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Behavior of Polymer-Modified Asphalt (PMA) Concrete Under Cyclic Loadings

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Abstract

This paper present result of a study on the rheological characteristics of polymer-modified asphalt (PMA) concrete under dynamic loading conditions. A number of dynamic creep tests were conducted on the PMA mix samples with two different polymers obtained from waste products. Also a series of resonant column tests were conducted to evaluate the shear modulus and damping values of PMA mixes. The results of the study indicated that polymer modification slightly decreases stiffness and substantially increases damping, making it very attractive material by using for road construction. Even though PMA may cost up to 100 % more than regular asphalt, the advantages such as increased service life of the road or proper waste utilization for a sustainable environment may justify the added cost.

Key words: Maximum Polymer-modified asphalt (PMA), damping, stiffness

1. Introduction

Designing of asphalt pavements is a critical task on road construction due to environmental concerns and traffic induced loadings. Even designing asphalt pavements according to top specifications generally do not provide acceptable, safe and sound usability due to early deterioration. Several factors can be considered for the deterioration such as quality of material and construction, traffic loading on the road, road geometry, environmental conditions etc. In general, most of the deterioration results from top down cracking. Enhancing the pavement life is possible if surface initiated cracking is taken into consideration during the design stage. Therefore, material quality plays an important role. Materials like in any other product must be selected to meet the required engineering criteria based on their characteristics. As new materials with enhanced capabilities are always being developed however increasing cost and energy, the utmost impact on the design and manufacturing endeavor may come from more efficient use of particularly waste materials because of environmental concerns.

The invention of the automobile shifted the demand to asphalt road construction. Since then various approaches developed for long-range solutions to meet future highway demands. Modification by addition of polymers is one of the common way to improve the performance of asphalt concrete. The idea behind is the use of polymers as high energy absorbent elastic materials in order to accommodate to traffic loads therefore increasing the service life of the road [1, 2].

Polymer-modified asphalt (PMA) is a bituminous mix, consisting of blended aggregates, recycled polymers and petroleum asphalt binding agents. For example, rubber tire is essentially

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an elastic hydrocarbon polymer. The features and benefits of PMA in this regard can be listed mainly as by extending the service life of the pavement, reduction in asphalt concrete layer or base thickness and low-cost.

There are also other advantages of PMA such as decreasing thermal instability, permanent deformation and as well as increasing resistance to low-temperature cracking. The characteristics of PMA depend on the concentration amount and the polymer type. The polymer is generally mixed in concentrations of about 4-6% by weight regarding to the asphalt concrete. Higher concentration mixes of polymers are believed to be less economical and also may cause other problems related to the material properties [3, 4, 5, 6].

Despite considerable research in this area, PMA have still not been comprehensively characterized, due to the complex nature and interaction of the asphalt and polymers [7, 8]. This paper presents a study on characteristics of PMA considering dynamic loading patterns.

2. Test Programme

Appropriate aggregate gradation for hot-mix bitumen was designed according to technical specification of General Directorate of Turkish Highways, (GDTH) 2006. The aggregates have a mean grain size (D_{50}) between 0.30-3.0 mm and a coefficient of uniformity (C_u) between 2.0-3.0. The boundaries of the GDTH and the prepared grading curves were given in Fig 1. The physical properties of the aggregates were given in Table 1.

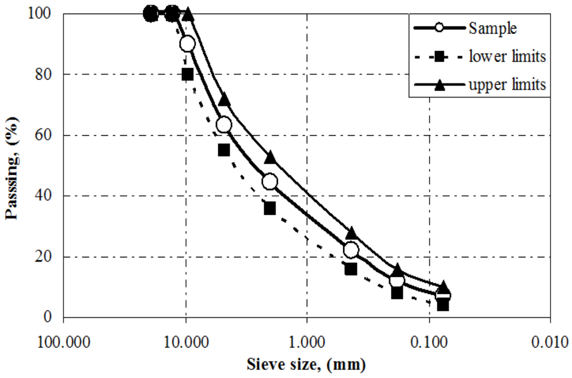

Figure 1. Aggregate grading curves for asphalt mixtures compared with the current GDTH

Marshall stability and flow tests are conducted according to ASTM D 1559-76 specifications in order to determine optimal bitumen content. Optimum bitumen ratio was found as 4.65 % for 50/70 penetration grade and bitumen was modified with two different polymers obtained from waste tire (Type-I) and waste plastic (Type-II) respectively. Pictures and SEM images of samples are given in Fig. 2 and Fig.3 respectively.

Table 1. The physical properties of aggregates used in tests

PROPERTIES	**TEST VALUES**	**STANDARTS**
Specific gravity of coarse aggregate	2.62	ASTM C127-07
Water absorption of coarse aggregate, %	0.23	ASTM C127-07
Specific gravity of fine aggregate,gr/cm^3	2.622	ASTM C128-07a
Water absorption of fine aggregate, %	1.04	ASTM C128-07a
Specific gravity of filler, gr/cm^3	2.708	ASTM C128-07a
Los Angeles wearing test , %	28.91	ASTM C535-09
Freezing and thawing test, %	5.467	ASTM C1646-08a
Bitumen absorption, %	0.14	ASTM D4469-01

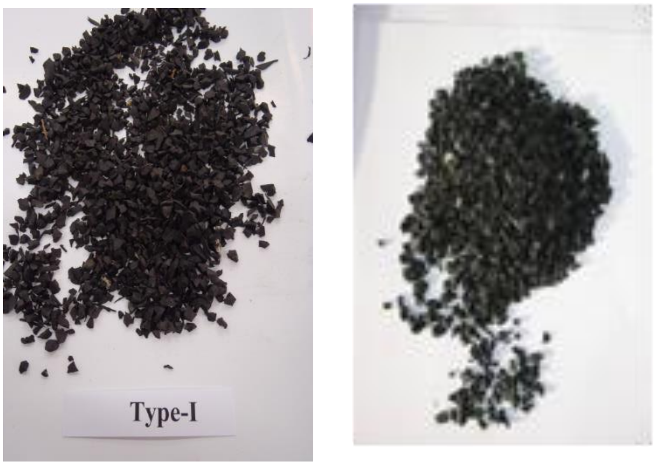

Figure 2. Waste polymers after shredding and grinding process a) Type-I b) Type-II

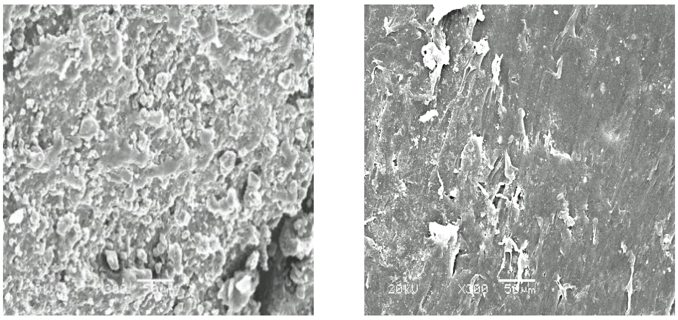

Figure 3. Scanning electron micrograph of polymers a) Type-I b) Type-II

Polymer contents of 2, 4, 6, 8, and 10% by weight of aggregate were blended with bitumen for each type at a mixing temperature of about 160 ^{o}C. To verify the repeatability of the result of the tests, three samples are prepared by way of an identical procedure (premixing the polymer with bitumen using a mixer at 500 rpm for 2 h) from each mix.

The Marshall test results are shown in Fig 4. Note that solid line shows the boundary value for control specimen.

Marshall stability has a general tendency to decrease as polymer content increases. Resolving of Type-II increased the viscosity of bitumen also caused binding and reinforcement effect and stick to aggregate surfaces better as seen in Fig.4.

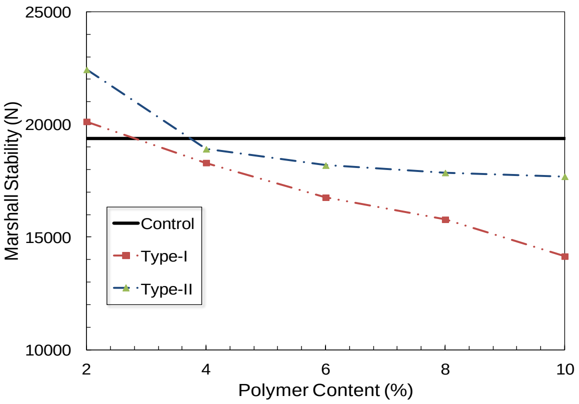

Figure 4. Effect of polymer content on Marshall stability

3. Dynamic Creep Test

In dynamic creep test a repeated uni-axial stress is applied to asphalt sample for a number of load cycles. The pulse duration was 0.5 seconds, and the rest period before the next pulse was 1.5 seconds. A static axial stress of σ_s=5 kPa were applied for ten minutes were applied to the top platen of sample for proper bedding as in static creep test. The deviator stress repeated loading was 500 kPa. Testing temperature was set to 50^{o}C. Failure criterion was defined as 5% axial strain or until complete failure, whichever occurred first.

Dynamic creep stiffness tends to decrease with increasing number of cycles only within the range of the first 200 cycles, either for control or modified samples, thereafter dynamic creep stiffness reduction becomes negligibly small (Fig. 5-Fig 6).

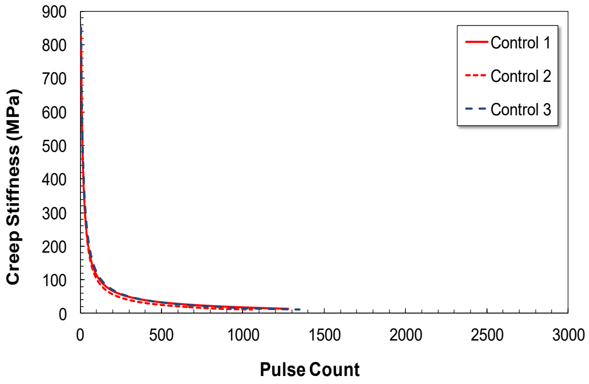

Figure 5. Change of dynamic creep stiffness for control sample

Progressive reduction in dynamic creep stiffness is obvious for test groups of Control, Type-I and Type-II.Axial strains tend to become considerably large especially in Control samples without a further increase in axial stress and failure takes place in fracture mode. However, in modified samples failure does not occur in the same strain range. The loading had been continued further up until the magnitude of axial strain increases above a level of about 6% as indicated in Fig 7 and Fig 8. The results of the tests indicate that the shear stiffness of Control samples give the highest value as compared to those Type-I, Type-II. The reason for that can be accounted for when polymer and asphalt are mixed at high temperatures such as 145-170 ^{o}C, polymer particles especially waste tire rubber may swell. Swelling has been postulated to occur as a result of both physical and chemical interactions between rubber particles and asphalt. Swelling also referred as the reaction between the asphalt and the rubber, which results an increase in viscosity of the mixture. Also the imperfect coupling between the rubber and aggregates due to swelling causes bigger void ratios which produces somewhat larger axial displacement than the Control sample

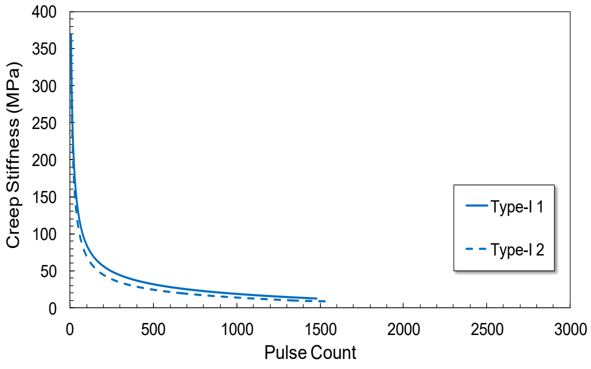

Figure 6. Change of dynamic creep stiffness for Type-I and Type-II PMA

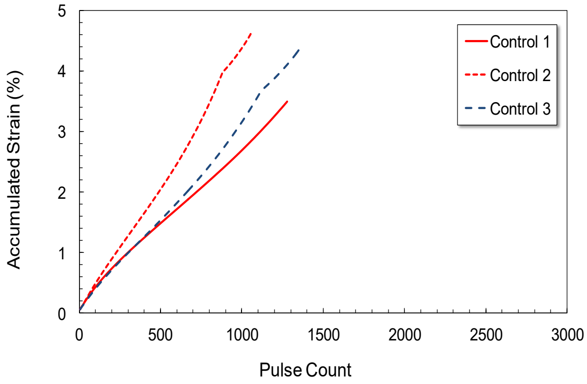

Figure 7. Variation of accumulated strain with and pulse count

3. Resonant Column Test

Resonant column (RC) test device is a commonly used laboratory test to measure low-strain dynamic properties of soils, concrete, and rocks. In this study a fixed-free type RC device is used to evaluate the shear modulus of PMA samples on the order of % 10^{-4}-10^{-3} strain levels under various confining pressures. A fixed-free system is where the sample is fixed at the bottom and free to rotate at the top at its fundamental frequency via a drive system. From measuring the motion of the free end, the velocity of the propagating wave and the degree of material damping can be derived. The shear modulus is then obtained from the derived velocity and the density of the sample.

The test specimen is a solid cylindrical sample with an approximately diameter height ratio of 70 mm and a height of 140 mm. The bottom is fixed on the base of the apparatus. Sinusoidal torsional excitation is applied to the top of the specimen by an electric motor system. Torsional harmonic load with constant amplitude is applied over a range of frequencies and the response curve (strain amplitude) is calculated. The output angular acceleration at the top of the sample is recorded by an accelerometer. The frequency of the cyclic torque is automatically and gradually changed until the first resonance of torsional vibration is obtained. The shear wave velocity is obtained from the first-mode resonant frequency. The shear modulus is then calculated using shear wave velocity and the sample density. The shear modulus and damping ratio under a range of shear strains were measured. The power is shut off at resonance (that is forced vibration is removed) and material damping is determined from free vibration decay.

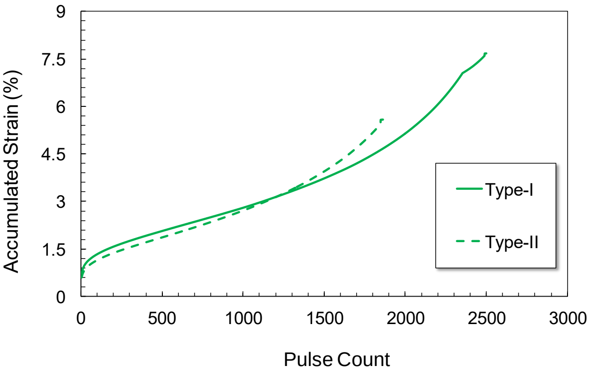

Figure 8. Variation of accumulated strain with and pulse count for PMA samples

The entire system is placed into a Perspex chamber in order to apply a uniform confining pressure on the sample where air pressure is used. In order to prevent diffusion of air into the specimen, a membrane is used to cover. Identical fresh specimens were prepared with the same procedure for Marshall stability tests. After the 300 mm diameter cylindrical asphalt specimen had cured, it was cored into standard size with a diameter of 70 mm for the resonant column test. The height of the samples was approximately 140 mm. The test setup is shown in Fig 9.

The samples were fixed onto the bottom pedestal using cyanoacrylate based fast-acting adhesive. Because the strength and rigidity of the adhesive is higher than that of the asphalt, it has almost no effect on the testing data. After the adhesive was cured, the RC device was set up. Each sample was tested in sequence with stepwise increased confining pressure. At each confining pressure, cyclic torques were applied to measure shear modulus, G and damping ratio D. The vertical pressure on the subgrade under a road is between 50-150 kPa when a car or loaded truck axle passes. So the tests were conducted by employing four confining pressures of σ_c=0, 50, 100 and 150 kPa. After the adjustment of each confining pressure in each test, the cell pressure was maintained for 30 minutes to allow for the volume change of the specimen before the test started.

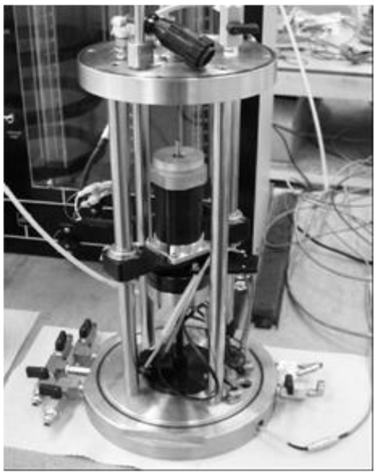

Figure 9. RC test device

Due to its high elastic nature the response of polymer modified mixtures are expected to show a more elastic behavior with increasing polymer content under cyclic loads. Results from tests specimens are for shearing strains less than about 0.0006%. It was not likely to achieve higher strains due to the torque limitation of the RC device. This limitation is satisfactory since ground vibrations produced by vehicles are considered to induce strains in the low-amplitude range levels (i.e., less than 0.001%). It can be seen in Fig 10 that the shear modulus of Type-I decrease quite a lot when content of polymers more than 2% compared to control sample and Type-II. The difference in stiffness of PMA samples can be accounted for the type of polymer used in the mix. Type-II have largest shear modulus values compared to Control and other polymer modified samples due to lower air void ratios and perfect coupling between the dissolved polymers and aggregates. As compared to those obtained for PMA samples the shear modulus was somewhat lower and damping ratio was considerably higher than that for Control samples at corresponding confining pressures. Thus, it can be concluded that adding a certain amount of polymer to asphalt mix can slightly decrease the shear stiffness whereas significantly increases damping (Fig. 11).

Increasing confining pressure from 0 to 150 kPa, increased the initial shear modulus approximately 20%. shear modulus increases noticeably in all cases with the increase of confining pressure. But the rate of its increase becomes small after the first stage of increase (from 0 to 50 kPa) whereas the increase rate diminishes after 100 kPa. The results are in a good agreement with characteristic properties of asphalt obtained from other tests such as Marshall Stability.

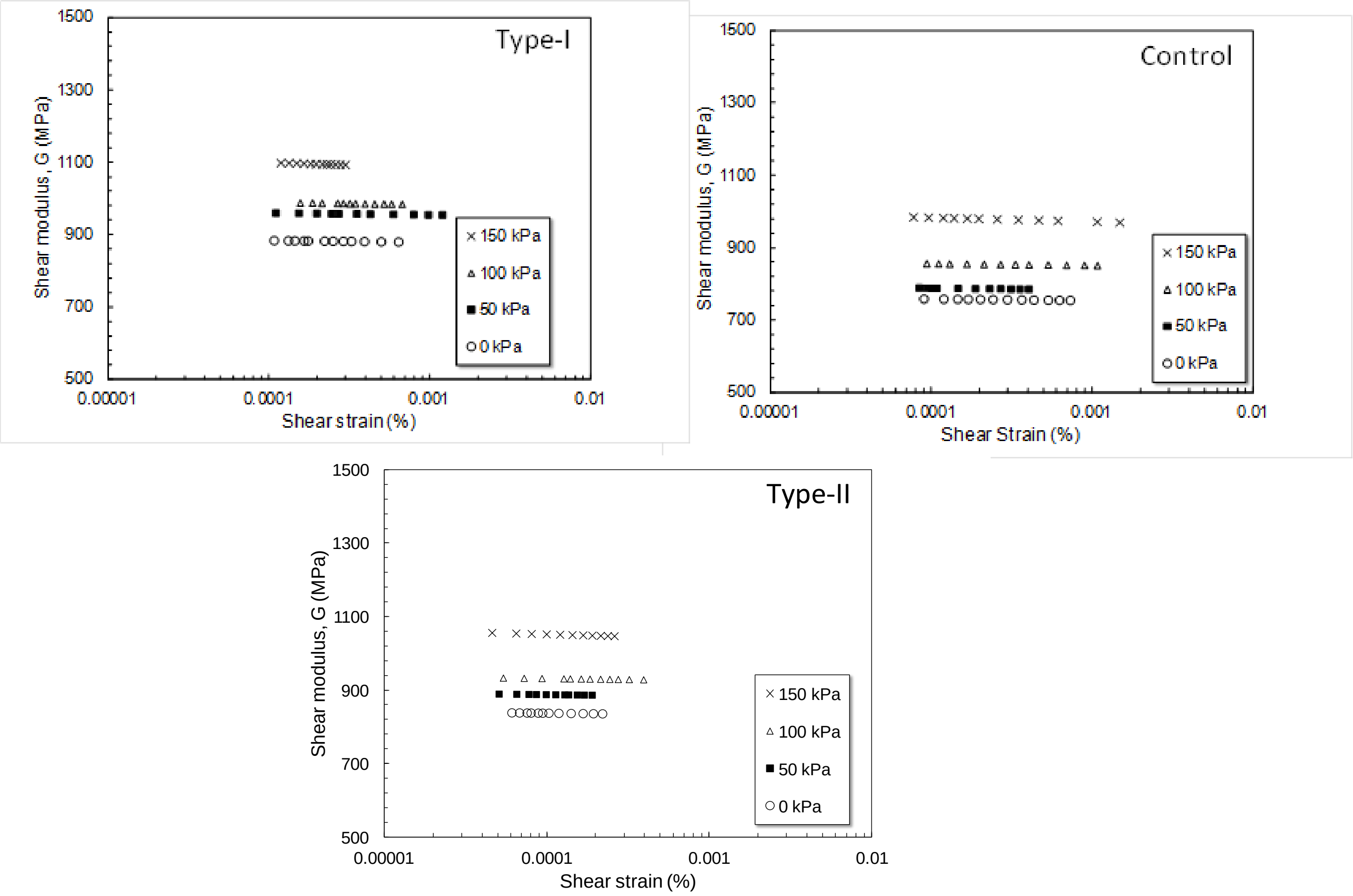

Figure 10. Variation of shear modulus

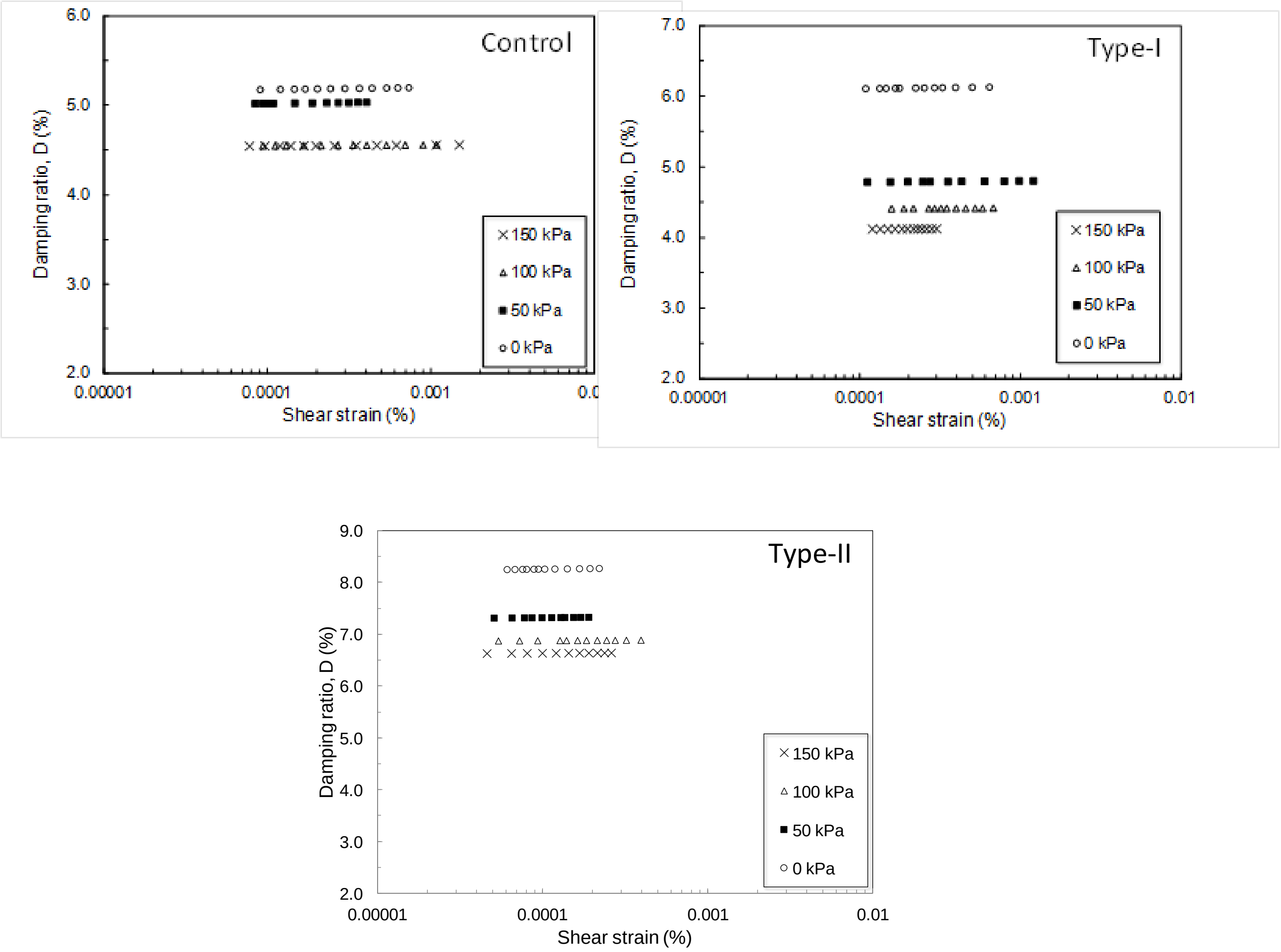

Figure 11. Variation of damping ratio

4. Conclusion

The aggregates in the asphalt concrete are very stiff; therefore, dissipate very little energy in particle deformation. In contrast, polymer consumes energy through deformation of particles themselves. It is indicated that, no matter the type of polymer, stiffness decreases with any proportion. However, modified asphalt provides improved longevity up to 5-12 times compared to Control samples.

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