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Performance of foamed bitumen bound asphalt mixtures under various mixing and compaction temperatures

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Abstract
Foamed bitumen is an environmentally friendly technology for asphalt pavements needing reduced mixing and laying energy. However, its performance varies as a function of actual mixing and laying temperatures since foamed bitumen can be used at ambient temperatures. When these asphalt mixtures are produced at freezing degrees, their stability is considerably decreased. The optimum foaming parameters (water content and temperature) were identified based on the expansion ratio and the half-life of resulting foamed bitumen.

Keywords: bitumen, asphalt mixture, binder modification, industrial by-product, asphalt duration

Introduction
Road infrastructure plays a crucial role in providing people with relocation and services because it is considered a wheel to economic development of all societies. In order to achieve this goal effectively, their careful construction and timely and professional maintenance are essential. Typically, construction and rehabilitation of roads uses new natural aggregate materials. The sustainability of road building operations can be defined as decreasing harmful environmental effects by reducing greenhouse emissions and the energy used in asphalt plants.

The environmentally friendly technologies have been studied by many researchers; one of their major outcome was the technique of warm mix asphalt (WMA) [1, 2]. There are three WMA technology categories [3]: organic additives group [4], chemical additives group [5] and foaming technology group [6]. A few years ago, quite 30 different WMA technologies were utilized in the US, while almost 60% of the technologies utilized foaming methods [7].

In the case of the so-called half-warm-mix asphalt (HWMA) technology, the lowering of mixing temperature is more obvious. This case the binder is bitumen foamed with water which makes the binder viscosity lower [8, 9] and so the mixing temperature can be decreased by about 40–60ºC compared to that of HMA [10, 11].

Until recently, foamed bitumen was used only in deep cold recycling [12], [13], [14]. The standard requirements set for foaming parameters are:

1. Maximum expansion—ER,
2. Half-life—HL of bitumen foam [15].

The quality of water-foamed bitumen can be measured by these two indicators which are determined by optimum water content and the temperature of blending [16].

Plenty of studies and research works focused on the properties of foamed bitumen. The performance of binder with different foaming water content was investigated [17], the results showed that the rise of foaming water content leads gradually to the reduction in the sensitivities of the storage and modulus loss in the foamed binder. Other works study the effect of asphalt binder and recycled crumb rubber on the properties of foamed CRMA asphalt binder [18].

Laser and ultrasonic distance-measuring tools were used for measuring the expansion and decay of foamed bitumen. Results indicated that higher water contents were related to higher

ER value but also faster rates of collapse [19].

In recent years, many research works on water-foamed bitumen are focused on performance evaluation and the deterioration procedure. The studies showed that the deeper ageing degree of foaming asphalt need higher temperature and water content, as increasing concerns of environmental degeneration from using more energy, depleting natural deposits and limited supplies of prime quality aggregates have prompted global emphasis on material selection.

Using reclaimed pavement materials in foamed bitumen stabilisation technique increased the possibility for saving virgin aggregate materials [1]. The availability of efficient target equipment has supported its increased applications worldwide, through both the cold in plant and cold in situ recycling techniques [15]. Foamed bitumen stabilisation is applied for base and subbase layers of pavement structures.

Foamed bitumen stabilisation process exhibit increased shear strength, cohesive strength, flexural strength and moisture durability [20].

Methods of production foamed bitumen

Production process of foamed bitumen can be summarised as follows: cold water injected into hot bitumen at temperatures ranging 150°C to 180°C under specific pressure in specialist machines.

Csanyi had worked out the first version of the production method more than 50 years ago; Mobile Oil company in the 1960's improved the initial technique using steam injected, which allowed addition water in the expansion chamber [3].

In the 1990s, foamed bitumen specialist tools manufacturer Wirtgen GmbH continued the development of production process of foamed bitumen by producing of a metered system, which uses injection of water with presence of air pressure as shown in Fig. 1.

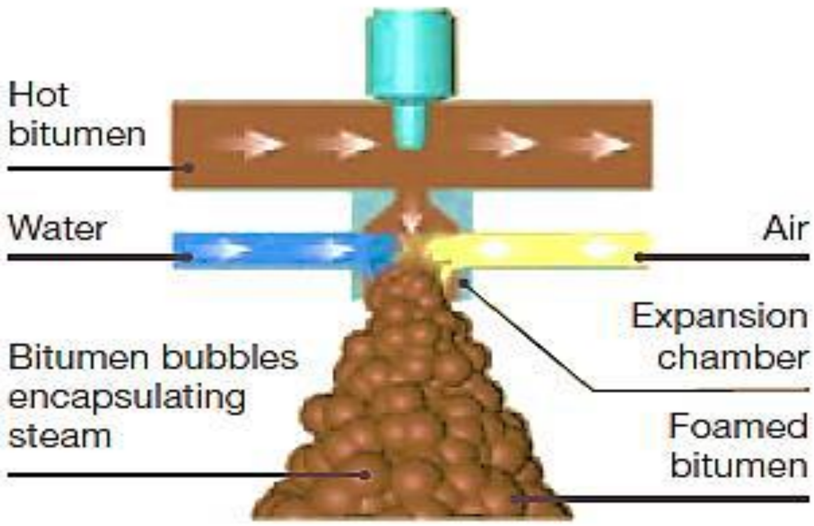

Fig.1: Production of foamed bitumen in expansion chamber [21].

This system is used in many of the presently utilised foamed bitumen cold recyclers due to the fact that a temporary low viscous state of the material is manufactured which resulted in the changes from liquid to vapour state while the volume increases [15].

The fragments created because of the rupturing of the bitumen bubbles during friction with aggregates, adhere to the finer particles of the aggregate. Under pressure, the result will be the mastic bitumen, which binds the uncoated aggregate particles [20].

Behaviour of foamed bitumen bound asphalt mixtures under changing weather

The behaviour of foamed bitumen bound asphalt mixtures is basically affected by air voids distribution and binder rate [21,22].

For foamed asphalt, it has been shown that the optimal compaction temperature is between 13 and 23ºC [23,24] knowing that compaction disperse the water from the bitumen influencing cohesion and curing time [26].

The relatively high moisture, low temperatures and rainfall during laying procedure have a significant impact on the performance of foamed bitumen mixture [27]

Curing methods (duration and temperature) selected by various researchers are basically different; Table 1 presents some methods published.

Table 1: Foam asphalt curing methods chosen by various researchers

	Temperature	Duration
[28]	room temperature	24 h
	40°C	48 h
	60°C	45 h
[29]	40°C	24 h
	40°C	48 h
[30]	ambient temperature	24 h
	40°C	3 days
[31]	60°C	6 h
	25°C	24 h
[32]	60°C	24 h
[33]	ambient temperature	24 h
	40°C	48 h
[34]	38°C	10 days

Guo et al. [35] investigated the changing in foamed characteristics under different environmental conditions (Table 2).

Table 2: The changing in foamed quality characteristics as a function of environmental conditions [35].

Phase type	Number of freezes –thaw cycles	Penetration	Softening point	Ductility	Viscosity
Evaporation	30	↓ 5.84 %	↑ 6.4 %	↓ 12.8 %	↑ 28.6 %
Frozen	30	↓ 13.8 %	↑ 7.2 %	↓ 77.6 %	↑ 12.5 %
	10	↓ 10 %	↑ 6.3 %	↓ 60.2 %	↑ 13.7 %
	5	↓ 8.6 %	↑ 4.5 %	↓ 52.4 %	↑ 11.3 %
Freeze – thaw	30	↓ 39.3 %	↑ 17.2 %	↓ 85.2 %	↑ 71.2 %
	10	↓ 31 %	↑ 12.5 %	↓ 75.6 %	↑ 65.1 %
	5	↓ 21.7 %	↑ 11.2 %	↓ 65.6 %	↑ 45.8 %

Fu et al. presented that the variability in the results is higher if cure temperature decreases below 15ºC since when foamed bitumen comes in touch with the cold aggregate it cannot be spread uniformly in the mix, even if the mix seems fully coated [36]. In addition to that, the decrease in temperature leads to higher heterogeneity.

Mixing conditions for mixtures

Foamed bitumen mixes are mainly dependent on aggregate interlock forces whereas hot asphalt mixes gain mechanical performance by the combination of the mastic cohesion and interlocking forces of the aggregates [13].

The compatibility of foamed bitumen with a vast group of granulated materials is the reason of its significant contribution in sustainable construction, which can be treated with combinations of additives under different conditions when it is necessary.[36, 37].

Another important mix design criterion is the amount of foamed bitumen binder needed to produce the mixture. High binder content would require more fines to mobilise the bituminous bonding effect.

Therefore, the optimum foamed bitumen binder content must be determined so that the best mix can be obtained. The guidelines recommend that the optimum foamed bitumen binder should be selected based on the relationship between Indirect Tensile Strength (ITS) and foamed bitumen content [20,38]. Some researchers determined the optimum binder contents in terms of stiffness modulus under both dry and wet curing conditions. The optimum binder content of foam mix is selected at its maximum stiffness modulus [40]. It is important to note that no consistent values or trends could be identified for the variation in foamed bitumen binder content [41].

It is difficult to control the impleanation of foamed mixtures in the field due to many factors will be added to the temperature, the cement additions in the foam mix, 1% and 2%, showed the same rate of increase in stiffness modulus of foam mix so we can say that the development of stiffness modulus is faster with additives as shown in Fig. 2 [42].

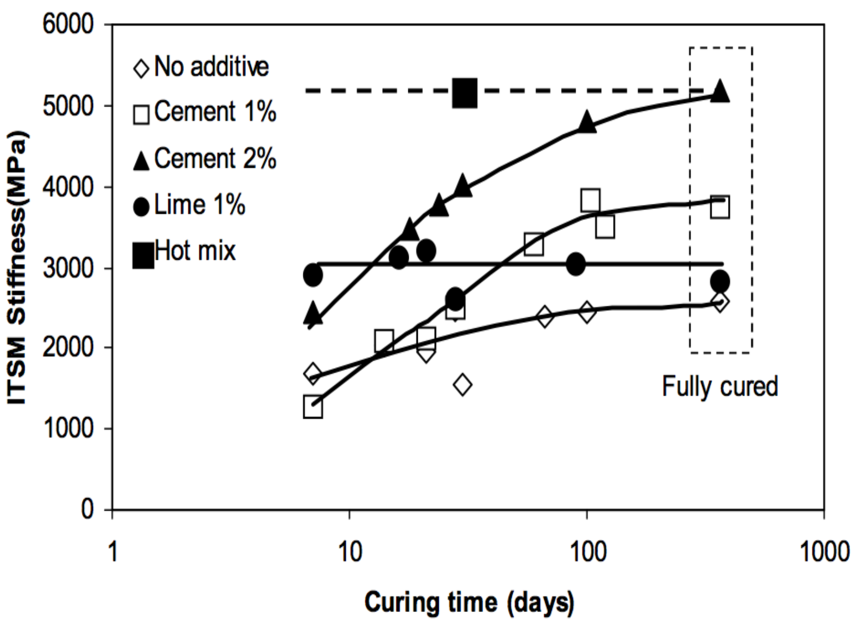

Fig. 1: Development of stiffness modulus of foamed mixtures with different composition [42].

Materials and methodology

Aggregate

A recent Syrian research work focused on asphalt mixtures that was produced with aggregate coming partly from recycled asphalt (RAP). Besides the influence of some bitumen foaming parameters on the foamed bitumen quality and the Marshall-stability of asphalt mixtures made with foamed bituminous binder.

First, an appropriate mix design was chosen. The mix of 50% RAP and 50% virgin aggregates was prepared in laboratory with the same gradation for each mix. The gradations of the RAP, virgin aggregate and the final mix are shown in Fig. 3 together with the minimum and maximum limits for particle-size distribution (PSD).

The RAP in this study comes from the direct scraping of a road pavement. The extracted RAP bitumen is PG 76-28. (PG - Performance Graded - asphalt binders are specified with the Superpave specifications to resist rutting at high pavement temperature and thermal cracking at low pavement temperature [43]).

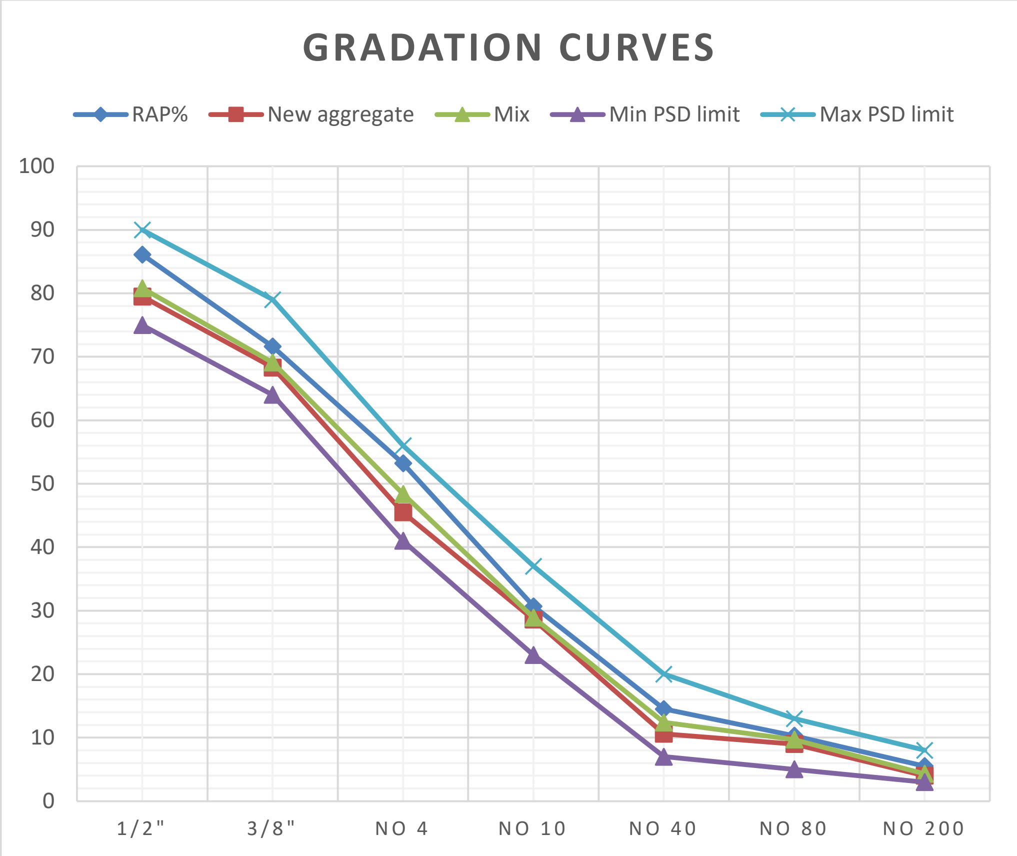

Fig. 2: Grading of aggregate mix

Foamed bitumen

The optimum foaming parameters were identified using the following methodology. Foamed bitumen was designed by 1-2-3-4 % water content, as well as 160, 170 and 180 C bitumen temperature for three types of bitumen [(50-70), (70-100), (60-70)]. The quality of various foamed bitumen variants produced were characterized its typical indicators: expansion ratio (maximum volume of foamed bitumen/volume of bitumen) and half-life (time measured in seconds for the foamed bitumen to subside from the maximum volume to half of the maximum volume) [44].

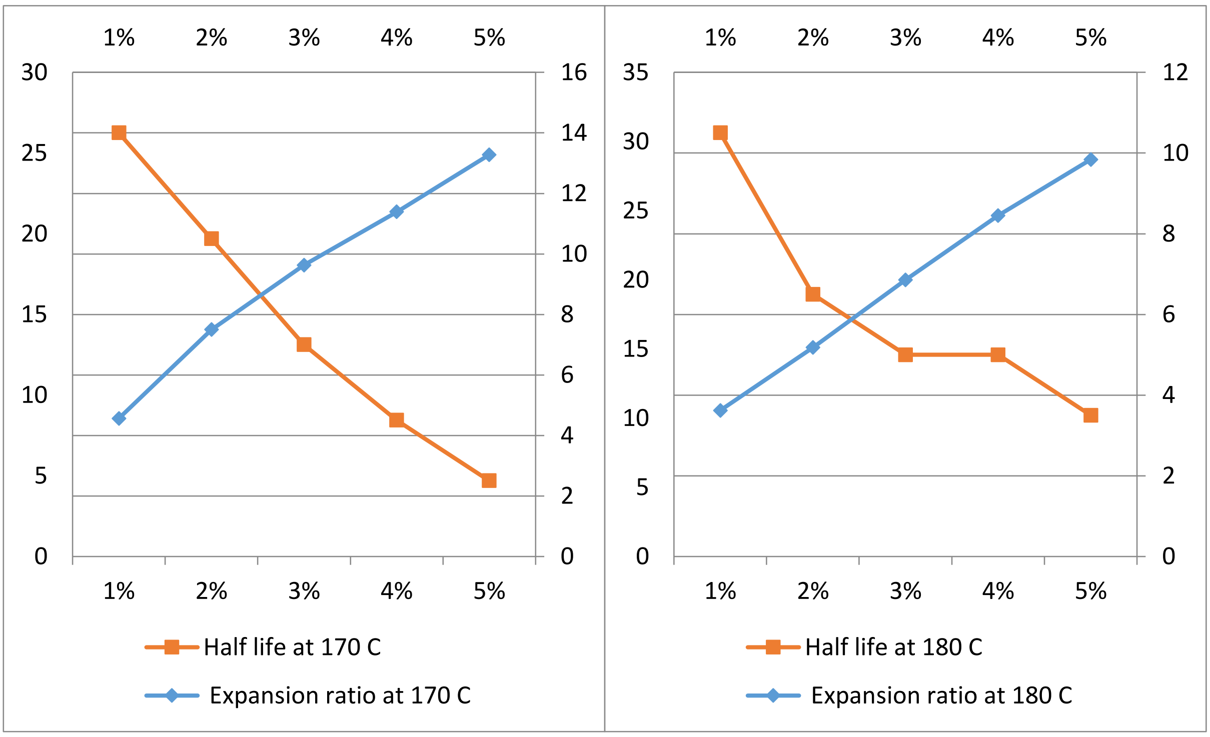

Fig. 3: Foaming parameters for bitumen (60-70)

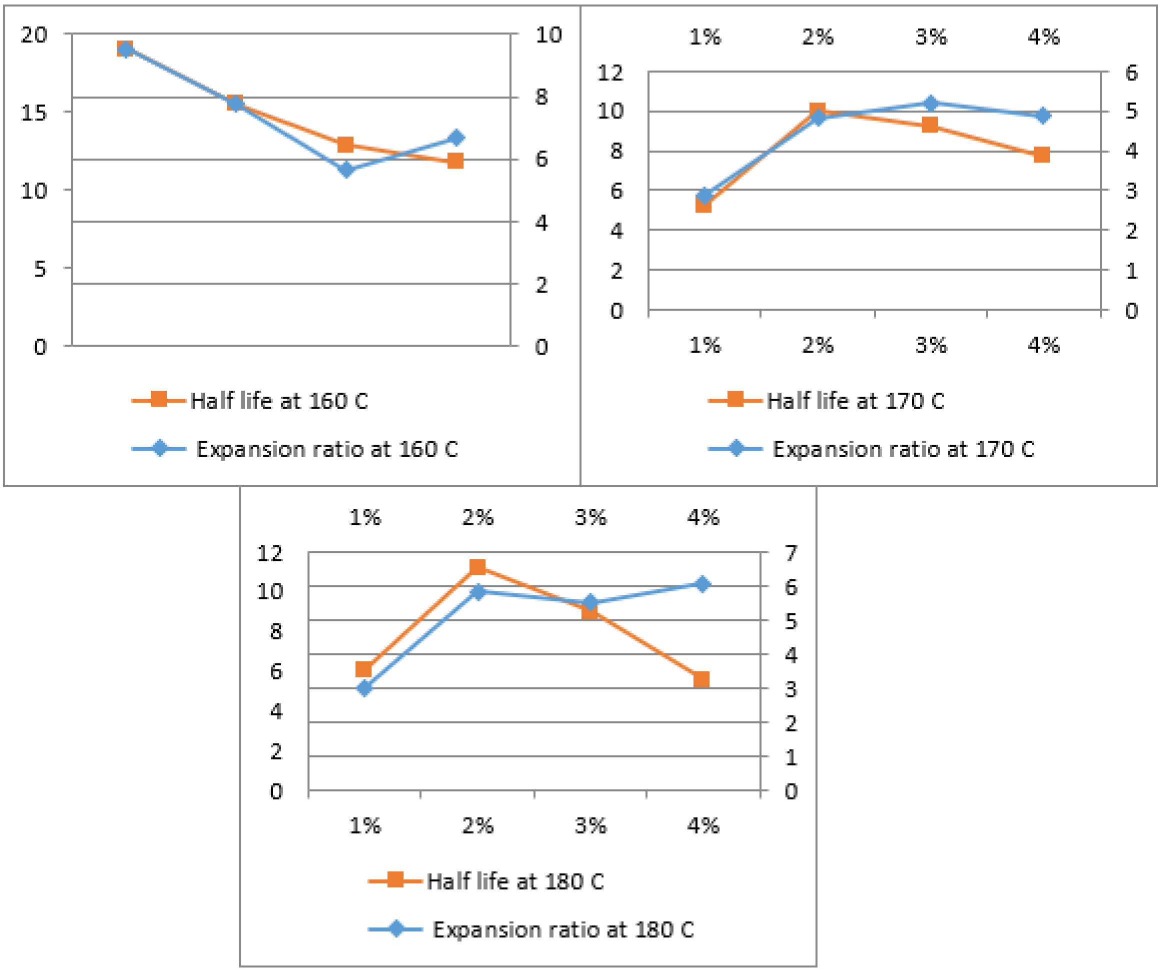

Fig. 4: Foaming parameters for bitumen (70-100).

As a result of an optimisation investigation, Fig. 6 shows that optimum water content (dosage) is 2.5% for foamed bitumen at 160 C temperature.

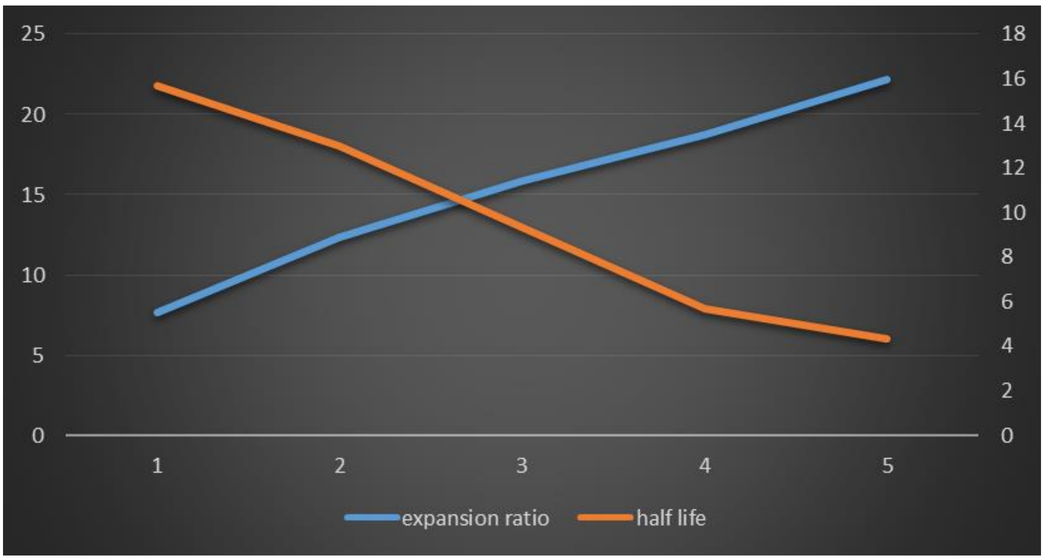

Fig. 5: Optimum water content (2.5%) for bitumen foaming at 160 C temperature

Foamed mixtures

The variants of air temperatures for doing the tests were 0, 5, 10 and 16 C. 16 C was the normal laboratory temperature, while the other two temperatures represent the lowest air temperatures that used to occur at the coastal area in Syria.

A mechanical mixer was applied for producing the asphalt mixture with 2.5% foamed bitumen. The mixer's bowl as well as the beater was stored at the same temperature as the RAP mixtures in question. The asphalt specimens were designed using Marshall-method (75 blows on each side).

Results and discussion

Figure 5 introduces the Marshall stability test values [45] done at various temperatures.

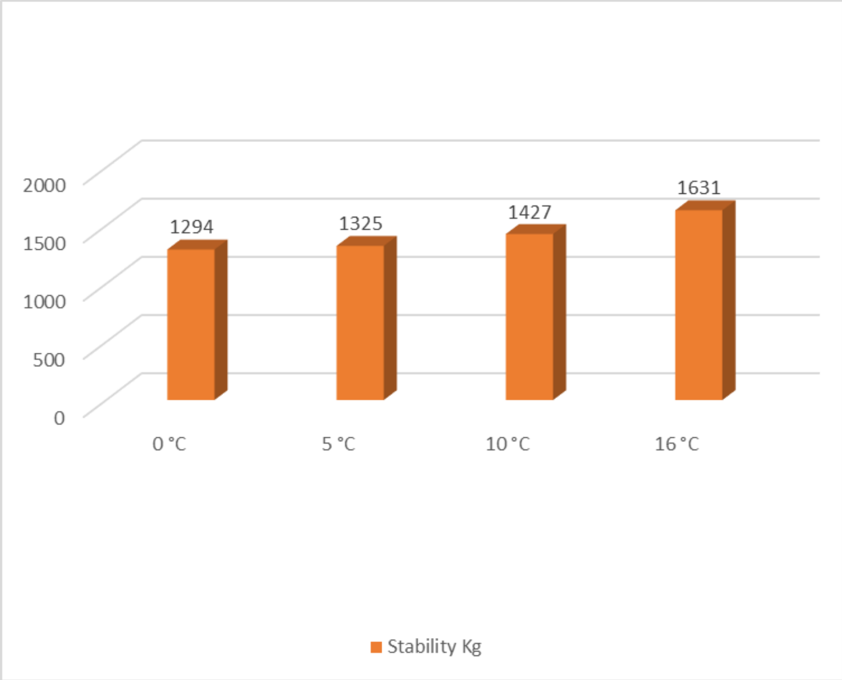

Fig. 6: Marshall.stability results as a function of testing temperature.

It can be seen that the stability value slightly decreases with reducing temperature. Its reason can be the gradual precipitation of internal moisture under the influence of temperature. Moreover, the asphalt will become brittle and hard at low temperatures, which may also accelerate the phenomenon of asphalt cracking.

The temperature of the bitumen reduces immediately when its hot droplets contact with the cold aggregate grains resulting increasing in viscosity; and so the adhesion will be decreased instead of having homogeneous mastic around the aggregate grains which leads to weaker quality in the mix.

Asphalt mixes with foamed bitumen binder are less sensitive to low temperature. This can be explained in part by the lower water content of foam mixes.

It would also be beneficial- and it is planned in the near future – to test also the strength of specimens at low temperature, like fatigue resistance, rutting resistance, or fracture energy in order to properly evaluate the impact of the end of season work (by cool and/or wet weather) done in the field on the long-term performance of the asphalt layers.

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