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Tesis

Variation of Mechanical Properties and Temperature Control in Hot Asphalt Mixtures Through the Incorporation of Glass Powder, Province of Huancayo

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Abstract Asphalt is a material composed of a mixture of various hydrocarbons of natural origin. In Peru, almost all of the paved roads are made of hot asphalt mixtures, some of which are constructed at altitudes exceeding 3000 meters above sea level (m.a.s.l.). However, maintaining the mixture temperature at the optimal level for placement and compaction is challenging. The difficulty in temperature control arises from the location of the asphalt plant, often due to a lack of aggregates that are situated far from the area where the asphalt mixture is to be placed. This study underscores the significance of improving the mechanical properties and extending the temperature sustainability of hot asphalt mixtures by incorporating glass powder-modified asphalt bitumen—a topic with limited literature in Peru. Tests were conducted on 93 Marshall specimens and 5 viscosity control points, divided into two groups: one for conventional asphalt mix and another for glass powder-modified mix. The results revealed substantial enhancements in stability, flow, and Lottman tensile strength when 3% of glass was added to the asphalt bitumen, along with a reduction in mixture temperature when 2% of glass was incorporated, resulting in a cooling effect during the addition of glass. In conclusion, glass-modified asphalt mix demonstrated a positive influence on its mechanical properties and the cooling process, making it a more effective choice for field applications.

Keywords Asphalt Bitumen, Stability and Flow, Glass Powder

1. Introduction

The construction and maintenance of roads and pavements have been fundamental aspects of urban and economic development [1]. In the past, ensuring the durability and safety of these structures necessitated the use of high-quality materials. One key material in pavement construction was hot asphalt mix.

Numerous studies have delved into this subject matter. For instance, Rondón-Quintana et al [2] focused on the compaction temperature of hot asphalt. Another noteworthy study by Reyes Ortiz et al [3] evaluated the effects of partial and total replacements of aggregates with Recycled Asphalt Pavement (RAP). Additionally, Atuesta et al [4] undertook a project related to productivity and variability measures in asphalt layer construction.

In this context, the current study centers on analyzing the mechanical properties of hot asphalt mixtures with asphalt bitumen modified by glass powder. At the time, the inclusion of glass powder in asphalt bitumen aimed to maintain temperature and enhance the mechanical properties of the asphalt mix. Thus, the primary objective of this thesis was to determine the extent to which glass powder-modified asphalt bitumen improved the mechanical properties of hot asphalt mixtures and contributed to the extension and maintenance of mix temperature.

The results obtained in this study provided a clearer understanding of how the inclusion of glass powder in asphalt bitumen could optimize the performance of asphalt mixtures used in pavements, enhancing their durability and safety under real-world usage conditions. In this manner, the aim was to advance the development of more efficient and sustainable construction materials that could benefit road infrastructure and the overall development of communities at that time.

2. Materials and Methods

Asphalt is a material composed of a mixture of various natural-origin hydrocarbons, whose excellent binding and hydrophobic properties have led to its widespread use in applications ranging from waterproofing to road construction [5].

In Figure 1, the location of the Jun ńdepartment, where the province of Huancayo is situated, and the study area at an altitude of 3,259 meters above sea level (m.a.s.l.), is depicted. Its geographical coordinates are a West longitude of 75 °12' 17.5", South latitude of 12 °3' 54.47", UTM Zone 18, and Latitudinal Band L [6]. Figure 2 displays the location of the Huancayo province, specifically the Pilcomayo district where the quarry under study is located at an altitude of 3,201 m.a.s.l. Its geographical coordinates are a West longitude of 75 °15' 28.18", South latitude of 12 ° 2' 50.45", UTM Zone 18, and Latitudinal Band L.

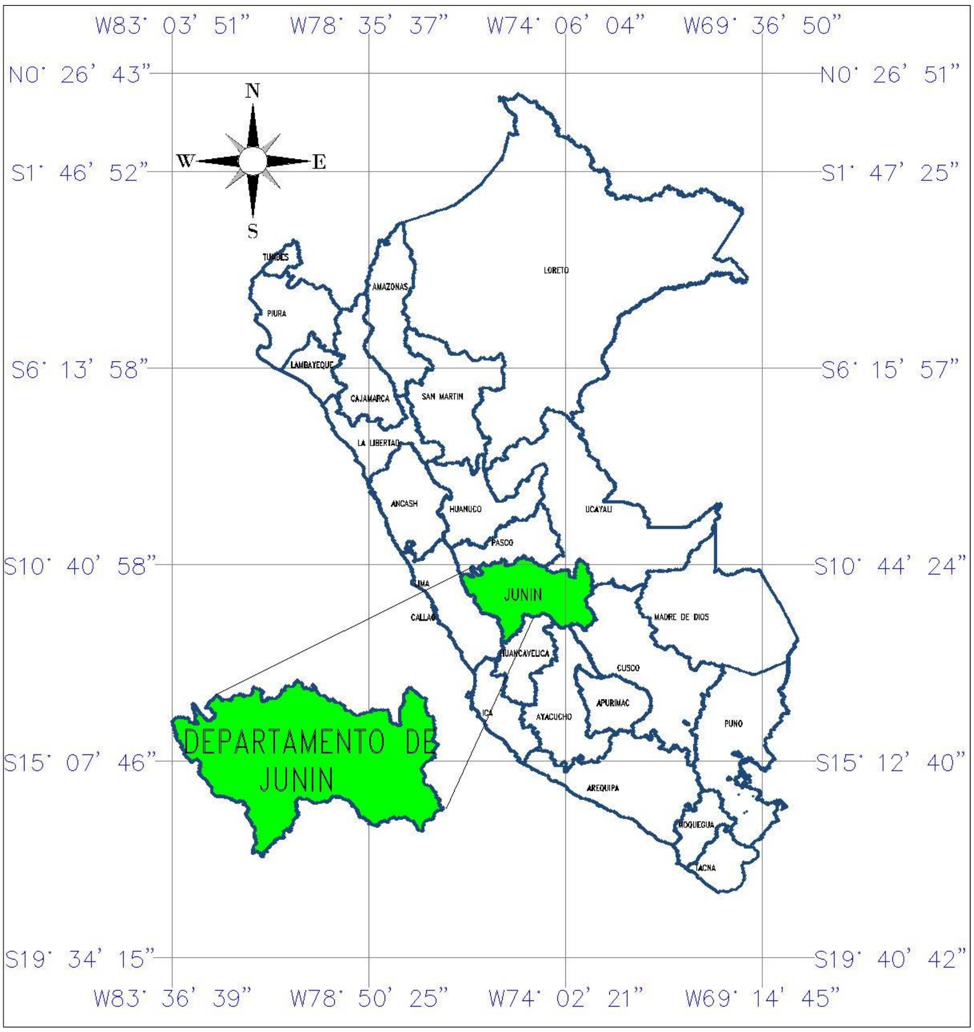

Figure 1. Departmental Location

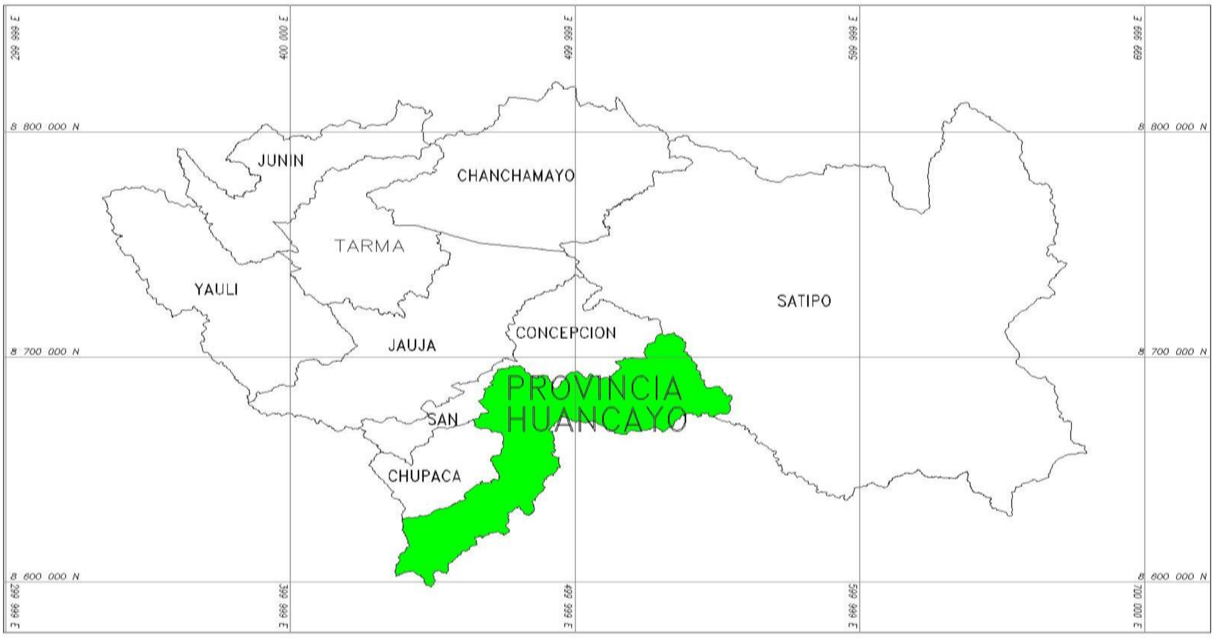

Figure 2. Quarry in the Province of Huancayo

At the project's outset, all laboratory tests were conducted, designed to simulate conditions close to real life. Firstly, a quarry study was carried out in Pilcomayo, part of the province of Huancayo in the Jun ń region. In this study, both coarse aggregates (crushed stone) and two types of fine aggregates (crushed sand and screened sand) were analyzed.

The tests conducted were as follows, as shown in Figure 3:

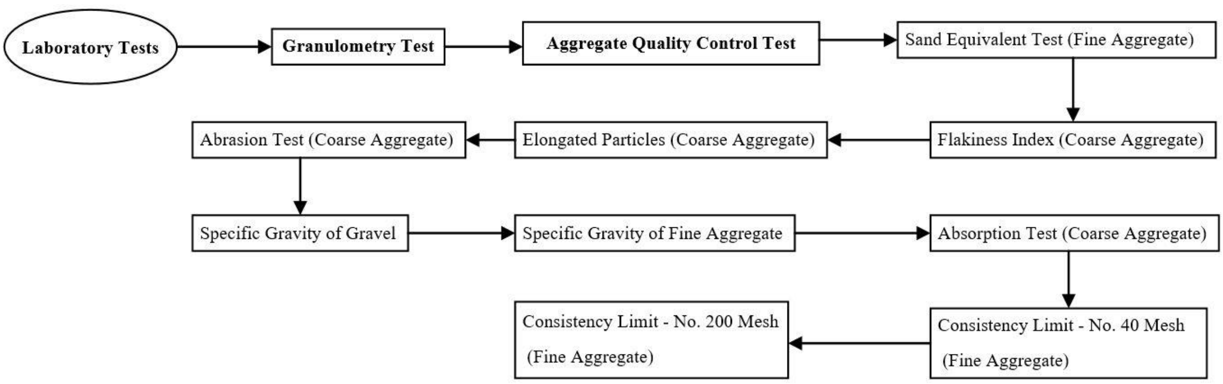

Figure 3. Flowchart of the granulometry test

Upon completion of the quality controls, the following test was conducted:

Asphalt Mix Design using the Marshall Method

The purpose of this test is to determine the optimum asphalt content [7]. For this, 3 briquettes weighing 1220 grams were prepared for each percentage of asphalt bitumen (5%, 5.5%, 6%, 6.5%, and 7%), which contained both coarse and fine aggregates and were compacted with 75 blows. In Figure 4, the parameters evaluated in this test are shown:

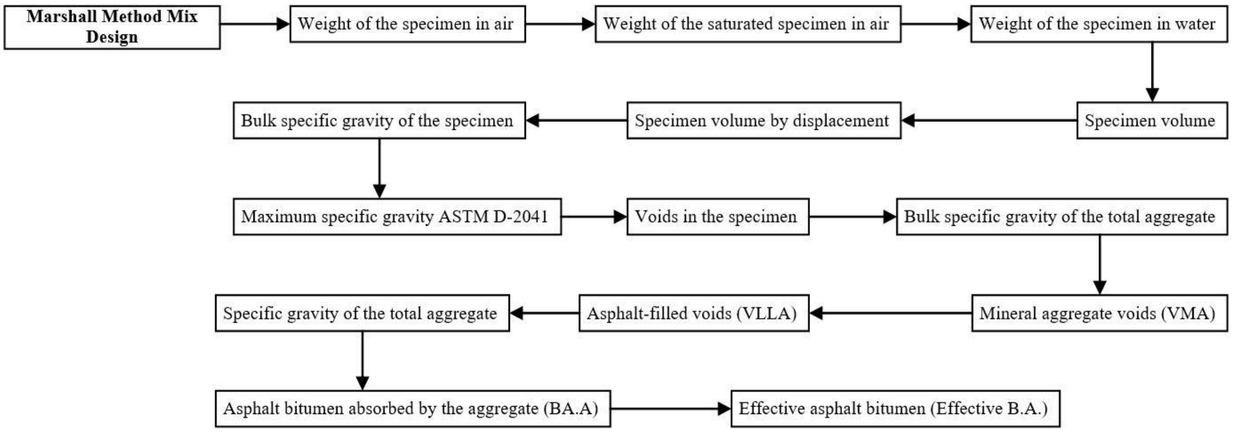

Figure 4. Flowchart Marshall Method Mix Design

Subsequently, the briquettes were subjected to a water bath at a constant temperature of 60 ℃ for 30 minutes and then tested in the Marshall press to determine stability and flow. According to the Asphalt Institute's method, an optimal asphalt content of 6.2% was obtained. Additional tests were conducted to verify other relevant parameters.

Retained Stability

The variation in stability and flow was evaluated after subjecting the briquette to a water bath for 24 hours compared to a 30-minute duration [8].

Compactibility Index

The percentage variation in the bulk specific gravity of the specimen was determined when compacted with 50 and 5 blows to the briquette.

Lottman Test

The optimal mix design with 6.2% asphalt bitumen was verified by evaluating the asphalt mixture's resistance to critical moisture conditions [9]. Marshall specimens were prepared at different compaction levels (10, 25, 50, 75), and then their void percentages were evaluated to determine the number of impacts required to reach 7%.

Viscosity Test

Viscosity was measured to identify the mixing and compaction temperature based on the viscosity of the asphalt bitumen [10].

Finally, once all the corresponding tests for a conventional asphalt mix were completed, the same tests were conducted while incorporating different percentages of glass (1%, 2%, 3%, and 4%) into the asphalt bitumen. The glass used in this process was obtained from the recycling of discarded glass, which underwent a washing process to remove impurities, followed by drying and pulverization [11], as shown in Figure 5.

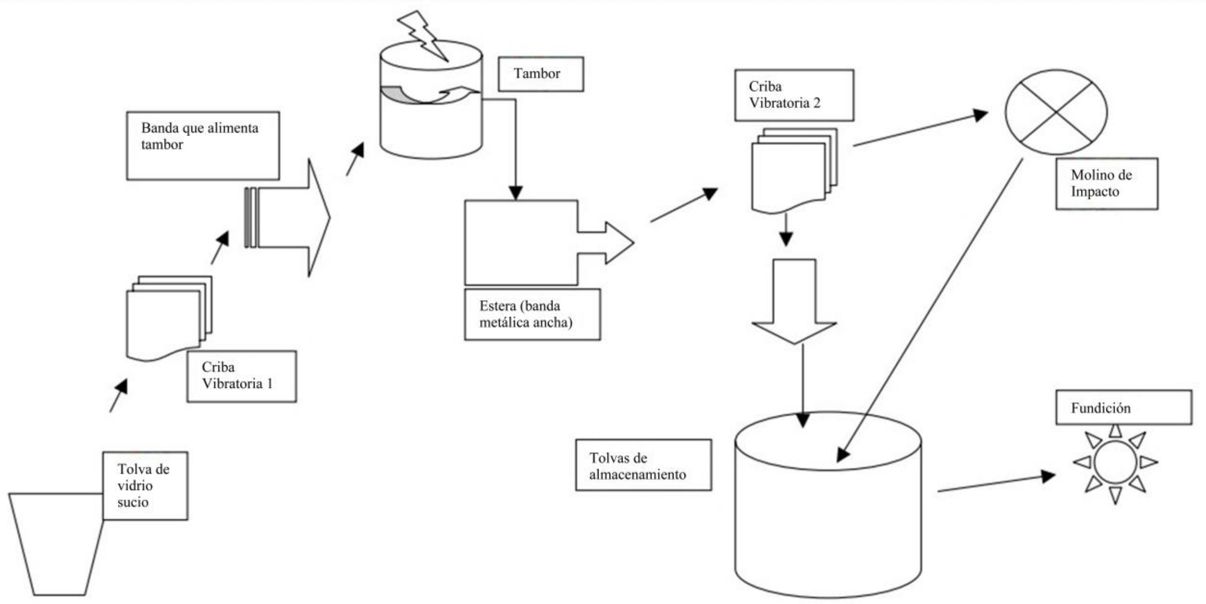

Figure 5. Glass Recycling Diagram

3. Results

Conventional Hot Asphalt Mix Design

Marshall Test

Following the evaluation, the optimal amount of asphalt bitumen in the hot asphalt mixture is determined to be 6.2%. Within a range of +/- 0.3% of asphalt bitumen, the mechanical properties meet the required specifications, as shown in Table 1.

Table 1. Summary of Results for the Optimal Asphalt Bitumen Percentage

SUMMARY OF BASE MIX RESULTS				
DESCRIPTION	**-0.3%**	**OPTIMUM %C.A.**	**+0.3%**	**SPECIFICATION**
Number of blows per face	75	75	75	**75**
Asphalt Bitumen (%)	5.90	6.20	6.50	**(+/- 0.3%)**
Bulk specific weight (gr/cc)	2.034	2.334	2.634	
Voids (%)	2.8	3.1	3.4	**3 - 5**
Mineral aggregate voids (%)	15.4	15.7	16.0	**Min 14**
Asphalt filled voids (%)	79.9	80.2	80.5	
Flow (mm)	2.83	3.13	3.43	**2 - 3.6**
Stability (kg)	736	1052	1367	**Min. 815**
Stability/flow (kg/cm)	2358	3368	4378	**1700 - 4000**
Compactibility index (%)	7.43	7.73	8.03	**5 % min**
Retained stability (%)	81.1	81.4	81.7	**80% Min**
DOSAGE				
Crushed stone 3/4"	**38.0%**			
Crushed sand 1/4"	**34.0%**			
Sieved sand	**28.0%**			
Asphalt cement	**6.20%**			
Type of Asphalt Bitumen	**PEN 85-100**			

Retained Stability and Compactibility Index

The retained stability and compactibility index of the asphalt mixture have been determined, and it is observed that they meet the minimum condition of 80% in retained stability and a minimum of 5% in the compactibility index, as shown in Table 2.

Table 2. Summary of Retained Stability and Compactibility Index

RETAINED STABILITY									
BRIQUETTE	**N º**	**1**	**2**	**3**	**PROM.**	**1**	**2**	**3**	**AVERAGE**
Blows	N º	75	75	75		75	75	75	
Asphalt cement	%	6.20	6.20	6.20		6.20	6.20	6.20	
Weight of the specimen in air	gr	1201.7	1210.2	1207.4		1198.0	1202.7	1193.9	
Weight of the specimen in air (saturated)	gr	1202.8	1210.7	1208.0		1198.7	1203.2	1194.5	
Weight of the specimen in water	gr	688.1	692.1	690.5		681.6	683.4	681.1	
Volume of the specimen	cc	514.7	518.6	517.5		517.1	519.8	513.4	
Bulk Specific Weight of the specimen	gr/cc	2.335	2.334	2.333		2.317	2.314	2.325	
Flow	mm	**2.80**	**3.30**	**3.30**	**3.1**	0.00	0.00	0.00	**0.0**
Uncorrected stability	kg	1004	1158.1	1093		866.6	886.8	814.6	
Correction factor		1.00	1.00	1.00		1.00	1.00	1.00	
Corrected stability	kg	**1004**	**1058**	**1093**	**1052**	**867**	**887**	**815**	**856**
Corrected stability	%	**81.4**							
COMPACTIBILITY INDEX									
BRIQUETTE	**N º**	**A**	**B**	**C**	**PROM.**	**A**	**B**	**C**	**AVERAGE**
Blows	N º	50	50	50		5	5	5	
Asphalt cement	%	6.20	6.20	6.20		6.20	6.20	6.20	
Weight of the specimen in air	gr	1204.1	1201.8	1205.7		1205.2	1204.8	1204.5	
Weight of the specimen in air (saturated)	gr	1205.0	1202.4	1206.4		1216.4	1214.7	1213.4	
Weight of the specimen in water	gr	674.4	673.4	673.8		649.9	651.7	653.0	
Volume of the specimen	cc	530.6	529.0	532.6		566.5	563.0	560.4	
Bulk Specific Weight of the specimen	gr/cc	**2.269**	**2.272**	**2.264**	**2.268**	**2.127**	**2.140**	**2.149**	**2.139**
Compactibility index	%	**7.73**							

Lottman Test

Once the optimal mix design with 6.2% asphalt bitumen is confirmed, the Lottman test is conducted to verify whether the asphalt mixture withstands 68 critical moisture conditions. Initially, Marshall specimens are prepared at various degrees of compaction, followed by the evaluation of their void percentage, as observed in Table 3 with 10 blows per face, Table 4 with 25 blows per face, Table 5 with 50 blows per face, and Table 6 with 75 blows per face.

Table 3. Samples with 10 impacts per surface

N ºSPECIMEN SAMPLES			M_01	M_02	M_03	AVERAGE
% Asphalt cement:	6.20%					
N ºImpacts per face:	10					
B	Weight of the specimen in air	gr	1215.4	1212.6	1210.4	
C	Weight of the Saturated Specimen	gr	1232.9	1231.8	1230.5	
D	Weight of the specimen in water	gr	679.7	678.3	676.0	
E	Volume of the specimen **(B-C)**	cc	553.2	553.5	554.5	
F	Bulk Specific Weight of the Test Specimen **(B/D)**	gr/cc	2.197	2.191	2.183	
G	Bulk Specific Maximum **(RICE)**	gr/cc	2.409	2.409	2.409	
H	**% Voids 100*((F-E)/F)**	%	**8.80**	**9.06**	**9.39**	**9.08**

Table 4. Samples with 25 impacts per surface

N ºSPECIMEN SAMPLES			M_01	M_02	M_03	AVERAGE
% Asphalt cement:	6.20%					
N ºImpacts per face:	25					
B	Weight of the specimen in air	gr	1216.5	1212.9	1208.7	
C	Weight of the Saturated Specimen	gr	1228.5	1223.9	1220.2	
D	Weight of the specimen in water	gr	686.7	682.8	681.2	
E	Volume of the specimen **(B-C)**	cc	541.8	541.1	539.0	
F	Bulk Specific Weight of the Test Specimen **(B/D)**	gr/cc	2.245	2.242	2.242	
G	Bulk Specific Maximum **(RICE)**	gr/cc	2.409	2.409	2.409	
H	% Voids 100***((F-E)/F)**	%	**6.80**	**6.95**	**6.91**	**6.89**

Table 5. Samples with 50 impacts per surface

N ºSPECIMEN SAMPLES			M_01	M_02	M_03	AVERAGE
% Asphalt cement:	6.20%					
N ºImpacts per face:	50					
B	Weight of the specimen in air	gr	1206.5	1209.7	1210.9	
C	Weight of the Saturated Specimen	gr	1212.5	1214.9	1216.9	
D	Weight of the specimen in water	gr	682.2	682.7	684.4	
E	Volume of the specimen **(B-C)**	cc	530.3	532.2	532.5	
F	Bulk Specific Weight of the Test Specimen **(B/D)**	gr/cc	2.275	2.273	2.274	
G	Bulk Specific Maximum **(RICE)**	gr/cc	2.409	2.409	2.409	
H	% Voids 100***((F-E)/F)**	%	**5.56**	**5.64**	**5.60**	**5.60**

Table 6. Samples with 75 impacts per surface

N ºSPECIMEN SAMPLES			M_01	M_02	M_03	AVERAGE
% Asphalt cement:	6.20%					
N ºImpacts per face:	75					
B	Weight of the specimen in air	gr	1210.4	1212.3	1208.7	
C	Weight of the Saturated Specimen	gr	1208.8	1212.0	1206.8	
D	Weight of the specimen in water	gr	689.4	692.5	689.0	
E	Volume of the specimen **(B-C)**	cc	519.4	519.6	517.8	
F	Bulk Specific Weight of the Test Specimen **(B/D)**	gr/cc	2.331	2.333	2.334	
G	Bulk Specific Maximum **(RICE)**	gr/cc	2.409	2.409	2.409	
H	% Voids 100***((F-E)/F)**	%	**3.26**	**3.14**	**3.09**	**3.23**

Based on the data presented in the previous tables, the number of impacts corresponding to a 7% air void content is determined, as shown in Table 7.

Table 7. Specimens with 24 impacts per face

N ºBLOWS	% VOIDS
24	7.00

Once the number of blows is determined, the effect of moisture on the asphalt mixture is evaluated with 6 specimens, and it is observed to exceed the minimum 80% TSR with 82.4%, as seen in Table 8.

Table 8. Lottman Test on Conventional Asphalt Mixture

N ºTEST TUBES			A	B	C		A	B	C	
% Asphalt cement:	6.20%		Saturated Group				Dry Group			
N ºImpacts per face:	24									
A	Specimen diameter	cm	10.18	10.18	10.18		10.19	10.16	10.16	
B	Specimen thickness	cm	6.10	5.98	6.05		6.08	6.12	5.95	
C	Weight of the specimen in air	gr	1207.5	1209.5	1208.4		1212.2	1210.3	1211.0	
D	Weight of the Saturated Specimen	gr	1216.6	1218.4	1217.4		1221.1	1219.5	1218.8	
E	Weight of the specimen in water	gr	691.1	692.2	690.4		693.2	691.1	690.8	
F	Volume of the specimen **(D-E)**	cc	525.5	526.2	527.0		527.9	528.4	528.0	
G	Bulk Specific Weight of the Test Specimen **(C-F)**	gr/cc	2.298	2.298	2.293		2.296	2.290	2.294	
H	Maximum P.E **(RICE)**	gr/cc	2.468	2.468	2.468		2.468	2.468	2.468	
I	% Voids 100***((H-G)/H)**	%	**6.90**	**6.87**	**7.10**		**6.95**	**7.20**	**7.06**	
J	Void Volume **(F*I)/100**	cc	36.26	36.15	37.42		36.69	38.05	37.27	
Sample Saturated Under Vacuum 19 to 28" Hg. for 5 to 15 minutes. Distilled water at 60 ℃										
K	Weight of the Saturated Specimen	gr	1233.5	1235.7	1233.9		**NO SE EJECUTA**			
L	Weight of the specimen in water	gr	705.6	707.4	704.9					
M	Volume of the specimen **(K-L)**	cc	527.9	528.3	529.0					
N	Absorption Water Volume **(K-C)**	cc	26.0	26.2	25.5					
O	saturation **(100*N)/J**	%	71.7	72.5	68.1					
P	swelling **100*((M-F)/F)**	%	0.45	0.39	0.37					
SATURATION CONDITION AT 24Hrs. Water Bath at 60 ℃										
Q	Specimen thickness	cm	**6.20**	**6.08**	**6.16**					
R	Weight of the Saturated Specimen	gr	**1234.6**	**1236.8**	**1235.0**					
S	Weight of the specimen in water	gr	**707.1**	**708.4**	**705.6**					
T	Volume of the specimen **(R-S)**	cc	527.5	528.4	529.4					
U	Absorption Water Volume **(R-C)**	cc	27.1	27.3	26.6					
V	saturation **(100*U)/J**	%	74.7	75.5	71.1	73.8				
W	swelling **100*((T-F)/F)**	%	0.38	0.41	0.45					
X	Indirect Tensile Load	kg	**457**	**420**	**474**		**521**	**551**	**541**	
Y	Dry Strength **(2*X)/(A*B*π)**	kg/cm^2					**5.3**	**5.6**	**5.7**	**5.6**
Z	Moisture Resistance **(2*X)/(A*Q*π)**	kg/cm^2	**4.6**	**4.3**	**4.8**	**4.6**				
TSR		%	**82.4**							

Viscosity

Viscosity results at different temperatures when the asphalt bitumen is a CAP PEN 85-100 to identify the mixing and compaction temperatures, are shown in Table 9.

Table 9. Viscosity of Asphalt Bitumen with CAP PEN 85-100

1_TEMPERATURE_1	1_VISCOSITY1	1_TEMPERATURE_1	1_VISCOSITY_1
℃el.	mPa.s	℃el.	mPa.s
135.00	296.00	155.00	201.00
135.00	298.00	155.00	193.00
135.00	300.00	155.00	200.00
135.00	301.00	155.00	195.00
135.00	303.00	155.00	199.00
135.00	298.00	155.00	196.00
135.00	302.00	155.00	198.00
135.00	296.00	155.00	198.00
140.00	265.00	160.00	182.00
140.00	262.00	160.00	177.00
140.00	268.00	160.00	182.00
140.00	266.00	160.00	175.00
140.00	264.00	160.00	175.00
140.00	268.00	160.00	173.00
140.00	267.00	160.00	177.00
140.00	269.00	160.00	180.00
145.00	242.00	165.00	165.00
145.00	243.00	165.00	165.00
145.00	245.00	165.00	164.00
145.00	245.00	165.00	162.00
145.00	247.00	165.00	168.00
145.00	247.00	165.00	166.00
145.00	242.00	165.00	170.00
145.00	245.00	165.00	168.00
150.00	223.00		
150.00	226.00		
150.00	222.00		
150.00	227.00		
150.00	228.00		
150.00	222.00		
150.00	225.00		
150.00	228.00		

The compaction temperature and mixing temperature are determined from the collected data of asphalt bitumen viscosity, as shown in Table 9, resulting in the minimum and maximum mixing and compaction temperatures as displayed in Table 10.

Table 10. Compaction and Mixing Temperature of Asphalt Mixture with Asphalt Bitumen PEN 85-100

BITUMEN	T °MIXTURE (Mín.)	T °MIXTURE (Máx.)	T °COMPACTION (Mín.)	T °COMPACTION (Máx.)
Asphalt bitumen PEN 85-100	158.0 ℃	162.3 ℃	137.7 ℃	143.4 ℃

Hot Asphalt Mix Design Modified with Glass Powder in Asphalt Bitumen

Marshall and Lottman Test

Once the conventional asphalt mixture had its bitumen component modified by glass, thereby altering its mechanical properties. Tables 11 and 12 summarize the data on properties as the percentage of glass in the asphalt bitumen increases.

Table 11. Properties of Hot Asphalt Mix with 1.0% and 2.0% Glass in Bitumen

DESCRIPTION		MODIFIED MIX DESIGN							
		M.1	M.2	M.3	MEDIA	M.1	M.2	M.3	MEDIA
% Asphalt Cement		6.2	6.2	6.2		6.2	6.2	6.2	
% glass		1.0	1.0	1.0		2.0	2.0	2.0	
stability		1085.0	1085.0	1116.0	***1095.3***	1112.0	1148.0	1164.0	***1141.3***
flow		3.10	2.90	3.00	***3.0***	2.80	2.70	2.90	***2.8***
voids		2.95	3.15	2.70	***2.9***	2.62	2.36	2.54	***2.5***
STABILITY/FLOW		3500	3741	3720	***3654***	3177	3588	3424	***3396***
LOTTMAN	DRY STRENGTH	5.55	5.85	5.91	***5.8***	5.78	5.86	6.12	***5.9***
	WET STRENGTH	4.71	4.82	4.97	***4.8***	5.06	4.95	5.26	***5.1***
	TSR	84.86	82.39	84.09	***83.8***	87.54	84.47	85.95	***86.0***

Table 12. Properties of Hot Asphalt Mix with 3.0% and 4.0% Glass in Bitumen

DESCRIPTION		MODIFIED MIX DESIGN							
		M.1	M.2	M.3	MEDIA	M.1	M.2	M.3	MEDIA
% Asphalt Cement		6.2	6.2	6.2		6.2	6.2	6.2	
% glass		3.0	3.0	3.0		4.0	4.0	4.0	
stability		1206.0	1184.0	1206.0	***1198.7***	1178.0	1145.0	1101.0	***1141.3***
flow		2.20	2.50	2.40	***2.4***	2.30	2.50	2.40	***2.4***
voids		2.26	2.55	2.11	***2.3***	2.88	2.24	2.13	***2.4***
STABILITY/FLOW		5482	4736	5025	***5081***	5122	4580	4588	***4763***
LOTTMAN	DRY STRENGTH	6.35	6.12	6.02	***6.2***	6.31	6.32	6.51	***6.4***
	WET STRENGTH	5.46	5.42	5.40	***5.4***	5.56	5.64	5.42	***5.5***
	TSR	85.98	88.56	89.70	***88.1***	88.11	89.24	83.26	***86.9***

Viscosity

The viscosity of the glass-modified bitumen has been determined, highlighting the mixing and compaction temperatures for each analysis, as shown in Table 13.

Table 13. Summary of Compaction and Mixing Temperature when Adding % of Glass in Asphalt Bitumen

DESCRIPTION	T °MIXTURE (Mín.)	T °MIXTURE (Máx.)	T °COMPACTION (Mín.)	T °COMPACTION (Máx.)
B.A._PEN 85-100 + 1% glass	156.3 ℃	160.8 ℃	135.2 ℃	141.1 ℃
B.A._PEN 85-100 + 2% glass	153.9 ℃	158.3 ℃	133.7 ℃	139.2 ℃
B.A._PEN 85-100 + 3% glass	150.9 ℃	155.3 ℃	131.3 ℃	136.8 ℃
B.A._PEN 85-100 + 4% glass	150.5 ℃	155 ℃	130.5 ℃	136.1 ℃

Table 14. Analysis of Temperature Variation Time and Conventional MAC Travel Distance

DESCRIPTION		T °MIXTURE (Min.)	T °MIXTURE (Max.)	T °COMPACTION (Min.)	T °COMPACTION (Max.)
TEMPERATURE		158	162.3	137.7	143.4
USED TEMPERATURE		162.3		137.7	
VARIATION		24.6			**AVERAGE**
VARIATION TIME		101 min	105 min	112 min	**106 min**
		1.68 hr	1.75 hr	1.87 hr	***1.8 hr***
DISTANCE	V=30km/hr	50.50 km	52.50 km	56.00 km	**53 km**
	V=40km/hr	67.33 km	70.00 km	74.67 km	**71 km**
	V=50km/hr	84.17 km	87.50 km	93.33 km	**88 km**
	V=60km/hr	101.00 km	105.00 km	112.00 km	**106 km**

Table 15. Analysis of Temperature Variation Time and Travel Distance for MAC + 1% Glass

DESCRIPTION		T °MIXTURE (Min.)	T °MIXTURE (Max.)	T °COMPACTION (Min.)	T °COMPACTION (Max.)
TEMPERATURE		156.3	160.8	135.2	141.1
USED TEMPERATURE		160.8		135.2	
variation		25.6			**AVERAGE**
VARIATION TIME		132 min	110 min	126 min	**123 min**
		2.20 hr	1.83 hr	2.10 hr	***2.0 hr***
DISTANCE	V=30km/hr	66.00 km	55.00 km	63.00 km	**61.3 km**
	V=40km/hr	88.00 km	73.33 km	84.00 km	**81.8 km**
	V=50km/hr	110.00 km	91.67 km	105.00 km	**102.2 km**
	V=60km/hr	132.00 km	110.00 km	126.00 km	**122.7 km**

Temperature Variation

Based on the compaction and mixing temperatures, the cooling time from the mixing temperature to the compaction temperature has been determined, as shown in Table 14. It can be observed that the average cooling time from 162.3 ℃ to 137.7 ℃ was 106 minutes, which is 1.8 hours. Therefore, considering the truck's travel distance from the asphalt plant to the compaction site at speeds of 30 km/hr, a distance of 53 km can be covered. At a speed of 40 km/hr, the distance reaches 71 km, at 50 km/hr it reaches 88 km, and at 60 km/hr it covers 106 km.

In Table 15, it can be observed that the average cooling time from 160.8 ℃ to 135.2 ℃ was 123 minutes, which is 2.0 hours. Therefore, considering the truck's travel distance from the asphalt plant to the compaction site at speeds of 30 km/hr, a distance of 61.3 km can be covered. At a speed of 40 km/hr, the distance reaches 81.8 km, at 50 km/hr it reaches 102.2 km, and at 60 km/hr it covers 122.7 km.

In Table 16, it can be observed that the average cooling time from 158.3 ℃ to 133.7 ℃ was 134 minutes, which is 2.2 hours. Therefore, considering the truck's travel distance from the asphalt plant to the compaction site at speeds of 30 km/hr, a distance of 67.2 km can be covered. At a speed of 40 km/hr, the distance reaches 89.6 km, at 50 km/hr it reaches 111.9 km, and at 60 km/hr it covers 134.3 km.

Table 16. Analysis of Temperature Variation Time and Travel Distance for MAC + 2% Glass

DESCRIPTION		T °MIXTURE (min.)	T °MIXTURE (max.)	T °COMPACTION (min.)	T °COMPACTION (max.)
TEMPERATURE		153.9	158.3	133.7	139.2
USED TEMPERATURE		158.3		133.7	
VARIATION		24.6			**AVERAGE**
VARIATION TIME		124 min	137 min	142 min	**134 min**
		2.07 hr	2.28 hr	2.37 hr	***2.2 hr***
DISTANCE	V=30km/hr	62.00 km	68.50 km	71.00 km	**67.2 km**
	V=40km/hr	82.67 km	91.33 km	94.67 km	**89.6 km**
	V=50km/hr	103.33 km	114.17 km	118.33 km	**111.9 km**
	V=60km/hr	124.00 km	137.00 km	142.00 km	**134.3 km**

In Table 17, it can be observed that the average cooling time from 158.3 ℃ to 133.7 ℃ was 134 minutes, which is 2.2 hours. Therefore, considering the truck's travel distance from the asphalt plant to the compaction site at speeds of 30 km/hr, a distance of 67.2 km can be covered. At a speed of 40 km/hr, the distance reaches 89.6 km, at 50 km/hr it reaches 111.9 km, and at 60 km/hr it covers 134.3 km.

Table 17. Analysis of Temperature Variation Time and Travel Distance for MAC + 3% Glass

DESCRIPTION		T °MIXTURE (min.)	T °MIXTURE (max.)	T °COMPACTION (min.)	T °COMPACTION (max.)
TEMPERATURE.		150.9	155.3	131.3	136.8
USED TEMPERATURE		155.3		131.3	
VARIATION		24.0			**AVERAGE**
VARIATION TIME		124 min	136 min	139 min	**133 min**
		2.07 hr	2.27 hr	2.32 hr	***2.2 hr***
DISTANCE	V=30km/hr	62.00 km	68.00 km	69.50 km	**66.5 km**
	V=40km/hr	82.67 km	90.67 km	92.67 km	**88.7 km**
	V=50km/hr	103.33 km	113.33 km	115.83 km	**110.8 km**
	V=60km/hr	124.00 km	137.00 km	142.00 km	**134.3 km**

In Table 18, it can be observed that the average cooling time from 155 ℃ to 130.5 ℃ was 133 minutes, which is 2.2 hours. Therefore, considering the truck's travel distance from the asphalt plant to the compaction site at speeds of 30 km/hr, a distance of 66.7 km can be covered. At a speed of 40 km/hr, the distance reaches 88.9 km, at 50 km/hr it reaches 111.1 km, and at 60 km/hr it covers 133.3 km.

Table 18. Analysis of Temperature Variation Time and Travel Distance for MAC + 4% Glass

DESCRIPTION		T °MIXTURE (min.)	T °MIXTURE (max.)	T °COMPACTION (min.)	T °COMPACTION (max.)
TEMPERATURE.		150.5	155	130.5	136.1
USED TEMPERATURE		155		130.5	
VARIATION		24.5			**AVERAGE**
VARIATION TIME		125 min	141 min	134 min	**133 min**
		2.08 hr	2.35 hr	2.23 hr	***2.2 hr***
DISTANCE	V=30km/hr	62.50 km	70.50 km	67.00 km	**66.7 km**
	V=40km/hr	83.33 km	94.00 km	89.33 km	**88.9 km**
	V=50km/hr	104.17 km	117.50 km	111.67 km	**111.1 km**
	V=60km/hr	125.00 km	141.00 km	134.00 km	**133.3 km**

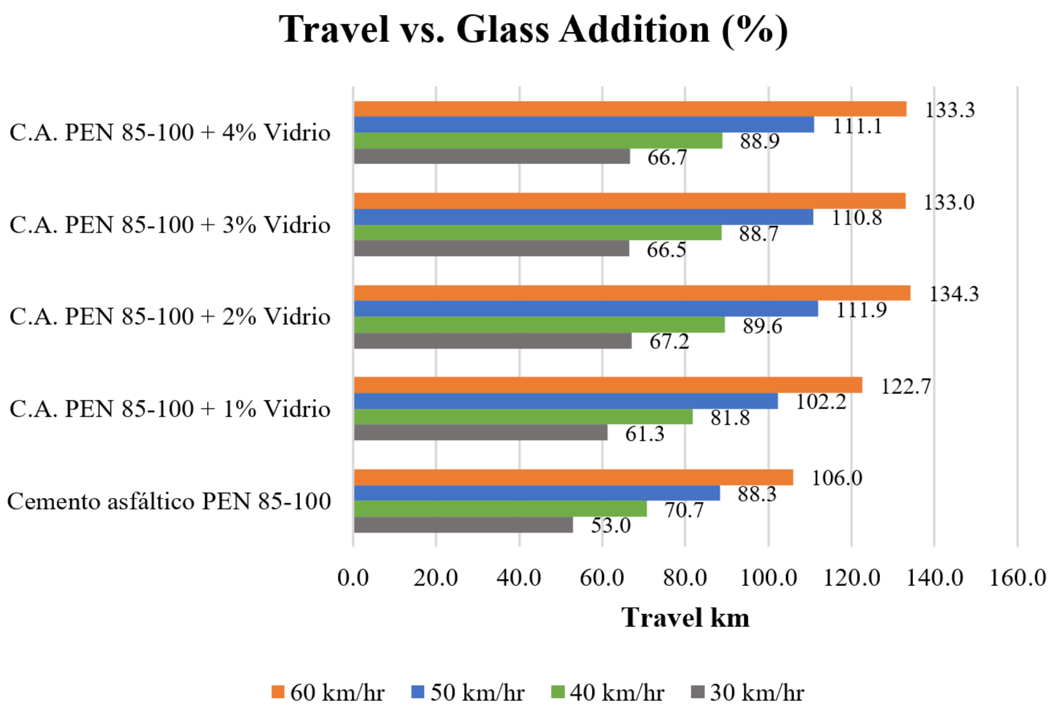

Figure 6. Travel at Different Speeds During the Cooling Period from Mixing Temperature to Compaction Temperature

According to the obtained data, it is evident that a higher addition of glass in the asphalt bitumen prolongs its cooling time. This can be observed in Figure 6, where it is seen that from the addition of 2% glass in the asphalt bitumen, there is not much change in the travel distance.

4. Discussion

Mechanical Properties of Hot Mix Asphalt

In the presented study, the mechanical properties varied according to the increase in glass powder in the asphalt bitumen. Based on the tables created, the following results were obtained:

Stability increased up to 1199 kg when 3% glass powder was added to the asphalt bitumen.

Flow decreased to 2.4 mm with a 3% addition of glass powder in the asphalt bitumen.

Comparing this with the study by Gutierrez Silvestre [12], who used glass in the asphalt mixture, they achieved a stability of 992 kg and a flow of 3.32 mm with a 2% glass addition. Additionally, Freire Alvear [13] obtained significant variations in stability and flow when increasing the ground glass content in the mixture. The stability with glass varied between 2400-2700 kg for each percentage, while the flow gradually reduced, reaching the allowable limit of 2 mm. This indicates that the asphalt mixture stiffened when glass was added as part of the aggregate in the hot mix asphalt.

Variation in Hot Mix Asphalt Temperature

Regarding the temperature of hot mix asphalt, it was found that different additions of glass caused variations in the mixing and compaction temperatures, as shown in Table 19.

Table 19. Mixing and Compaction Temperatures for Standard and Modified Asphalt Mixes

GLASS PERCENTAGE	0%	1%	2%	3%	4%
Mixture temperature	162.3	160.8	158.3	155.3	155.0
Compaction temperature	137.7	135.2	133.7	131.3	130.5

5. Conclusions

The use of asphalt bitumen modified with glass powder has demonstrated a significant impact on hot mix asphalt (HMA). Despite a reduction in mixing and compaction temperatures, the negative influence is offset by the benefit of prolonging the mixture temperature, which enhances pavement quality.

In terms of mechanical properties, substantial improvements have been observed in stability, with an increase of up to 14.0%, and a significant reduction in flow of up to 23.3%. Furthermore, there has been a significant reduction in air voids and an increase in the stiffness index (Stability/Flow) by 50.9%. Additionally, there has been a 6.9% increase in indirect tensile strength according to the Lottman test, indicating greater resistance to moisture-related damage.

The addition of glass to asphalt bitumen has proven effective in enhancing resistance to deformations and surface damage in roadways, contributing to greater durability and pavement lifespan.

Moreover, the temperature variation during the cooling process has been effectively and strategically extended by incorporating glass into the asphalt bitumen. This extension of the cooling time ensures that the mixture temperature remains within an optimal range for a longer period, promoting proper compaction and a more resilient structure.

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