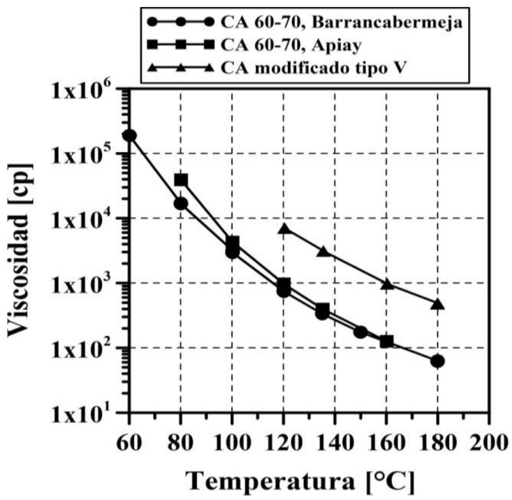


Fig. 1. Viscosity curve of the analyzed asphalts

Table 8 summarizes the optimum percentage of asphalt obtained from the design of the MD12-A, MG20-A, MS25-A (manufactured with CAA), MD12-B, MG20-B, MS25-B mixes. (manufactured with CAB) and the MAM20 mixture (made with CAV). The design of the mixtures was obtained by performing the Marshall test (AASHTO T 245) and was based on the criteria established in the IDU technical specifications [9]. Additionally, the following criteria were used: i) the tensile strength of the wet-conditioned mixture was higher than 80% of that reached under the dry condition; ii) the deformation speed in the plastic deformation resistance test using the laboratory track (UNE-EN 12697-25: 2006; CEN, 2005) was not higher than 15 μm / minute.

Table 8. Design of mixtures

Characteristics	Unit	MD12-A	MD12-B	MG20-A	MG20-B	MS25-A	MS25-B	MAM20
Optimum asphalt content	%	5,2	5,4	4,7	4,7	4,7	5,0	4,7
Stability	kN	18,0	16,4	16,6	13,25	20,3	14,2	23,0
Bulk density	kg /m^3	2310	2334	2286	2304	2312	2324	2313
Flow	mm	3,5	3,5	3,5	3,4	3,5	3,4	3,5
Stability /Flow	kN/mm	5,14	4,56	4,74	3,90	5,80	4,15	6,39
Air voids	%	4,3	4,0	5,3	4,5	5,0	4,2	5,0
Voids filled with asphalt	%	72	73	65	68	65	70	66
Voids in the mineral aggregate	%	14,6	14,3	15,2	14,5	14,2	14,1	14,3

Determination of M_r in laboratory

For the measurement of M_r in the laboratory, the criteria established in the specification ASTM D 4123-82 were followed, and it was determined, under three temperatures (10, 20 and 30°C) and load frequencies (2,5, 5,0 and 10.0 Hz), using a Nottingham Asphalt Tester (NAT) equipment. The test was carried out on mixtures type MD12-A, MG20-A, MS25-A, MD12-B, MG20-B, MS25-B. In the case of the MAM20 mixture, the test temperatures were 20, 25 and 30°C. Each test was performed on 9 samples (3 for each temperature). The samples were compacted to 75 blows per side, following the guidelines established in AASHTO T 245. Additionally, to simulate the short-term aging of the mixtures during the manufacturing, extension and compaction processes, they were subjected to a process called STOA (Short Term Ageing Test), following the procedure recommended by von Quintus et al. [10] (the mixtures in loose state are subjected in a furnace during 4 hours to 135°C and then they are compacted).

Mathematical calculation of E * and correlation analysis with M_r

In equation (1), the main parameter that can vary ostensibly the E^* of the mixtures is η. The other parameters do not change significantly, are usually fixed and obtained based on the granulometry (P_{200}, P_{34}, P_{38} and P_4), the design of the mixture (V_a, V_{beff}) and the speed of vehicle circulation (f). Using the equations (2-3) can be determined η simply by means of 4 forms (each one called Simulation i, where i is the number of each simulation). These forms of production are described below and are listed based on ease of use in practice:

- Simulation 1. Based on the classification of asphalt by penetration, parameters A and VTS are determined in table 1. Then these parameters are introduced into equation (3) and estimated η.
- Simulation 2. In the laboratory, the penetration test is performed on the asphalt at the temperature at which we want to estimate η and this parameter is calculated using equation (2).

- Simulation 3. Based on the classification of the asphalt by viscosity, parameters A and VTS are determined in table 2. Then these parameters are introduced into equation (3) and estimated η.
- Simulation 4. Based on the classification of the asphalt by PG, parameters A and VTS are determined in table 3. Then these parameters are introduced into equation (3) and estimated η.

Once η is obtained, this parameter is introduced in equation (1) to calculate mathematically E^*. In the present study, E^* calculated using equation (1) is compared with M_r obtained in the laboratory by the relationship between the two ($ER=E^*/M_r$), in order to show if there is any correlation. A fifth way of obtaining η was not taken into account by direct method, using a Dynamic Shear Rheometer (DSR), since the necessary tests to execute are not easy to perform at temperatures of 10, 20 and 30°C, and in that meaning, the correlation would lose practical simplification.

RESULTS

Resilient modulus obtained in the laboratory (M_r)

Table 9 shows the evolution of M_r with the temperature and load frequency of the mixtures designed and analyzed.

Table 9. Summary of the magnitude of M_r

MD12-A								
F [Hz]	T [°C]	M_r [MPa]	F [Hz]	T [°C]	M_r [MPa]	F [Hz]	T [°C]	M_r [MPa]
2,5	10	8469	2,5	20	4621	2,5	30	1963
5		10678	5		5283	5		2276
10		11261	10		6264	10		2851
MD12-B								
F [Hz]	T [°C]	M_r [MPa]	F [Hz]	T [°C]	M_r [MPa]	F [Hz]	T [°C]	M_r [MPa]
2,5	10	7786	2,5	20	3826	2,5	30	1658
5		9286	5		4508	5		1979
10		10863	10		5589	10		2526
MG20-A								
F [Hz]	T [°C]	M_r [MPa]	F [Hz]	T [°C]	M_r [MPa]	F [Hz]	T [°C]	M_r [MPa]
2,5	10	9677	2,5	20	5385	2,5	30	2211
5		11071	5		6318	5		2677
10		12207	10		7391	10		3265
MG20-B								
F [Hz]	T [°C]	M_r [MPa]	F [Hz]	T [°C]	M_r [MPa]	F [Hz]	T [°C]	M_r [MPa]
2,5	10	10268	2,5	20	5331	2,5	30	1812
5		11673	5		6077	5		2186
10		13663	10		7265	10		2968
MS25-A								
F [Hz]	T [°C]	M_r [MPa]	F [Hz]	T [°C]	M_r [MPa]	F [Hz]	T [°C]	M_r [MPa]
2,5	10	10111	2,5	20	4497	2,5	30	1922
5		11259	5		5320	5		2362
10		12210	10		6799	10		2972
MS25-B								
F [Hz]	T [°C]	M_r [MPa]	F [Hz]	T [°C]	M_r [MPa]	F [Hz]	T [°C]	M_r [MPa]
2,5	10	10397	2,5	20	4501	2,5	30	1816
5		12282	5		5821	5		2195
10		13532	10		7289	10		2573
MAM20								
F [Hz]	T [°C]	M_r [MPa]	F [Hz]	T [°C]	M_r [MPa]	F [Hz]	T [°C]	M_r [MPa]
2,5	20	7256	2,5	25	5412	2,5	30	3707
5		8154	5		6113	5		4123
10		9976	10		6596	10		4897

Correlation analysis

Figures 2-5 present schematically the results obtained from the sensitivity analysis carried out based on the 4 ways of obtaining η and E^* listed previously in the methodology. Specifically, the evolution of the ER ratio of each type of mixture analyzed with the load frequency for each temperature is presented. It can be observed in Figures 2-5 that it is not easy to interpret the results, since there is no clearly defined trend. For this reason, it was necessary to perform a statistical analysis by determining the mean ($\bar{y}$) and standard deviation (σ) of the results obtained (see tables 10-11). In Figures 2-5 and Table 10 it is observed that most of the E^* estimates using equation (1) are superior to the M_r obtained in the laboratory (ER tends to be greater than 1 in most of the cases). The above means that, in the asphalt mixtures analyzed, the E^* develops greater magnitude compared to M_r.

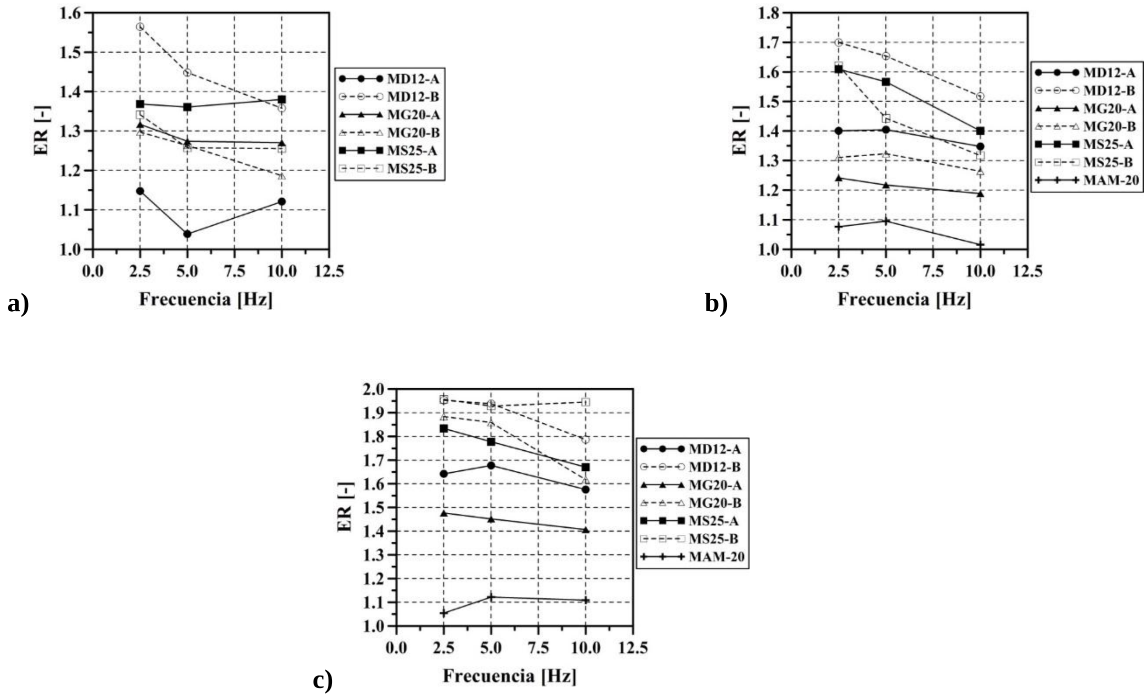


Fig. 2 - Evolution of ER based on the classification of asphalt by penetration (Simulation 1). a) 10 ° C, b) 20 ° C and c) 30 ° C

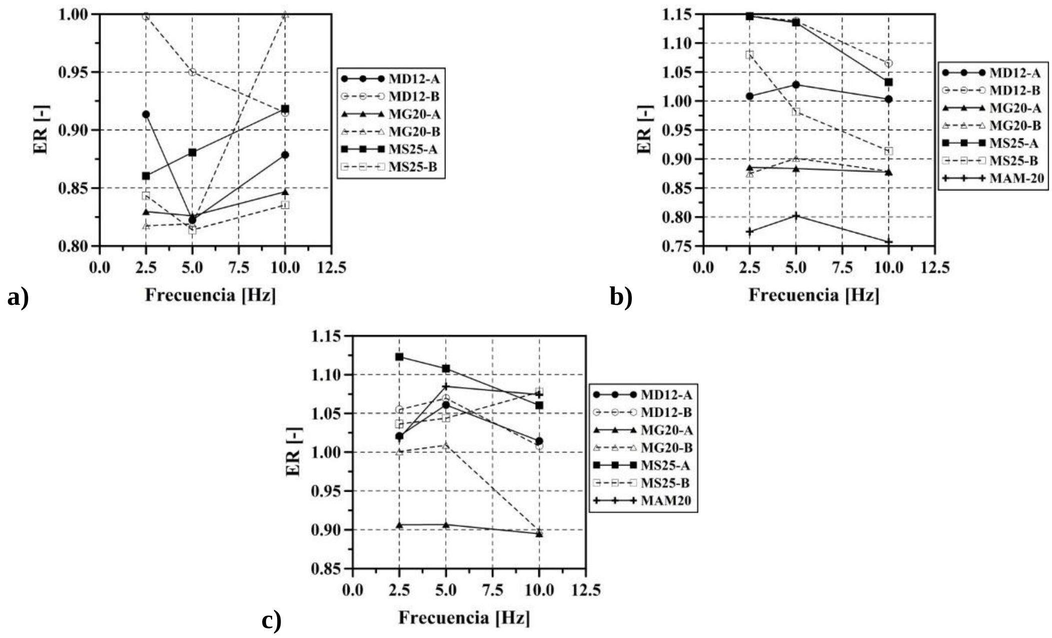
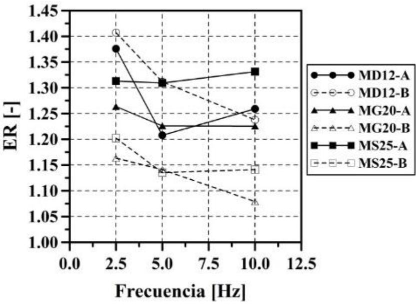
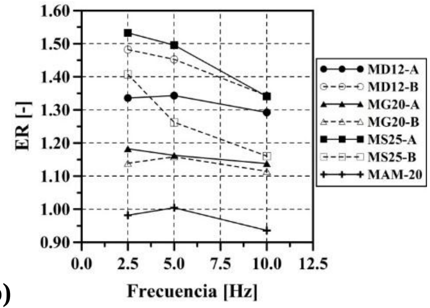


Fig. 3. Evolution of ER using equation (2) (Simulation 2). a) 10 ° C, b) 20 ° C and c) 30° C

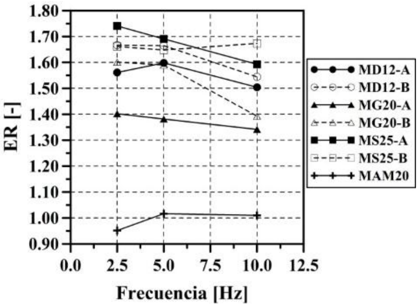
These results are consistent with those reported by Loulizi et al.[4], where they were compared in laboratory, E^* and M_r of different asphalt mixtures. If the temperature of the mixture is 10, 20 and 30°C, the E^* obtained using equation (1) is superior in magnitude, with respect to the M_r measured in the laboratory, between 33 and 42%, 42 and 56% and 72 and 94%, respectively, when Simulations 3 and 1 are used. For the case of Simulations 2 and 4, the maximum averages that are reported are 11, 11 and 21% for mixing temperatures of 10, 20 and 30°C, respectively.



a)

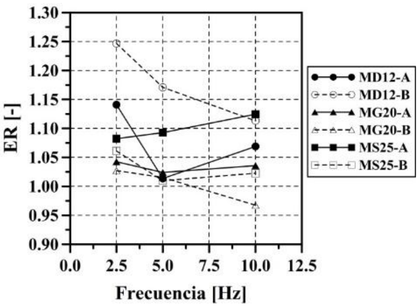


b)

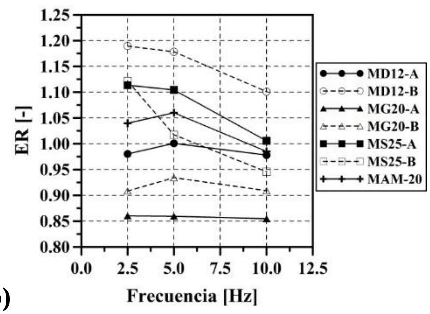


c)

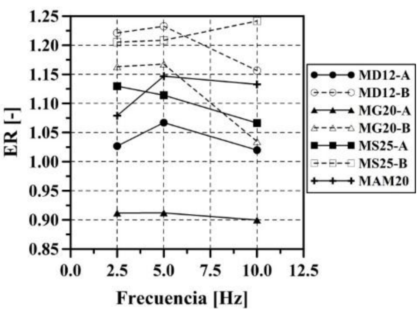
Fig. 4 - Evolution of ER based on the classification of asphalt by viscosity (Simulation 3). a) 10°C, b) 20°C and c) 30°C



a)



b)



c)

Fig. 5 - Evolution of ER based on the classification of asphalt by PG (Simulation 4). a) 10°C, b) 20°C and c) 30°C

Table 10 - Summary of results for the statistical analysis

Simulation	Figure	ȳ	σ	Standard range	
				Maximum	Minimum
10° C					
1	2a	1.33	0.089	1.42	1.24
2	3a	0.88	0.061	0.94	0.82
3	4a	1.24	0.090	1.33	1.15
4	5a	1.05	0.059	1.11	1.00
20° C					
1	2b	1.37	0.195	1.56	1.17
2	3b	0.97	0.124	1.09	0.84
3	4b	1.25	0.173	1.42	1.08
4	5b	1.01	0.102	1.11	0.91
30° C					
1	2c	1.65	0.288	1.94	1.36
2	3c	1.02	0.068	1.09	0.95
3	4c	1.49	0.235	1.72	1.25
4	5c	1.10	0.105	1.21	1.00

CONCLUSIONS

In the present study, the possibility of a correlation between the dynamic modulus E^* (calculated mathematically with the equation recommended by the MEPDG[3]) and the resilient modulus M_r (measured in laboratory) of 7 mixtures of asphalt concrete manufactured with 3 types of asphalt, was evaluated. Realizing a statistical analysis of the results, it is concluded that when calculating η knowing the PG of the asphalt or by determining the penetration of the asphalt at the temperature of the mixture analysis, the E^* tends on average to be higher in magnitude with respect to to M_r at 11, 11 and 21% for mixing temperatures of 10, 20 and 30°C, respectively. When η is calculated based on the classification tests of asphalt by penetration and viscosity, E^* tends on average to be superior in magnitude with respect to the M_r between 33 and 94% depending on the test temperature. This leads us to think that there is no clear correlation between the laboratory M_r and the E^* obtained using the equation recommended by the MEPDG[3] and the NCHRP[8], and this correlation is more dispersed the temperature of the mix gets higher.

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