at a constant rate of 51 mm/minute acting parallel to and along the vertical diametrical plane of the sample through two opposite loading strips.

The WTT was performed at 60 °C to evaluate the permanent deformation performance (rutting) due to traffic loads at high temperature. The rolling wheel with a standard load of 0.7 MPa passed over the sample at a constant speed of 42 load cycles per minute for 60 min. To simulate the heavy loading and improve the rutting resistance all experiments were performed at 60 °C.

3. Results and discussions

3.1. Marshal stability

The results indicated that the Marshall stability of all mixing methods increased with the addition of CRM up to 12% and then decreased, while the CRM complex method presented a significant increase in the Marshall stability as illustrated in Fig. 3. It is observed that the ideal percentage of the CRM that improves the Marshall Stability considerably is 12%. At this percentage, the Marshall Stability values of CRM complex process mixtures increased by 49%, 17%, and 13% with respect to the control mixtures, dry, and wet methods' mixtures respectively when the CRM concentration increased from 6% to 12%, and those of dry and wet process

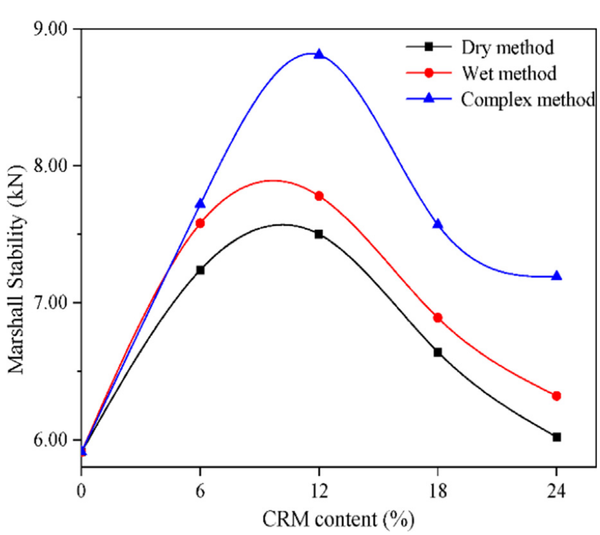

Fig. 3. Marshall Stability of the CRM-modified asphalt mixtures.

mixtures increased by 27% and 32% with respect to control mix respectively. Therefore, the complex method is playing a critical part in enhancing the Marshall stability of the asphalt mixtures. The % increase in Marshall Stability of a complex process with respect to the neat asphalt, dry, and wet methods' mixtures was showed in Table 7.

3.1.1. Mixtures volumetric

The volumetric proportions for control and CRM-modified bitumen mixtures was illustrated in Table 8. The standard deviation in Table 8 tells how the Marshall stability of a group are spread out from the average (mean). The low standard deviation at 12% and 18% CRM dry process, 6%, 18%, and 24% CRM wet process, and 12%, 18%, and 24% CRM complex process means that the most of the numbers are very close to the average. The high standard deviation at 6% and 24% CRM dry process, 12% CRM wet process, and 6% CRM complex process means that the Marshall stability values are spread out from the average.

3.2. Indirect tensile strength

The tensile strength values of the conditioned, as well as unconditioned specimens, were determined. The IDTS results of the CRM-modified bitumen mixtures with various CRM concentrations both the conditioned and unconditioned samples were showed in Fig. 4. The % decrease due to conditioning and % increase in strength with respect to control were illustrated in Table 9. It is evident that the results gained by the complex method showed the tensile strength and indirect tensile strength ratio (ITSR) higher than those obtained by wet and dry processes. Referring to Table 9 the consequence demonstrated that the tensile strength and the tensile strength ratio increased as the CRM concentration increased, reach a maximum value at 12% and then decreased.

The temperature-cracking and rutting are the primary distress mechanisms were evaluated in the current study by utilising the three CRM methods (e.g. dry, wet, and complex process). Because the results obtained from both the conditioned and unconditioned samples, thus the results can be utilised to assess the moisture susceptibility of the crumb rubber modified asphalt mixtures by using the tensile strength ratio (ITSR) which represented as the most significant measure of the water sensitivity.

By referring to Table 9, there was a reduction in the tensile strength with the sample conditioning regardless of the CRM content. It is clear from the results, the IDTS values in the complex process were far higher than those of dry and wet methods, as well as control samples. Variations of IDTS of the CRM-modified asphalt mixtures with different concentrations conditioned and unconditioned samples were given in Fig. 5. The variations of the tensile strength of the CRM-modified asphalt mixtures (three methods) demonstrated an increasing trend up to the CRM content 12%, and it is found to decrease with the CRM content increased.

The maximum tensile strength was achieved at 12% CRM content for both conditioned and unconditioned samples. The percentage increase in strength for the complex method mixtures with the

Table 7
The % increase in Marshall Stability of the complex method with respect to control, dry, and wet methods' mixtures.

CRM content (%)	Marshall Stability (kN)			% increase in Marshall Stability of a complex process with respect to		
	Dry process	Wet process	Complex process	Dry process	Wet process	Control
0	5.91	–	–	–	–	–
6	7.24	7.58	7.72	7	2	31
12	7.50	7.78	8.81	17	13	49
18	6.64	6.89	7.57	14	10	28
24	6.02	6.32	7.19	19	14	22

Table 8
Volumetric values of control and CRM-modified asphalt mixtures.

CRM method	CRM content (%)	Air void content (%)			
		Maximum	Minimum	Average	Standard deviation
Control	0	4.36	3.66	4.01	0.49
Dry	6	4.41	3.57	3.99	0.59
	12	4.10	3.93	4.02	0.12
	18	4.15	3.84	4.00	0.22
	24	4.44	3.66	4.05	0.55
Wet	6	4.25	3.96	4.11	0.21
	12	4.97	3.63	4.30	0.95
	18	4.28	4.16	4.22	0.08
	24	4.48	4.21	4.35	0.19
Complex	6	4.74	3.85	4.30	0.63
	12	4.59	4.27	4.43	0.23
	18	4.65	4.34	4.50	0.22
	24	4.68	4.43	4.56	0.18

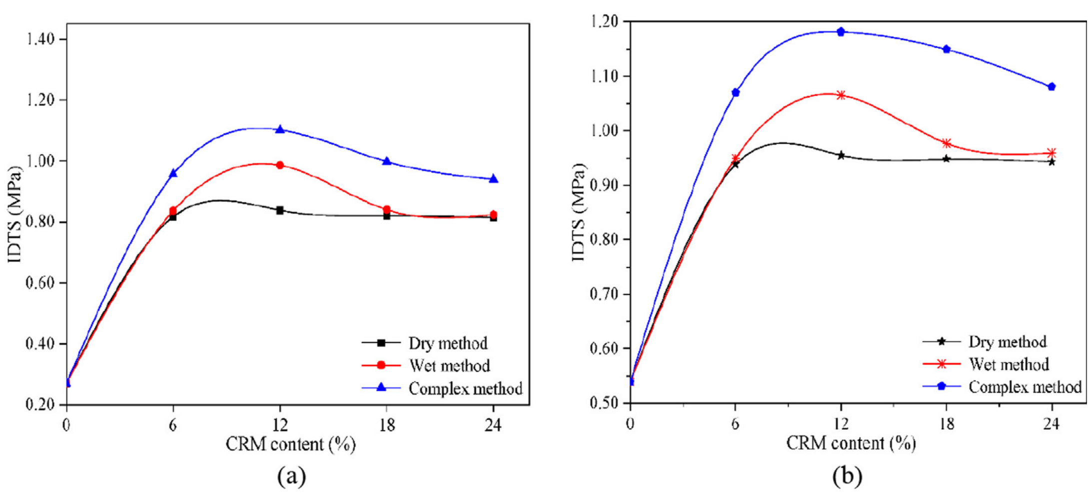

Fig. 4. IDTS of CRM-modified bitumen mixtures: (a) Conditioned, (b) Unconditioned.

concentration of 12% CRM with respect to control mixture is 308%, and 119% respectively for conditioned and unconditioned samples. Back to Table 9, the percentage increase in the IDTS in complex method samples concerning to the dry and wet methods' samples both conditioned and unconditioned were 31%, 24%, 12%, and 11% respectively. Thus, the CRM complex method mixtures have the highest tensile strength than those of wet and dry methods' mixtures.

3.2.1. Moisture susceptibility

Based on the indirect tensile strength test results, it can be conceivable to conclude that the IDTS values of CRM samples using complex process are much higher than those values obtained from the dry and wet methods and the effect is more influential in the conditioned case. Thus, complex process mixtures have a high strength followed by the wet and dry process mixtures. Although all the CRM complex process mixtures showed higher IDTS and ITSR, the addition of 12% CRM resulted in the higher tensile strength and exhibited the superior resistance to moisture susceptibility.

3.3. Wheel tracking test

3.3.1. Rut depth

The results demonstrated that the rut depth values obtained from the CRM complex method were far lower than those derived from the wet and dry processes and unmodified asphalt mixtures which range from 4.404 to 5.362 mm as shown in Fig. 6. The schematic diagram of the deformation versus time is illustrated in Fig. 7. The dynamic stability (DS) defined as the number of cycles

Table 9
The % decrease in strength due to conditioning and % increase in strength with respect to control.

CRM process	CRM content (%)	Indirect Tensile Strength (kPa)			% decrease in strength due to conditioning	% increase in strength with respect to control	
		Conditioned	Unconditioned	ITSR (%)		Conditioned	Unconditioned
Control	0	269.90	538.74	50.10	50		
Dry	6	817.08	938.19	87.09	13	203	74
	12	838.43	955.37	87.76	12	211	77
	18	820.01	948.19	86.48	14	204	76
	24	814.14	942.35	86.40	14	202	75
Wet	6	836.23	949.79	88.04	12	210	76
	12	986.05	1064.90	92.60	7	265	98
	18	840.01	976.86	85.99	14	211	81
	24	823.56	959.51	85.83	14	205	78
Complex	6	956.45	1068.69	89.50	11	254	98
	12	1101.96	1181.21	93.29	7	308	119
	18	997.82	1149.24	86. 82	13	270	113
	24	939.49	1080.83	86.92	13	248	101

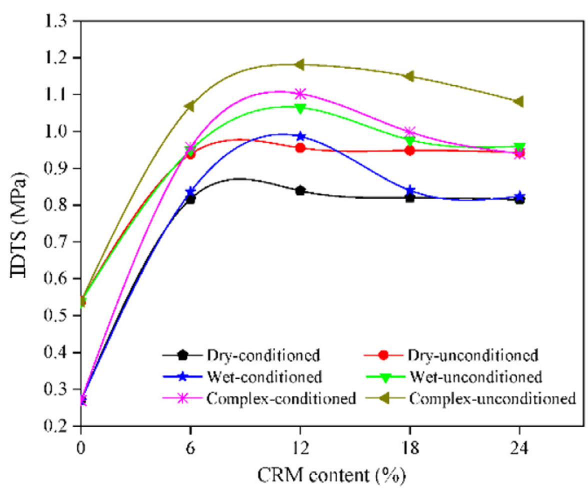

Fig. 5. Variation of IDTS of CRM-modified bitumen mixtures.

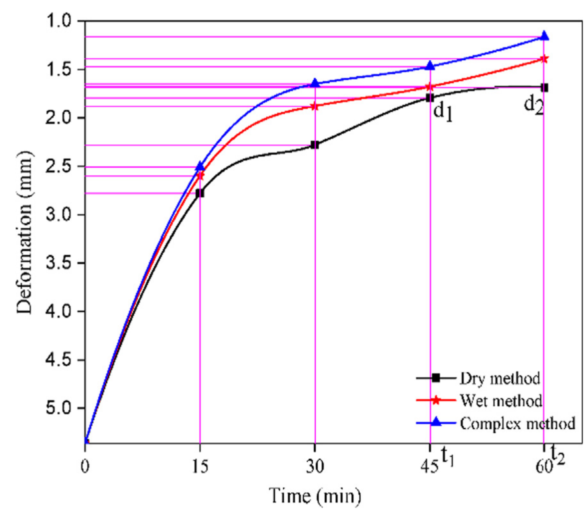

Fig. 7. Schematic diagram of deformation versus time.

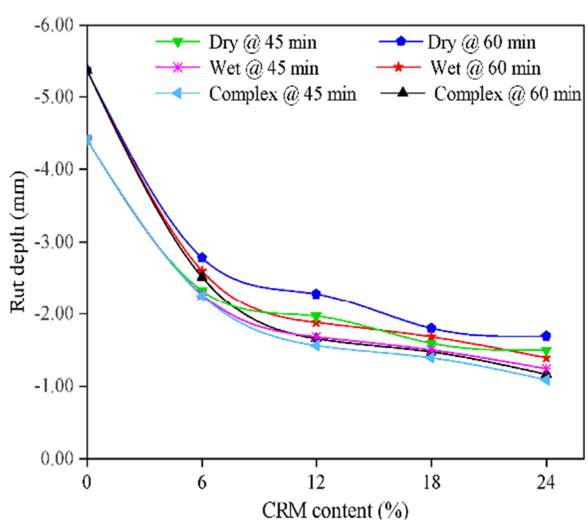

Fig. 6. Rut depth in the CRM-modified asphalt mixtures.

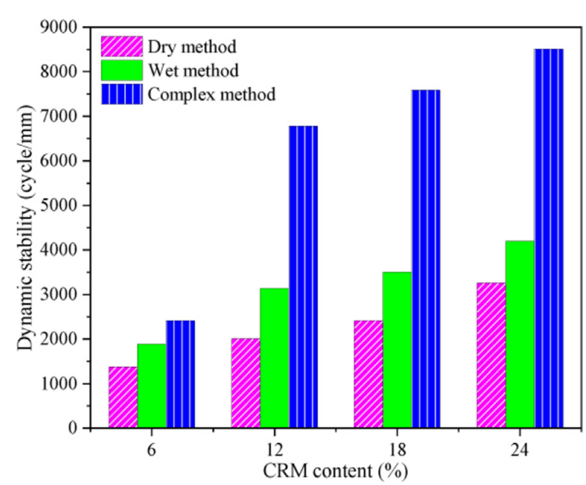

Fig. 8. The comparison between the DS obtained from the CRM-modified bitumen mixtures.

required to produce 1 mm of rut depth in the interval of testing time ranging from 45 to 60 min. The DS results were displayed in Fig. 8. It was observed that the DS increased with the increase of the CRM content.

In comparison, the dynamic stability of complex process specimens is hugely higher than those of wet and dry methods as appeared in Fig. 8. Also, observed that the effect of complex process CRM modification on the rutting resistance is thus more significant

Table 10
The % decrease of rut depth in complex method with respect to wet and dry methods.

CRM content (%)	Dry process		Wet process		Complex process		% decrease of RD in complex method with respect to wet and dry			
							Dry process		Wet process	
	d_1(mm)	d_2(mm)	d_1(mm)	d_2(mm)	d_1(mm)	d_2(mm)	d_1(%)	d_2(%)	d_1(%)	d_2(%)
6	2.321	2.779	2.265	2.599	2.251	2.512	3	10	0.6	3.3
12	1.965	2.278	1.677	1.878	1.559	1.652	21	27.5	7	12
18	1.789	2.05	1.499	1.679	1.388	1.471	22.4	28.2	7.4	12.4
24	1.495	1.688	1.239	1.389	1.088	1.162	27	31	12.2	16.3

than that using a dry and wet methods. The results indicated that the rate of rutting (RR) in the CRM-modified asphalt mixtures has a lower amount in the complex process in comparison with the dry and wet mixture methods with the same source of CRM and aggregate. Consequently, the CRM-modified bitumen mixtures using the dry and wet methods have less resistance against the permanent deformation. The % decrease of the rut depth in a complex process with respect to wet and dry methods is illustrated in Table 10. As a result, the CRM-modified asphalt mixtures utilised the complex method has the better resistance against the permanent deformation; thus, CRM-modified asphalt mixtures using complex method have the better performance than those of dry and wet method mixtures. It was noted that the utilisation of CRM-modified mixtures complex method resulted in the lowest rut depth followed by wet and dry processes. Thus, the usage of the CRM modifier as complex method could be encouraging to increase the service life of the pavement by the high traffic conditions.

4. Conclusions

From the consequences of the current study, the following conclusions can be drawn:

1. The obtained values of Marshal stability of the CRM complex method were higher than those of dry and wet methods.
2. Results indicated that the IDTS values of CRM samples using complex process are much higher than those values of dry and wet methods and the effect is more influential in the conditioned state.
3. It is observed from the results the CRM-modified asphalt mixtures achieved by the complex process have a higher ITSR; thus, the moisture susceptibility was improved significantly in CRM complex process better than wet and dry methods.
4. The consequences indicated that the rut depth values obtained from the complex process mixtures were less than those of the wet and dry mixes.
5. The utilisation of the CRM modifier complex method could be encouraging to increase the service life of the pavement by the high traffic conditions.

Note that this study investigated only the Marshall Stability, IDTS, ITSR, and rut depth (RD), further research is as yet needed to conduct the more experiments for implementation of the CRM complex process to ascertain the application of this method and conserve natural resources and preserve the environment.

Declaration of Competing Interest

The authors have no conflict of interest.

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