



Laval (Greater Montreal)

June 12 - 15, 2019

ENHANCING ASPHALT CEMENT PROPERTIES USING GEOPOLYMER-BASED ON FLY ASH AND GLASS POWDER

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Abstract: This research aimed to investigate the possibility of using waste and by-product materials to enhance the properties of the asphalt cement. An experimental matrix of laboratory testing was conducted to study the properties of the PG 58-28 asphalt cement; with different percentages of geopolymer-based on fly ash and glass powder; 0%, 4%, 8%, and 12%. Rotational Viscometer and Dynamic Shear Rheometer (DSR) devices were performed to measure the performance of virgin and modified asphalt cement. Moreover, the Viscoelastic Continuum Damage (VECD) model with the Linear Amplitude Sweep (LAS) test was utilized to evaluate the fatigue behavior of asphalt binders. Results indicated that geopolymer would have a significant effect on the rheological behavior of asphalt cement by increasing its viscosity and complex shear modulus. Samples with 8% of geopolymer exhibited better potential performance in term of fatigue resistance. Moreover, the results showed that the rutting resistance would be improved along with the increase in the geopolymer percentages. Furthermore, geopolymers could be utilized to increase the high-temperature grading of asphalt cement. Overall research conclusion is that geopolymer application resulted in a significant potential enhancement for asphalt cement properties. However, these findings need to be confirmed through further lab testing on asphalt mixes and field validation through a pilot project.

Keywords: Asphalt Cement, Rheology, Geopolymer, Fatigue, Rutting, PG Grading

1 INTRODUCTION

Asphalt cement is the world's most commonly used pavement materials; however, is facing several highly sensitive financial and environmental issues. The manufacture of asphalt cement consumes a lot of energy that involves the emission of CO₂ into the atmosphere. Meanwhile, Greenhouse Gas (GHG) emissions must be decreased 50 to 80% by 2050 to limit the global temperature increase to 2 °C which is considered a challenge to achieve reductions of this magnitude (Kay, et al., 2014). Ma et al. (2016) noted that reducing (GHG) emission from the construction of asphalt pavement should be focused on the manufacturing stage

of raw materials and the mixing process of asphalt concrete. Thus, reducing the usage of asphalt cement and decreasing the energy consumed during the preparation of hot mix asphalt will have potential financial and environmental benefits.

Geopolymer Modified asphalt cement is a new method to capitalize on the use of waste and by-product materials in paved roads. Geopolymer concept was first presented by Davidovits in 1978 (Davidovits, 1991). The geopolymer is inorganic polymers with aluminosilicates base. The geopolymers produce from the interaction between pozzolanic materials with an alkaline solution, sodium hydroxide (NaOH) and sodium silicate (Na_2SiO_3) or potassium hydroxide (KOH) and potassium silicate (K_2SiO_3) (Görhan & Kürklü, 2014). Materials stemming from solid wastes and by-products endowed with silica and/or aluminas such as fly ash, red mud, mine waste, and blast furnace slag qualify as a pozzolanic component of geo-polymerization (Shadnia, et al., 2015). Geopolymer has also proven its ability to develop mechanical properties rapidly, to improve the high fire resistance property, and to reduce energy consumption and greenhouse emissions (Davidovits, 1994; Gourley & Johnson, 2005; Wallah & Rangan, 2006; Rangan, 2010).

Recently, there is a tendency to enhance the asphalt rheological properties using by-product and waste materials that has rapidly accumulated worldwide over in the last few decades. It is very effective to reuse and recycle waste materials to decrease the consumption of natural resources and to reduce environmental pollution. However, waste material such as waste glass was considered as a crucial problem worldwide because the collected glass has different properties. Therefore, waste glass recycling and reusing is a challenging process for glass manufacturers (Polley, et al., 1998; Shi & Zheng, 2007; Vafaei & Allahverdi, 2017). Globally, more than 10 million tons of waste glass are produced annually in the world (Ghasemi & Marandi, 2013). Therefore, it is a challenge to facing and solving this problem. Jony et al. (2011) utilized glass powder as an alternative to traditional limestone powder and ordinary Portland cement fillers in hot asphalt mixtures. Limestone powder, ordinary Portland cement, and glass powder with different concentrations, 4%, 7%, and 10% of total aggregate weight, were investigated. The results showed that the glass powder could be used as a filler in hot asphalt mixtures. Also, glass powder at 7% was found to be the optimum content to produce higher stability, lower density, and lower flow compared to limestone and ordinary Portland cement. Ghasemi and Marandi (2013) investigated the efficiency of using crumb rubber and recycled glass powder to modify asphalt mixture and binder. Results showed that there are no negative effects on the efficiency of the asphalt mixture and binder. Vafaei and Allahverdi (2017) used waste glass powder and calcium aluminate cement with different percentages while preparing the geopolymer. The results showed that adding waste glass powder to the calcium alumina cement leads to enhancing the reactions of the geo-polymerization process whereby resulting in higher compressive strength.

Review of the literature has recently indicated that modifying asphalt cement using geopolymer-based on fly ash and glass powder has not investigated. The main objective of this study is to evaluate the potential usage of geopolymer, with the concentrations of 4%, 8%, and 12%, to enhance the asphalt cement properties which will have potential financial and environmental benefits during the construction of asphalt pavements. Moreover, the LAS test with the VECD model was utilized to investigate the fatigue performance of virgin and modified asphalt cement.

2 EXPERIMENTAL METHODS

2.1 Materials

2.1.1 Geopolymer Preparation

Geopolymer mixture of fly ash and glass powder with alkali activator is used in this project. The alkali activator was sodium silicate solution (Na_2SiO_3) and sodium hydroxide (NaOH) pallet diluted in water to produce 8 Molar (8M) NaOH solution. A mixture of sodium silicate solution and sodium hydroxide solution was prepared to activate the alumino-silicate precursors in fly ash and glass powder. In this study, fly ash

with Class F is used which satisfies this chemical composition $\text{SiO}_2 + \text{Al}_2\text{O}_3 + \text{Fe}_2\text{O}_3 \geq 70\%$ according to the ASTM C618-17a. The fly ash chemical composition is listed in Table 1. Geopolymer additives were prepared using the alkaline medium as the chemical activator and fly ash and glass powder as the aluminosilicate source. Figure 1 shows the adopted mixing procedure to prepare the geopolymer. The following steps summarize the preparation of geopolymer:

1. Prepared alkaline solution using sodium hydroxide (8M) and sodium silicate solution with percentages of 100% and 50% by weight respectively.
2. 140 grams of fly ash and 60 grams of glass powder were mixed with 90 grams of the alkaline medium for 5 minutes.
3. The formed slurry was transferred to silicon molds, as shown in Figure 1.
4. Geopolymers were cured at room temperature (23-25 °C) for six days and in the oven (60 °C) for 24 hours.

The particles size greater than 0.25 mm may impact the consistency of results obtained from tests such as DSR. Therefore, geopolymer samples were manually ground into powder, as shown in Figure 1, and then were sieved using sieve No. 100 to avoid particles with a diameter of more than 0.15 mm.

Table 1: Chemical Composition (%) of Fly ash

Constituent %	SiO ₂	Al ₂ O ₃	Fe ₂ O ₃	CaO	MgO	SO ₃	Na ₂ O
Fly ash	57.2	23.5	3.8	9.3	1.0	0.2	2.43

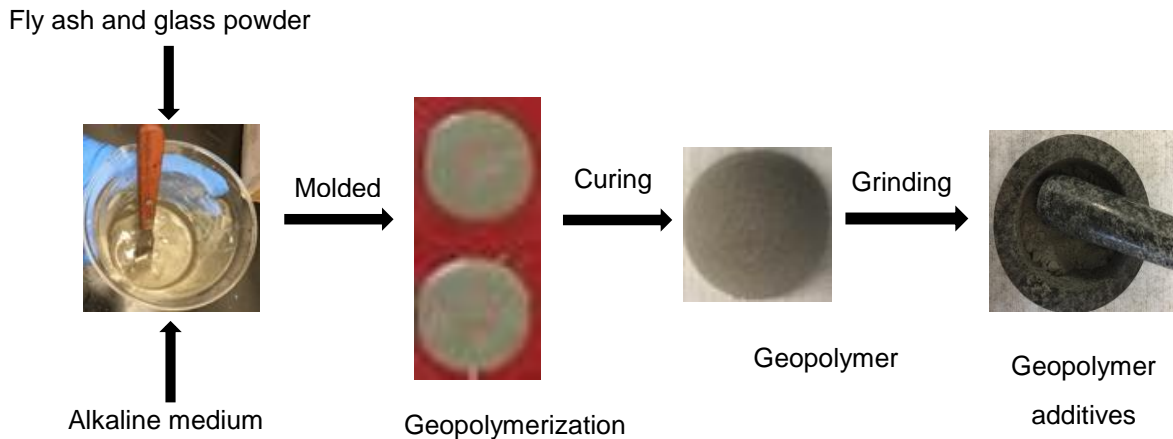


Figure 1: Preparation of geopolymer additives

2.1.2 Modified Asphalt Cement Preparation

The base asphalt cement used was a straight run bunder with a performance grade PG 58-28. The base asphalt cement of 500 g was heated until it becomes fluid, then the geopolymer was added into the base asphalt blend with doses of 4%, 8%, and 12% by weight of the asphalt cement and the blends were mixed using high shear mixer for 60 minutes under a speed of 2000 r/min with a temperature of 140 °C ±2 to produce a homogenous blend.

3 EXPERIMENTAL TEST PROCEDURES

3.1 Rotational Viscometer Test

The viscosity of virgin and modified asphalt cement was measured using the Rotational Viscometer with 10 g of asphalt binder. Three readings were determined for each test temperature, and the average was recognized as the test result. Also, the test temperatures were ranged from 90 °C to 165°C and using 15°C as an interval.

3.2 Dynamic Shear Rheometer (DSR) Test

The DSR utilizes the study of rheological behavior of asphalt cement, as shown in Figure 2(b). Moreover, DSR measures the phase angle (δ) complex shear modulus (G^*) of asphalt cement. In this study, DSR-Linear Amplitude Sweep (LAS) test was conducted for the virgin and modified asphalt cements using an 8 mm diameter plate and a 2 mm gap. The tests were performed at a temperature of 20°C. A frequency sweep test is performed before the strain sweep test to determine the responding of the undamaged material. Consequently, the strain sweep test is held at a constant frequency (10 Hz) to stimulate fatigue damage at an accelerated rate. The VECD model was used to analyze the test result and predict the fatigue life (N_f) of asphalt cement. The approximate total time for this test is 30 min which is considered as a main benefit (Hasan, et al., 2019).

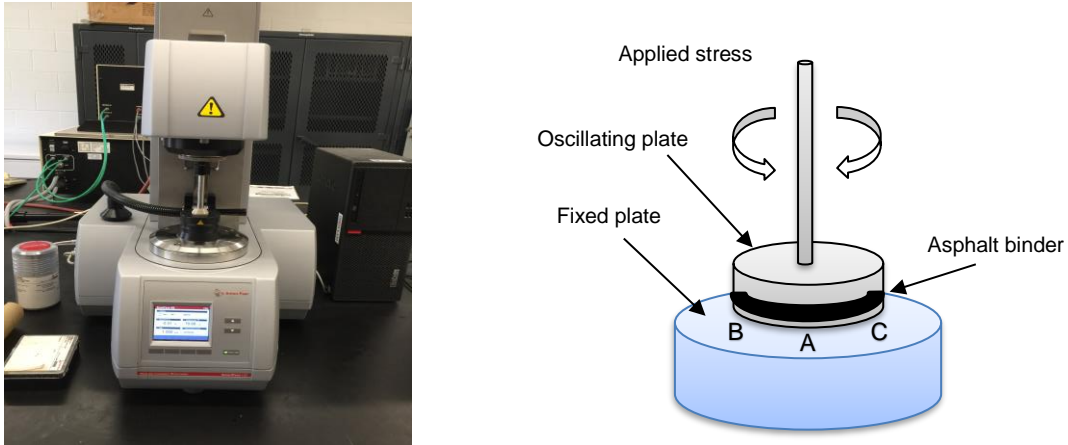


Figure 2: DSR test operational mechanism

The VECD model was used to predict asphalt cement fatigue life (N_f) as the following (AASHTO, 2016):

$$[1] N_f = A (\gamma_{\max})^{-B} \quad \text{where } B = 2\alpha, \quad \alpha = \frac{1}{m} \text{ and}$$

γ_{\max} = the maximum binder strain, %.

$$[2] A = \frac{f(D_f)^k}{K(\pi C_1 C_2)^\alpha} \quad \text{where } f \text{ is the loading frequency (10 Hz), } K \text{ is calculated using Equation [3].}$$

$$[3] K = 1 + (1 - C_2)\alpha$$

$$[4] D_f = \left(\frac{C_0 - C \text{ at peak stress}}{C_1} \right)^{\frac{1}{C_2}} \quad \text{where } D_f \text{ is the value of } D(t) \text{ at failure which can be calculated using equation [5].}$$

C_1 and C_2 are the curve-fit coefficients that were calculated from the relationship between $C(t)$ and $D(t)$ as represented in equations [3] and [4] respectively.

$$[5] D(t) \cong \sum_{i=1}^N [\pi \gamma_0^2 (C_{i-1} - C_i)]^{\frac{\alpha}{1+\alpha}} (t_i - t_{i-1})^{\frac{1}{1+\alpha}}$$

$$[6] C(t) = \frac{|G^*|(t)}{|G^*|_{initial}} \quad \text{where } |G^*| \text{ is the complex shear modulus and } t \text{ is the testing time, second.}$$

In this study, the pseudo strain energy (PSE) was used to validate the VECD model. The damage evolution based on the work potential theory that was proposed by Schapery (1984). Wang et al. (2015) noted that stored PSE is an effective parameter to describe the failure of asphalt cement regarding LAS tests. Moreover, they showed that there is a good relationship between fatigue life and PSE release rate. The pseudo strain energy can divide into stored (W_s^R), which can be calculated using Equation [7], and released (W_r^R), which can be calculated using Equation [8]. W_s^R represented the stored energy after each cycle of loading. Increase of W_s^R indicates the material has the capability to store more energy for more the loading. While, decrease of the W_s^R indicates failure has occurred because the material is losing the ability to store energy as the loading increases.

$$[7] W_s^R = \frac{1}{2} C(S) (\gamma_p^R)^2$$

$$[8] W_r^R = \frac{1}{2} [1 - C(S)] (\gamma_p^R)^2$$

where γ_p^R is the peak pseudo-strain for a cycle $C(S)$ is pseudo-stiffness which can be calculated using Equation [8]:

$$[9] C(S) = \frac{\tau_p}{DMR \times \gamma_p^R}$$

τ_p is the peak shear stress, DMR is the dynamic modulus ratio between $|G^*|_{initial}$ and $|G^*|(t)$.

$$[10] \gamma_{pi}^R = \gamma_{pi} \times |G^*|(t)$$

4 RESULTS AND DISCUSSION

4.1 Effects of Geopolymer on Viscosity

The asphalt cement viscosity is considered an important value to assess the workability of asphalt cement during mixing and compaction operations. Hence, determination of the adequate asphalt mixing temperature and compaction is significantly impacted by the geopolymer content. The percentage of geopolymers significantly affects the viscosity of asphalt cement (Tang, et al., 2018). Figure 3 shows the average viscosity of asphalt cement with different percentages of geopolymer (0, 4, 8, and 12%). Analysis of viscosity testing concluded that virgin asphalt cement has the lowest viscosity, whereas the modified asphalt cement sample with 12% of geopolymer, based on fly ash and glass powder, has the highest viscosity which indicates that 12% of geopolymer has better performance regarding rutting resistance. Also, the viscosity results of asphalt cement with 4, 8 and 12% geopolymer content dropped below the maximum limit of 3 Pa.s at the temperature of 135°C according to the Superpave specifications. Moreover, the addition of geopolymer increases the viscosity values that results have been proposed, for using polymers as additives to the asphalt cement, by different researchers including (Airey, 2003; Al-Mansob, et al., 2014; Swamy, et al., 2017).

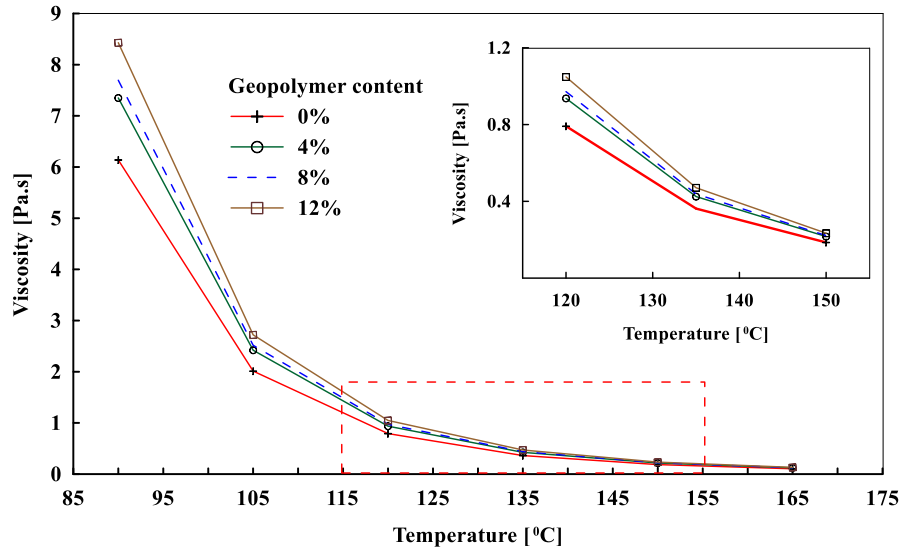


Figure 3: Asphalt cement viscosity changing with the temperature at different geopolymer additives

4.2 Geopolymer Effects on PG and Rutting potential

Error! Reference source not found. shows the results of the high PG grade temperatures of the continuous PG grade obtained from the DSR test. This value is the true high temperature in the performance grade before reducing it to the 6 degrees corresponding temperature used in the PG grade. The virgin asphalt cement had the lowest high temperature nearly 61.6°C compared to geopolymer modified binder, with 4%, 8% and 12% of geopolymers resulted in an increase of 3.9%, 4.7%, and 5.7% in the high temperature respectively. The analysis concludes that geopolymers based on fly ash and glass powder could be used to increase the high-temperature grading of asphalt cement.

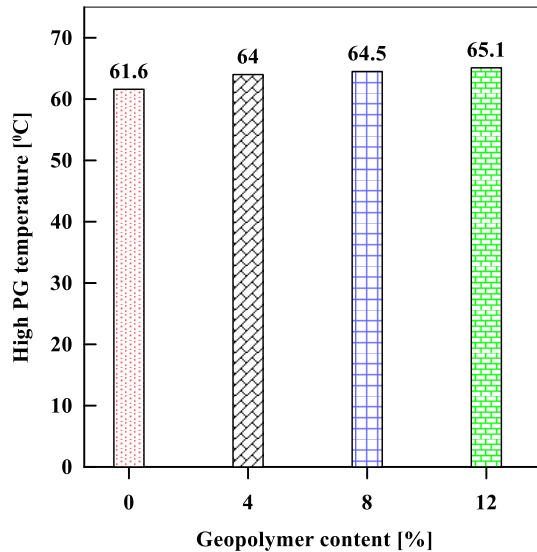


Figure 4: Effects of geopolymer content on performance grading

Error! Reference source not found. shows the effect of geopolymer-based on fly ash and glass powder on the rutting factor ($G^*/\sin \delta$), which represents a measure of the high-temperature stiffness of the asphalt

binder's response to repeated load application at high temperatures. According to Superpave specification, the rutting factor must be a minimum 1.0 kPa for the unaged asphalt cement at 10 rad/sec. This specification is set to minimize the contribution of the asphalt cement to rutting. The results showed that the rutting factor increased by increasing the geopolymer additives which indicates that rutting resistance is improved. For example, the rutting factor at 58 °C increased by 19.8%, 25.8%, and 40.4% through adding 4, 8 and 12% of geopolymers by weight respectively, compared to the virgin asphalt cement. This result gives a strong indication that the resistance to rutting would be improved with the increase of the geopolymer rates in the asphalt.

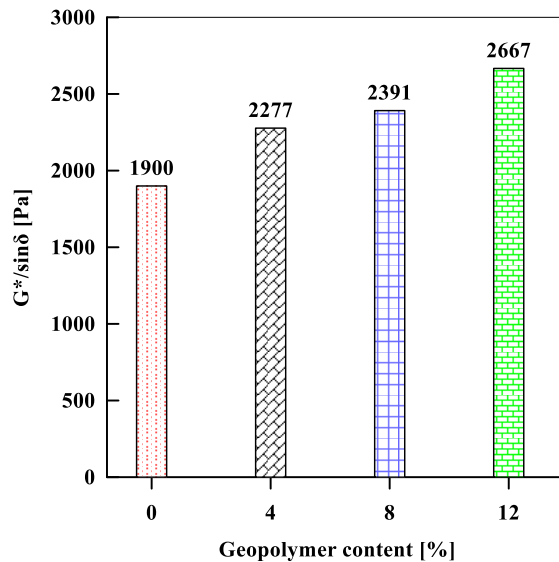


Figure 5: Effects of geopolymer content on rutting resistance at 58 °C

4.3 Effects of Geopolymer on Fatigue Life

The process of blending geopolymer and asphalt cement resulted in an increase in binder stiffness and reduction in phase angle. As a result, the modified asphalt cement may have the approximately same fatigue factor ($|G^*| \cdot \sin\delta$) value as the virgin asphalt. Thus, assessment of fatigue performance for a modified asphalt cement is unfeasible using the PG test-based fatigue parameter. In addition, this parameter has been shown to be inadequate to predict the fatigue performance of asphalt mixes (Baaj et al., 2003).

Hasan et al. (2019) investigated the fatigue performance of Styrene-Butadiene-Styrene (SBS) modified binders using Time Sweep (TS) fatigue test, LAS test, and Four Point Flexural Beam (FPFB) test. The results indicated that there is a strong correlation between mixture fatigue endurance limit from the FPFB test and asphalt cement N_f from the LAS test. Sabouri et al., (2018) utilized gilsonite and SBS polymer to modify several asphalt cements and conducted LAS and FPFB tests to investigate the capability of LAS test to predict the fatigue performance of asphalt mixtures. The results indicated that the LAS test is an effective test to predict the fatigue performance of asphalt mixtures.

Figure 6 presents the effects of geopolymer on the complex modulus and phase angle at a temperature of 20 °C. The test results indicate that the complex modulus of the virgin asphalt cement is low compared to the modified asphalt cement with 4%, 8%, and 12% of geopolymer whereas the phase angle of the modified asphalt is low compared to the virgin asphalt cement. Airey (2003) studied the rheological behavior of SBS modified asphalt with 3%, 5%, and 7% and noted an increase in complex shear modulus with an increase in the modifier percentages.

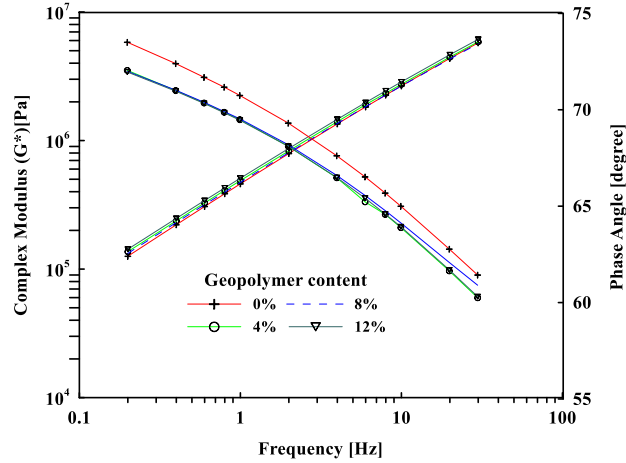


Figure 6: Effects of geopolymer content on the complex modulus and phase angle

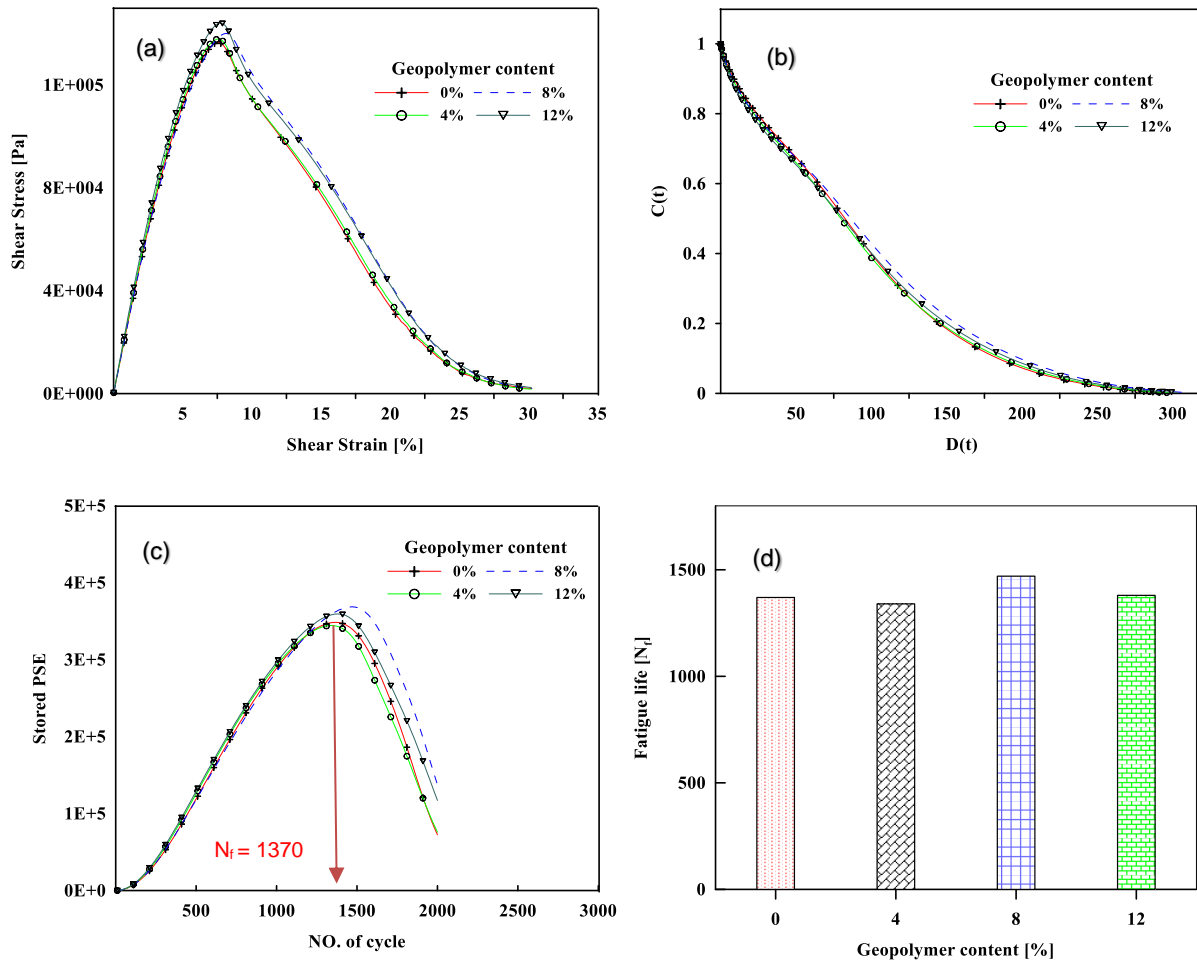


Figure 7: Effect of geopolymer on (a) stress-strain relationship, (b) binder damage, (c) stored PSE, and (d) fatigue life

Figure 7(a) shows the stress-strain relationship for virgin and modified asphalt cement. The peak stress of the virgin asphalt cement is lower than the peak stresses of the modified asphalt cement. It observes that

12% of geopolymer-based on fly ash and glass powder have higher peak stress. Meanwhile, Hasan et al. (2019) investigated the effects of SBS modified asphalt cement with 1%, 3%, and 5% on the stress-strain relationship and noted that peak stresses of the base asphalt cement are lower than the modified asphalt cement. Figure 7(b) shows the increase of $D(t)$ with a decrease of $C(t)$ for virgin and modified asphalt cement. For the same reduction in $C(t)$, the damage intensity of the modified asphalt cement is higher than virgin asphalt. Virgin asphalt cement shows a fast decrease in $C(t)$, which can be relevant to the reduction in shear stress. Figure 7(c) illustrates the stored PSE for every cycle of loading for virgin and modified asphalt cement. N_f was calculated as the cycles number when the stored PSE reaches the greatest value. Figure 7(d) shows the N_f values for virgin and modified asphalt cement. The results indicate that modified asphalt cement with 8% of geopolymer has the highest N_f compared to other asphalt cement. This result confirms that the fatigue performance of asphalt cement could be enhanced by utilizing geopolymer based on fly ash and glass powder. This finding will be verified using a comprehensive fatigue damage approach that uses a homogenous tension-compression test (Baaj, et al., 2005).

5 CONCLUSION

This paper presents a laboratory study to investigate the influences of geopolymer content on the asphalt cement properties. The following conclusions have been drawn:

- Modified asphalt cement had the highest PG high temperature compared to the virgin asphalt cement whereby this temperature increased by 3.9%, 4.7%, and 5.7% through adding 4, 8 and 12% of geopolymers by weight respectively. The analysis concludes that geopolymers could be used to increase the high-temperature grading of asphalt cement.
- Modified asphalt cement with 12% of geopolymer would help improving the rutting resistance of asphalt mixes whereby the rutting factor, at 10 rad/sec and 58 °C, increased by 19.8%, 25.8%, and 40.4% through adding 4, 8 and 12% of geopolymers by weight respectively, compared to the virgin asphalt cement.
- Modified asphalt cement with 8% of geopolymer would have the highest fatigue life (N_f) compared to other asphalt cement. The analysis indicates that the fatigue performance of asphalt cement could be enhanced by utilizing geopolymer based on fly ash and glass powder.
- Geopolymer-based on fly ash and glass powder has a strong potential to be an effective modifier in the enhancement of asphalt cement properties. The findings of this paper should be confirmed through lab testing of asphalt mixes with geopolymers and through a full-scale pilot project.

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