

Effects of ferrochromium slag with neat and polymer modified binders in hot bituminous mix

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In this study the properties of hot bituminous mix containing ferrochromium slag with neat and styrene-butadiene-styrene modified binders have been investigated. The ferrochromium slag is used as coarse aggregate and total aggregate. Three different binders, B 50/70, B 160/220 and B 160/220+3% SBS, are used in mixtures. The physical and mechanical properties of polymer modified binders and binder-aggregate mixes are evaluated in terms of their fundamental engineering properties such as dynamic shear rheometer (DSR), rotational viscometer (RV) for binders, Marshall stability, indirect tensile stiffness modulus, tensile strength and moisture susceptibility for mixtures. It has been concluded through the laboratory tests that using ferrochromium slag as coarse aggregate provided satisfactory results. The usage of ferrochromium slag as total aggregate does not exhibit good performance in terms of stability and stiffness modulus. However, the mixtures prepared entirely with ferrochromium slag showed good resistance to moisture damage. It is found that in spite of the similarity between high temperature performance grades of B 50/70 and B 160/220+3% SBS, the mechanical properties of the mixtures prepared with these binders do not show the same performance.

Keywords: Hot bituminous mix, Ferrochromium slag, Stability, Stiffness modulus, Moisture susceptibility

Hot bituminous mix (HBM) used in flexible pavements consists of aggregate for more than 90% by weight of mixture. The construction and maintenance of these pavements require large amount of aggregate resources. The aggregate resource management does not seem to be in line with the country's strategy for sustainable construction that requires for protecting the environment and minimizing the consumption of natural resources. Due to the great demand for aggregates, many mountains are being exploited which leads to the pollution and destruction of environment. The use of waste materials reduces the demand for extraction of natural resources. Prior to using waste materials in large scale it must be assessed in terms of the engineering, environmental and economical concerns¹⁻³. The earlier studies⁴⁻⁶ indicate that the addition of steel slag enhances the performance characteristics of the pavement by improving its skid resistance. The high specific gravity and angularity of the steel slag provide good interlocking in hot bituminous mix, thus leading to more stability and resistance to rutting. The waste materials such as ferrochrome slag⁷, waste glass⁸, marble dust⁹ and plastic items^{10,11} have been

used as aggregate in the hot bituminous mix and the studies indicate that using of this waste materials improves the mechanical properties of hot bituminous mix. Yilmaz and Sutas¹², investigated ferrochromium slag to be used in base layer of road pavements. The results proved that ferrochromium slag could be used for granular layers of road pavements instead of natural aggregate in terms of its physical and mechanical characteristics.

Ferrochrome slag is a by-product obtained from the production of ferrochrome that is an essential component in stainless steel. Ferrochromium is a master alloy of iron and chromium, containing 45-80% Cr and various amounts of Fe, C and other elements¹³. Ferrochromium is produced pyrometallurgically by carbothermic reduction of chromite ore ($\text{FeO} \cdot \text{Cr}_2\text{O}_3$)¹³. The study shows that 1.3 million tons of ferrochromium slag is expected to remain inactive until 2009 and this value increases about 100,000 tons per year in Elazığ Ferrochromium Factory¹⁴.

The rheological behaviour of bitumen is a very complex phenomenon varying from being purely viscous to elastic depending on loading time and temperature. As a visco-elastic material, bitumen plays a prominent role on determining many aspects

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of road performance. Bituminous binders need to be flexible enough at low temperatures to prevent pavement cracking and to be stiff enough at high temperatures to prevent permanent deformation. Numerous investigations have been carried out on incorporating polymer modified bitumens to satisfy flexible pavement at low temperatures and provide stiff pavement at high temperatures. Among polymers, the elastomer styrene-butadiene-styrene (SBS) block copolymer is the one used most widely. Most of the results obtained from laboratory and full-scale trials demonstrate an improvement in the performance of SBS modified bituminous mixes in terms of increased resistance to permanent deformation, improvement in fatigue life, improved durability and resistance to moisture damage¹⁵⁻¹⁷.

In this study ferrochromium slag obtained from Elazığ ferrochromium production plant was used as aggregate in hot bituminous mix. Neat binders and the SBS modified binders were used in order to investigate the effects of polymer modified binder on the mixture including ferrochromium slag. The usage of ferrochromium slag as aggregate was investigated by subjecting the specimens to Marshall stability and flow, indirect tensile stiffness modulus, tensile strength and moisture susceptibility tests.

Table 1—The gradation of aggregate

Sieve size	Total cumulative passing (%)
19 mm (3/4")	100
12.5 mm (1/2")	95
9.5 mm (3/8")	88
4.75 mm (# 4)	65
2.36 mm (# 8)	39
1.18 mm (# 16)	24
0.600 mm (# 30)	18
0.300 mm (# 50)	14
0.150 mm (# 100)	10
0.075 mm (# 200)	6

Table 2—The physical properties of aggregate

Properties	Standard	Aggregate					
		Limestone			Ferrochromium slag		
		Coarse	Fine	Filler	Coarse	Fine	Filler
Los Angeles abrasion, (%)	ASTM C131	21	-	-	16.4	-	-
Frost action, (%) (with Na ₂ SO ₄)	ASTM C88	5.32	-	-	4.13	-	-
Specific gravity	ASTM C127	2.629	-	-	2.772	-	-
Specific gravity	ASTM C128	-	2.677	-	-	3.016	-
Specific gravity	ASTM D854	-	-	2.690	-	-	3.125

Materials and Methods

Ferrochromium slag and limestone were used as aggregate for the asphalt mixtures. A crushed coarse and fine aggregate of ferrochromium slag and limestone with maximum size of 19 mm, were selected for a dense-graded asphalt mixture. The gradation of the aggregate is shown in Table 1¹⁸. The physical properties of ferrochromium slag and limestone aggregates and the chemical properties of ferrochromium slag are given in Tables 2 and 3, respectively.

Two types of neat asphalt cement, B 50/70 and B160/220, obtained from Turkish Petroleum Refineries were used as binder for mixture preparation. The B 160/220 asphalt was also modified with different SBS (Kraton D 1101) contents in order to achieve the same high temperature performance grade of B 50/70 asphalt cement according to ASTM D 6373¹⁹. For this purpose five different SBS contents varying from 1% to 5% were tested in modification. The SBS modified bitumens were prepared by using the propeller mixer. The asphalt binder was heated to 150°C for 1 h and then subjected to mixing process with SBS at 175°C and the shear rate of 500 RPM for 1.5 h. Neat and modified binders were subjected to aging processes by using rolling thin film oven test (RTFOT) according to ASTM D 2872²⁰. The physical properties of neat and modified asphalts are given in Table 4.

Dynamic shear rheometer (DSR) test

The DSR test was performed on all bitumens by using a Bohlin DSR II rheometer under controlled-stress loading (120 Pa for neat binders and 220 Pa for RTFOT residues) conditions at a constant frequency

Table 3—The chemical properties of ferrochromium slag

SiO ₂ (%)	Al ₂ O ₃ (%)	MgO (%)	Cr ₂ O ₃ (%)	FeO (%)	CaO (%)
30.47	31.09	33.66	3.4	0.69	0.49

Table 4-Properties of binders

Property	Standard	Binder type						
		B 50/70	B 160/220	PMB ₁	PMB ₂	PMB ₃	PMB ₄	PMB ₅
Penetration (0.1 mm), 100 g, 5 s	ASTM D5	68	190	129	115	98	80	71
Softening point (°C)	ASTM D36	51.7	40.9	46.1	48.9	50.9	56.7	61.3
Specific gravity	ASTM D70	1.039	1.035	1.034	1.031	1.029	1.029	1.027
Penetration index (PI)	-	-0.016	0.123	0.424	0.86	0.868	1.64	2.251
After RTFOT								
Mass loss (%)	ASTM D2872	0.442	0.935	0.911	0.884	0.87	0.763	0.651
Penetration (0.1 mm), 100 g, 5 s	ASTM D5	47	97	71	62	59	51	48
Retained penetration (%)	ASTM D5	69	51	55	54	60	64	68
Softening point (°C)	ASTM D36	59.9	50.3	55.2	57.6	59.7	65	69.2
Increase in Sof. Point (°C)	ASTM D36	8.2	9.4	9.1	8.7	8.8	8.3	7.9
Penetration index (PI)	-	0.855	0.673	0.943	1.097	1.4	2.027	2.593

of 10 rad/s and temperatures between 52°C and 82°C with an increment of 6°C. The tests were carried out using samples with a diameter of 25 mm and 1 mm gap and parallel plate testing geometry was employed.

The principal viscoelastic parameters obtained from the DSR were the complex shear modulus (G^*), and the phase angle (δ). G^* is defined as the ratio calculated by dividing the absolute value of the peak-to-peak shear stress by the absolute value of the peak-to-peak shear strain²¹. The phase angle defined above is the phase difference between peak stress and peak strain in an oscillatory test²². G^* and δ are used in two ways in the SHRP specifications. The parameter of resistance to permanent deformation ($G^*/\sin\delta$) is controlled by limiting to at least 1000 Pa before ageing in RTFOT and at least 2200 Pa after ageing.

Rotational viscometer test

A Brookfield viscometer (DV-III) was used for the viscosity tests on the neat and modified bitumen. The viscosity-temperature relationship was developed to determine the mixing and compaction temperatures²³. The rotational viscosity was determined by measuring the torque required to maintain a constant rotational speed (20 rpm) of a cylindrical spindle while submerged in bitumen maintained at a constant temperature. The mixing and compaction temperatures of the mixtures were determined according to results of rotational viscometer tests.

Preparation of the mixtures and Marshall stability and flow test

In this study the ferrochromium slag was used as both coarse aggregate and total aggregate of the

mixtures (35 % total aggregate by weight) in order to determine the effects of the ferrochromium slag clearly. Furthermore three types of binders were used, one of which was SBS modified. The mixtures were produced in seven different combinations. These different combinations allow to compare to each other and to determine the effects of using ferrochromium slag as aggregate and also to determine the effects of using SBS modified binder together with the ferrochromium slag in hot bituminous mix. The mix design of the asphalt mixtures was conducted by using the standard Marshall mix design procedure with 75 blows on each side of cylindrical samples (10.16 cm in diameter and 6.35 cm thick). Marshall samples were compacted and tested by deploying the following standard procedures: Bulk specific gravity (ASTM D2726²⁴), stability and flow test (ASTM D6927²⁵), and maximum theoretical specific gravity (ASTM D2041²⁶). The optimum binder contents were found for unmodified mixtures. They were chosen for SBS modified mixtures so that the amount of binder would not confound the analysis of the test data. The mixtures types and optimum bitumen contents are given in Table 5. The volumetric properties of mixtures are given in Table 6.

The Marshall stability and flow test were applied to normal and conditioned specimens in order to determine the effects of water. The specimens were separated into two groups; each consists of 21 specimens and the average specific gravity of the specimens of each group is equal. The first group of specimens was immersed in water at 60°C for 30 min and then loaded to failure by using curved steel

loadings plates along with a diameter at a constant rate of compression of 51 mm/min. The stability and flow and also the ratio of stability (kN) to flow (mm), stated as the Marshall quotient (MQ), and as an indication of the stiffness of mixes were determined. The second group of specimens (conditioned specimens) were placed in water bath at 60°C for 24 h. and then the same loading as described above was applied. The retained Marshall stability (RMS) was then found through the average stability of each group using the following formula,

$$\text{RMS} = \frac{MS_{\text{cond}}}{MS_{\text{uncond}}} \times 100 \quad \dots (1)$$

where RMS is retained Marshall stability, MS_{cond} is average Marshall stability for conditioned specimens (kN) and MS_{uncond} is average Marshall stability for unconditioned specimens (kN).

Indirect tensile stiffness modulus test

The indirect tensile stiffness modulus is a non-destructive test that can be used to evaluate the relative quality of materials and to study effects of temperature and load rate. The repeated-load indirect tensile stiffness modulus (ITSM) test defined by BS DD 213²⁷ has been identified as a potential means of

measuring this property. The ITSM S_m in MPa is defined as,

$$S_m = \frac{F(R + 0.27)}{LH} \quad \dots (2)$$

where F is the peak value of the applied vertical load (repeated load, N), H is the mean amplitude of the horizontal deformation (mm) obtained from 5 applications of the load pulse, L is the mean thickness of the test specimen (mm), and R is the Poisson's ratio (assumed 0.35). 42 specimens were prepared for ITSM test. The test was done via the universal testing machine (UTM) in deformation-controlled mode. The magnitude of the applied force was adjusted by the system during the first five conditioning pulses such that the specified target peak transient diametral deformation was achieved. A value was chosen to ensure that the sufficient signal amplitudes are obtained from the transducers in order to produce consistent and accurate results. The value was selected as 6 micrometers in this test. The rise time, which is measured from when the load pulse commences and taken for the applied load to increase from zero to a maximum value, was set at 124 ms. The load pulse application was equated to 3.0 s.

Table 5—The contents of mixtures

Specimen types	Coarse aggregate	Fine aggregate + Filler	Binder	Optimum binder content (%)
C2	Limestone	Limestone	B 160/200	4.885
C1	Limestone	Limestone	B 50/70	4.905
SL	Ferrochromium slag	Limestone	B 50/70	5.093
S	Ferrochromium slag	Ferrochromium slag	B 50/70	5.345
PL	Limestone	Limestone	B 160/220 + %3 SBS	4.905
PSL	Ferrochromium slag	Limestone	B 160/220 + %3 SBS	5.093
PS	Ferrochromium slag	Ferrochromium slag	B 160/220 + %3 SBS	5.345

Table 6—Volumetric properties of the mixtures

Specimen types	Binder content (%)	Mix density (D_p , g/cm ³)	Air void content (V, %)	Voids in mineral aggregate (VMA, %)	Voids filled with asphalt (V_f , %)
C2	4.885	2.400	3.21	14.02	77.09
C1	4.905	2.403	3.08	13.90	77.84
SL	5.093	2.420	3.53	15.02	76.52
S	5.345	2.569	4.02	16.81	76.06
PL	4.905	2.397	3.32	14.12	76.46
PSL	5.093	2.416	3.68	15.15	75.70
PS	5.345	2.561	4.35	17.10	74.53

Tensile strength test

In the tensile strength test (TS), cylindrical specimens were subjected to compressive loads, which act parallel to the vertical diametral plane by using the Marshall loading equipment. This type of loading produces a relatively uniform tensile stress, which acts perpendicular to the applied load plane, and the specimen usually fails by splitting along with the loaded plane. Based upon the maximum load carried by a specimen at failure, the TS in kPa is calculated through the following equation,

$$TS = \frac{2F}{\pi LD} \quad \dots (3)$$

where F is the peak value of the applied vertical load (kN); L is the mean thickness of the test specimen (m); and D is the specimen diameter (m). The tensile strength test was used for the determination of the asphalt concrete mixture moisture susceptibility in accordance with ASTM D 4867²⁸. The effects of ferrochromium slag and usage of SBS modified binder together with the ferrochromium slag on moisture-induced damage of asphalt concrete mixtures were evaluated. Totally 105 specimens were prepared for TS test. Three unconditioned (dry) and three conditioned (wet) specimens were tested for each group of mixtures. Wet specimens were vacuum-saturated with distilled water so that 50 to 80% of their air voids were filled with water and then they were wrapped tightly with plastic film. The specimens were placed into a leak-proof plastic bag containing approximately 3 mL of distilled water. Wet specimens then were subjected to successive freeze-thaw cycling. One freeze-thaw cycle consists of freezing for 16 h at -18°C , followed by soaking in a 60°C water bath for 24 h. Different number of freeze-thaw cycles such as 1, 2, 3 and 4 were applied to mixtures to determine obviously the effects of water on the mixture containing ferrochromium slag. At the end of the each cycle the bag and the wrapping were removed and were placed in a water bath for 1 h at 25°C before being subjected to failure. The tensile strength of dry specimens was determined directly. Dry specimens were only placed in a water bath for 1 h at 25°C before being subjected to failure. The tensile strength ratio (TSR) was found through following equation,

$$TSR = \frac{P_{cond}}{P_{uncond}} \times 100 \quad \dots (4)$$

where P_{cond} is the tensile strength of the wet specimens and P_{uncond} is the tensile strength of the dry specimens. The TSR value is considered to be higher than 0.70 after first freeze-thaw cycle by most of agencies.

Results and Discussion

Tests on binders

The DSR results of unaged neat binders (B 50/70 and B 160/220) and 1%-5% SBS modified B 160/220 named as PMB₁-PMB₅ are given in Fig. 1. The DSR results and calculations showed that the values of rutting resistance parameter ($G^*/\sin\delta$) of B 160/220 increased as the SBS content increased. PMB₃ binder (B 160/220 + 3%SBS) exhibited similar properties to B 50/70 in terms of high temperature performance grade and softening point. Therefore B 50/70 binder as well as PMB₃ was used to investigate whether the mixtures containing B 50/70 and PMB₃ would exhibit similar attitude at performance tests. The DSR results of aged binders are given in Table 7. It is seen from Table 7 and Fig.1 that while the unaged B 50/70 and PMB₃ have similar effects, the aged ones do not.

In Table 8, the viscosity of binders and mixing-compaction temperatures are given by using the

Table 7—DSR results of aged binders

Binder	Temperature (°C)	G^* (Pa)	δ (°)	$G^*/\sin\delta$ (Pa)
B 50/70	70	3487.03	74.92	3611.40
B 160/20	58	5086.33	72.53	5332.26
B 160/200 + 1%SBS	64	4579.95	69.92	4876.45
B 160/200 + 2%SBS	64	5952.83	65.75	6528.93
B 160/200 + 3%SBS	70	4664.91	67.11	5063.48
B 160/200 + 4%SBS	70	4431.95	66.47	4833.89
B 160/200 + 5%SBS	76	5159.19	60.68	5917.20

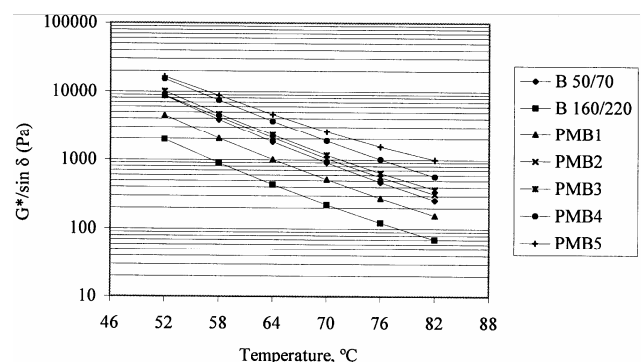


Fig. 1—DSR results of binders versus temperature

viscosity values of 170 ± 20 cP and 280 ± 30 cP, respectively. The viscosities of PMB₃ for 135°C and 165°C are higher than that of B 50/70 by 50% and 75% respectively.

Tests on bitumen aggregate mixes

Marshall stability and flow test

The Marshall stabilities and flows and MQ values are given in Table 9 for each mixture. The values are the average of three samples. The Marshall stabilities of the mixtures are shown in Fig. 2. It is seen that the SL mixture, which includes ferrochromium slag as coarse aggregate, has the highest stability within all

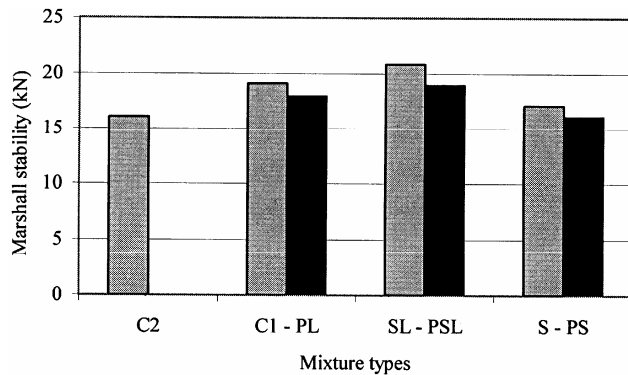


Fig. 2—Marshall stabilities of the mixtures

type of the mixtures. The stability values of SL mixtures are higher than those of the C2 and C1 control mixtures. A decrease was observed in the stability value of the mixture (S) containing ferrochromium slag as total aggregate. Due to the similar high temperature performance grades of B 50/70 and PMB₃, the stability values of the mixtures prepared with these binders are expected to be similar. On the contrary it is seen that the stability values of the mixtures prepared with PMB₃ are lower than that of the mixtures prepared by B 50/70. However, the stability values of the PL and PSL were found to be higher than that of the C2 control mixture by 12% and 18%, respectively. It is seen from Table 9 that the mixtures containing ferrochromium slag have the lowest flow values; especially the usage of the ferrochromium slag as total aggregate (S) decreased the flow value significantly. As for the conditioned specimens the PS mixture has the lowest flow value and hence the highest MQ. According to these results it is considered that the ferrochromium slag shows difference in texture from limestone especially in porosity characteristic and this difference makes slag surface texture rougher than limestone and it is a factor affecting their adhesion ability with asphalt binder. The retained Marshall stability values of the

Table 8—Viscosity values and mixing-compaction temperatures of binders

Binder type	Viscosity (cP)		$\eta_{\text{modified}}/\eta_{\text{neat}}$		Temperature range (°C)	
	135°C	165°C	135°C	165°C	Mixing	Compaction
B 50/70	525	150	-	-	159-165	148-153
B 160/220	237.5	87.5	1	1	142-149	127-133
PMB ₁	387.5	125	1.63	1.42	154-160	141-147
PMB ₂	562.5	187.5	2.36	2.14	165-171	151-157
PMB ₃	787.5	262.5	3.31	3	174-180	161-166
PMB ₄	1113	362.5	4.68	4.14	182-189	169-175
PMB ₅	1650	462.5	6.94	5.28	186-192	174-180

Table 9—Results of Marshall stability and flow test

Specimen types	Stability, 30 min. at 60°C, MS ₁ (kN)	Flow, F ₁ (mm)	MQ ₁ , MS ₁ /F ₁ (kN/mm)	Stability, 24 h at 60°C MS ₂ (kN)	Flow, F ₂ (mm)	MQ ₂ , MS ₂ /F ₂ (kN/mm)	RMS, MS ₂ /Δ (%)
C2	16.04	3.12	5.14	12.40	4.02	3.08	77
C1	19.11	3.54	5.40	14.90	3.65	4.08	78
SL	20.84	3.22	6.28	17.05	3.90	4.37	82
S	17.10	2.56	6.68	13.74	2.72	5.05	80
PL	17.94	3.23	5.55	13.44	3.48	3.86	75
PSL	18.97	3.17	5.98	15.71	3.74	4.20	83
PS	16.12	2.64	6.10	12.41	2.29	5.42	77

mixtures are given in Fig. 3. The mixtures containing ferrochromium slag were found to be more resistant to water effect than control mixtures. The PSL mixture has superior retained Marshall stability value compared to others. However the RMS value of PL and PS mixtures prepared by PMB₃ were not higher than those of the C1 and S mixtures respectively. This indicates that the usage of the polymer-modified binders is more suitable for the mixtures containing ferrochromium slag as coarse aggregate.

Indirect tensile stiffness modulus test

All types of specimens were subjected to indirect tensile stiffness modulus test (ITSM) at three different temperatures as 5°C, 20°C and 35°C. The average stiffness modulus results obtained from seven different types of mixtures are given in Fig. 4. Each value was obtained from three specimens. Stiffness modulus values were the highest at 5°C and the lowest at 35°C. It is seen that the SL mixture, which includes ferrochromium slag as coarse aggregate, has the highest stiffness modulus among all types of the mixtures at all temperatures. The stiffness values of all mixtures tend to converge at high temperatures. The results indicate that the stiffness modulus values of the SL mixtures are higher than that of the control mixture (C1) by 17% at 35°C. This rate reaches to 25% at 5°C. The usage of slag as total aggregate did not improve the stiffness modulus value compared to control mixture (C1) both of which were prepared by B 50/70. ITSM values of the mixtures prepared by PMB₃ were lower than those of the mixtures prepared by B 50/70. However, the PSL mixtures had higher ITSM by 23% than that of the PL mixtures at 5°C. The PSL mixtures showed the best performance within the mixtures prepared by PMB₃. The usage of slag as coarse aggregate with 3% SBS modified B 160/220 increased the ITSM by 40% and 55% compared to control mixture (C2) at 5°C and 35°C respectively.

Tensile strength test

Average tensile strengths of the mixtures under different freeze-thaw cycles are given in Fig. 5. It can be seen that the tensile strengths for all mixtures decrease as the number of freeze-thaw cycles increase. The tensile strength of the SL mixture was higher than those of the other mixtures after the same number of freeze-thaw cycles. The C2 control mixture not including ferrochromium slag and prepared with B160/220 binder, which is softer than B 50/70,

showed the least tensile strength. The tensile strength values of the PL, PSL, PS mixtures prepared with PMB₃ were lower than those of the C1, SL, S mixtures prepared with B 50/70 respectively. Despite the high temperature performance grades of B 50/70 and PMB₃ were similar, the mixtures prepared with these binders did not exhibit the same performance

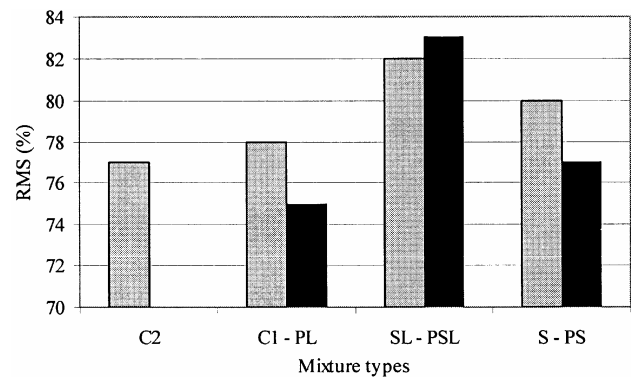


Fig. 3— Variation on the RMS of the mixtures

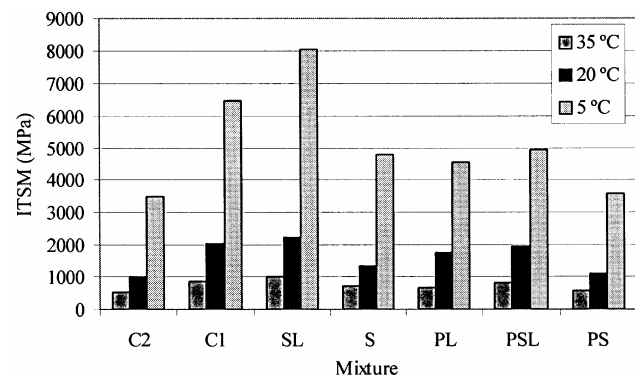


Fig. 4— ITSM values of the mixtures at different temperatures

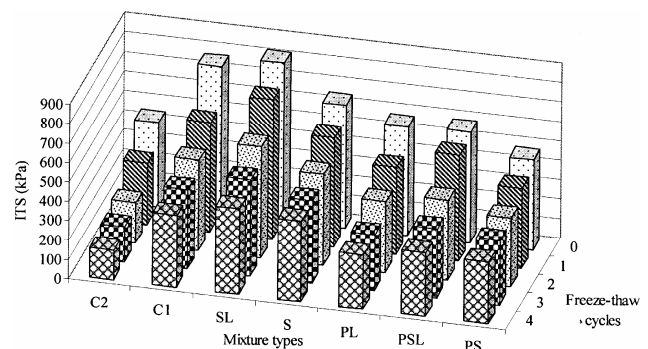


Fig. 5— Variation on TS of the mixtures under different freeze-thaw cycles

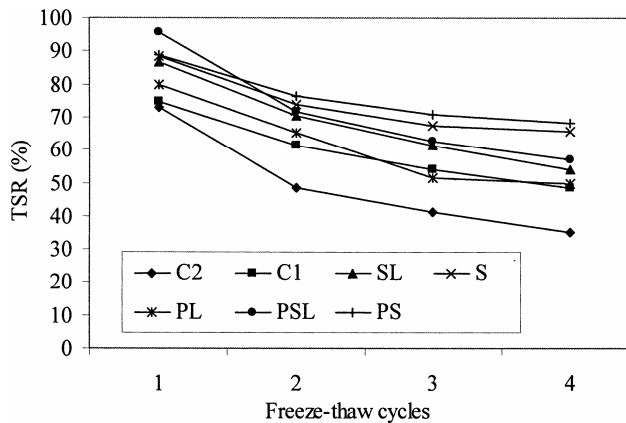


Fig. 6— Tensile strength ratios of the mixtures

under different freeze-thaw cycles. The tensile strength ratios of the mixtures are given in Fig. 6. A TSR value above 70% is suggested as a criterion for a mixture resistant to moisture damage. It is seen that all type of mixtures fulfilled the criterion of 70% after the first freeze-thaw cycle. While the TSR values of the control (C1, C2) and PL mixtures remained below 70% after the second cycle, the values of SL, PSL, S and PS remained above 70%. The tensile strength ratio of PS mixture remained above 70% after the third cycle; this constitutes the least reduction in TSR. None of the mixtures provided 70% TSR after the fourth cycle; however the TSR value of PS mixture was higher than those of the other mixtures even after the fourth cycle. While the TSR value of the mixtures ranges as $PSL > PS > SL > S > PL > C1 > C2$ after the first freeze-thaw cycle, the ranking changes as the cycle number increases. It was determined that the mixtures containing ferrochromium slag had the highest tensile strength ratio after final period and the TSR values of the mixtures ranged as $PS > S > PSL > SL > PL > C1 > C2$. Besides, the mixtures prepared with PMB_3 had higher TSR value than the mixtures containing B 50/70.

Conclusions

The following conclusions were drawn based on the laboratory test results:

- (i) The DSR results and calculations showed that 3% SBS modified B 160/220 and B 50/70 belong to the same high temperature performance grade, PG 70. These binders have also similar properties in terms of softening point. However, they have different mixing and compaction temperatures.
- (ii) In the Marshall stability test, SL mixture, which includes ferrochromium slag as coarse

aggregate, had the highest stability among all types of the mixtures. The mixtures containing slag had the lowest flow values. Especially the usage of the ferrochromium slag as total aggregate (S) decreased the flow value significantly. The mixtures containing ferrochromium slag were more resistant to water effect than the control mixtures according to retained Marshall stabilities. The PSL mixture had the superior retained Marshall stability value compared to others.

- (iii) In the indirect tensile stiffness modulus tests, the SL mixture was found to have the highest stiffness modulus among all type of the mixtures at all temperatures. The stiffness modulus values of the SL mixtures were higher than that of the control mixture (C1) by around 17% at 35°C. This rate increased to 25% at 5°C.
- (iv) In the tensile strength test, it was obtained that the tensile strength of the SL mixture was higher than those of the other mixtures after the same number of freeze-thaw cycles. The C2 control mixture not including ferrochromium slag and prepared with B160/220 binder, which is softer than B 50/70, showed the least tensile strength. It was determined that all types of mixtures fulfilled the criterion of the 70% after the first freeze-thaw cycle. The mixtures containing ferrochromium slag had the highest tensile strength ratio after the final period. Only the tensile strength ratio of PS mixture remained above 70% after the third cycle so the PS mixture showed the least reduction in TSR. The mixtures prepared with PMB_3 had higher TSR values than the mixtures containing B 50/70.
- (v) Despite the similarity of high temperature performance grades of B 50/70 and PMB_3 , the mechanical properties of the mixtures prepared with these binders did not show the same performance.

It was concluded through the laboratory tests that the usage of ferrochromium slag as coarse aggregate provided satisfactory results. The usage of ferrochromium slag as total aggregate did not exhibit good performance in terms of stability and stiffness. However the mixtures prepared entirely with ferrochromium slag showed good resistance to moisture damage. The usage of this mixture can be available for the pavements, which are exposed to severely water effects and have lower traffic volumes.

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