Viscoelastic behaviour of cold recycled asphalt mixes

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Abstract. Behaviour of cold recycled mixes depends strongly on both the bituminous binder content (bituminous emulsion or foamed bitumen) and the hydraulic binder content (usually cement). In the case of cold recycled mixes rich in bitumen and with low hydraulic binder content, behaviour is close to the viscoelastic behaviour of traditional hot mix asphalt. With decreasing bituminous binder content together with increasing hydraulic binder content, mixes are characteristic with brittle behaviour, typical for concrete pavements or hydraulically bound layers. The behaviour of cold recycled mixes with low content of both types of binders is similar to behaviour of unbound materials. This paper is dedicated to analysing of the viscoelastic behaviour of the cold recycled mixes. Therefore, the tested mixes contained higher amount of the bituminous binder (both foamed bitumen and bituminous emulsion). The best way to characterize any viscoelastic material in a wide range of temperatures and frequencies is through the master curves. This paper includes interesting findings concerning the dependency of both parts of the complex modulus (elastic and viscous) on the testing frequency (which simulates the speed of heavy traffic passing) and on the testing temperature (which simulates the changing climate conditions a real pavement is subjected to).

1. Introduction

As the stress-strain ratio of a linear elastic material is expressed by Young’s modulus of elasticity, so the stress-strain ratio of a linear viscoelastic material is expressed by the complex modulus. The complex modulus is determined at steady harmonic varying oscillation with regard to the time displacement of the stress and strain. The strain is phase-delayed due to the viscoelastic behaviour of the asphalt mixtures. The designation "complex" comes from the fact that complex numbers are used for this characteristic in the analysis of results. The basic formula for calculating of the complex modulus is given by the equation (1):

\[
E^*(i\omega) = \frac{\sigma^*}{\varepsilon} = \frac{\sigma_0 \cdot \sin(\omega t)}{\varepsilon_0 \cdot \sin(\omega t - \phi)} = \frac{\sigma_0 \cdot e^{i\omega t}}{\varepsilon_0} = \frac{\sigma_0}{\varepsilon_0} \cdot e^{i\phi}
\]  

(1)

where
\(\sigma_0\) = maximum stress (stress amplitude), (MPa),
\(\varepsilon_0\) = maximum axial strain (amplitude of the cyclic component), (MPa),
\(\omega\) = angular speed (rad/sec), \(\omega = 2\pi f\), where \(f\) is the frequency of loading
\(i\) = the imaginary component of the complex modulus, \(i^2 = -1\),
\(\phi\) = phase angle (rad).
The relationship of the sinusoidal load and the strain response, including the phase shift and the stress and strain amplitudes is shown in Figure 1. The phase angle indicates the time delay between the peaks of the sinusoidal load and the peaks of the response of a linear viscoelastic material. In other words it determines the shift between stress application and the induced strain. In viscoelastic materials the phase angle reaches values between 0° to 90°, in a completely viscous material it equals to 90°. In completely flexible materials, the phase angle is 0 degrees, and the complex modulus of a resilient material is reduced only to the Young's modulus.

![Figure 1. Sinusoidal stress and strain waveform in time.](image1)

![Figure 2. Graphic representation of the complex modulus components including the phase angle φ.](image2)

The term dynamic modulus is then used for the absolute value of the complex modulus calculated as the proportion of the maximum stress and the reversible axial deformation of the material, which is subjected to the repeated sinusoidal axial load pressure in the range at least from 0 to 25 kN at a specified temperature and load frequency. [1]

According to [2], at any combination of temperature and time, the linear viscoelastic behaviour of any material can be characterized by two properties. These are the total resistance to deformation and the relative distribution of this resistance between the elastic and viscous component. This pair of properties can be expressed in two ways according to [3]. The first method consists in the separation of the complex modulus into its real (elastic) part $E_1$ or $E'$, also called storage modulus, and the imaginary (viscous) part $E_2$ or $E''$, known as the loss modulus. The relationship of these two components is expressed by equations from (2) to (4):

$$E^* = E_1 + iE_2 = |E^*| \cdot \left(\cos(\phi) + i \cdot \sin(\phi)\right)$$  \hspace{1cm} (2)

$$E_1 = |E^*| \cdot \cos(\phi)$$  \hspace{1cm} (3)

$$E_2 = |E^*| \cdot \sin(\phi)$$  \hspace{1cm} (4)

The second and more common way of expressing the total resistance to deformation and the distribution of this resistance between elastic and viscous component is described in (5) and (6). It is also evident from Figure 2.

$$|E^*| = \sqrt{E_1^2 + E_2^2}$$  \hspace{1cm} (5)

$$\phi = \arctg\left(\frac{E_2}{E_1}\right)$$  \hspace{1cm} (6)
The elasticity of the material corresponds to its ability to store the deformation energy, while \( \tan(\phi) \) is the ratio of energy lost (converted into heat) and energy stored under cyclic deformation. The relative distribution of the elastic and viscous component is then the function of the material composition, the temperature and the loading time.

During the stiffness test, the force required for deforming the specimen and the phase delay between the signal of force and the signal of deviation are measured as the function of time. Based on these values, the value of complex modulus is set using the equations (7), (8), (9), (10), (11) and (12). These equations are based on the modified first-order approximation of the exact solution of the deformation due to pure bending.

\[
E_1 = \gamma \left( \frac{F}{Z} \cos(\phi) + \mu \omega^2 \right) \tag{7}
\]

\[
E_2 = \gamma \left( \frac{F}{Z} \sin(\phi) \right) \tag{8}
\]

where
- \( F \) = force applied to the beam (N),
- \( Z \) = beam deformation as measured (m),
- \( \phi \) = phase angle (rad),
- \( \omega \) = angular speed (rad/sec),
- \( \gamma \) = shape factor (1/m),
- \( \mu \) = weight factor, for classical test conditions the weight factor is negligible.

The \( \gamma \) and \( \mu \) factors are determined as follows:

\[
\gamma = \frac{L^2 A}{bh^3} \left( \frac{3}{4} - \frac{A^2}{L^2} \right) \tag{9}
\]

\[
\mu = R\{x\} \left( \frac{M}{\pi x^2} + \frac{m_1}{R(A)} \right) \tag{10}
\]

\[
R\{x\} = \frac{12L}{A} \left( \frac{1}{3 \frac{x}{L} - \frac{x^2}{L^2} - \frac{A^2}{L^2}} \right) \tag{11}
\]

\[
A = \frac{L-l}{2} \tag{12}
\]

where
- \( L \) = effective length of the beam (m),
- \( h \) = height of the beam (m),
- \( b \) = width of the beam (m),
- \( A \) = distance between the external clamp and the next internal clamp (m),
- \( l \) = distance of internal clamps (m),
- \( M \) = weight of the beam (kg),
- \( m_1 \) = weight of the movable part (kg) in location A (m),
- \( m_2 \) = weight of the movable part (kg) in location y (m),
- \( x \) = location of the probe for the beam deformation measurement (m). [3]
2. Measurements of complex modulus by the 4PB-PR method

Complex modulus was measured by the four-point bending test method (4PB-PR) according to [3]. Test specimen in the shape of beams with the dimensions of 50 x 50 x 400 mm were produced by cutting slabs (305 x 50 x 400 mm), which were produced by using the segmental compactor in accordance with [4]. The test specimens were cured for at least 28 days at laboratory temperature and relative humidity of 40-70%. The test was conducted in the controlled strain mode with the desired deformation of 50 microstrain. The measurements were performed at the temperatures of 0 °C, 10 °C, 20 °C and 30 °C. Lower or higher test temperatures are not necessary, because the use of the tested type of cold-recycled mixes is expected to the base layers, where the temperature variations usually don’t exceed that spectrum. For each tested temperature the measurements were performed at 9 chosen test frequencies (50, 30, 20, 10, 8, 5, 2, 1 and 0.5 Hz).

Composition of the tested mixes is presented in Table 1. For production of the tested mixes two kinds of bituminous binder were used – firstly the cationic slow-breaking bituminous emulsion C60B7, commonly used in the Czech Republic and secondly the foamed bitumen, which was produced by using the laboratory equipment Wirtgen WLB10S from common road bitumen 70/100. When preparing foamed bitumen, 3.8% of water were added into the hot asphalt binder (quantity determined in accordance with the procedure recommended by Wirtgen Manual [5]).

| Table 1. Composition of the tested mixtures. |
|---------------------------------------------|
| Mix A | Mix B | Mix C | Mix D | Mix E | Mix F | Mix G | Mix H |
| RAP 0/22 Středokluky | 91.0 % | 90.5 % | 94.0 % | 93.5 % | 93.0 % | 89.0 % | 91.5 % | - |
| Water | 2.5 % | 2.0 % | 2.5 % | 2.0 % | 2.5 % | 3.5 % | 3.5 % | - |
| Bituminous emulsion | 3.5 % | - | 3.5 % | - | - | - | - | - |
| Foamed bitumen | - | 4.5 % | - | 4.5 % | 4.5 % | 4.5 % | - | 4.5 % |
| Cement | 3.0 % | 3.0 % | - | - | 3.0 % | - | - | - |

Each measurement was always carried out on five specimens. The higher number of specimens was necessary because of the difficulties arising from the application of the test designed for hot mix asphalt to the cold recycled mixes. Nevertheless, the cold recycled mixes are characterized by high heterogeneity, bigger grain size, higher voids content and lower cohesion. The difficulties with the application of the 4PB-PR test on the cold recycled mixes were worsened also by the fact that it is a test highly prone to imperfections. As a result, even the production of the test specimens was already demanding, because the edges were often breaking off (see Figures 3 and 4).

The above mentioned reasons resulted in destruction of several specimens during the test itself, although the measurements of the complex modulus should be a strictly non-destructive test and the maximum strain occurring during the test is therefore limited to a much lower value than the one that should lead to the specimen breakdown. The specimen damage occurred in all cases at the test temperature of 30 °C. Possible difficulties at the highest temperature were assumed, based on the previous experience with the application of this test on cold recycled mixes. Therefore, the measurement at 30 °C was carried out as the last one after all the other test temperatures, and thus at least the number of test specimens for other temperatures was not reduced. Another consequence was the need not to count the value measured on some specimens to the average values, which were used
for subsequent calculations. If the value measured on a specimen differed too much from the average, it was not further used. Therefore, the resulting values were always the average of 3-5 measurements.

Figure 3. Test specimens of mix E after measurements of the complex modulus by the 4PB-PR method.

Figure 4. Test specimens of mix F after measurements of the complex modulus by the 4PB-PR method.

3. Discussion of results

The main advantage of the complex or dynamic modulus measurements consists in the fact that based on the values of the dynamic modulus set at various temperatures and frequencies it is possible to construct the so-called master curve. Master curve is currently the most comprehensive way to analyse the deformation behaviour of a bituminous mix under different conditions. Master curves for all tested mixtures were created by horizontal shifting of the experimental data in the program IRIS Rheo Hub. As the reference temperature, to which all the results of conducted measurements are related, was chosen 20 °C.

Figure 5 depicts the master curves for both components of the complex modulus of mixtures A-D and Figure 6 shows the phase angle master curves of these mixtures. For better comparison of the behaviour of the tested mixtures in a wide range of temperature and frequency with the behaviour typical for hot mix asphalt, these graphs also include values obtained on a conventional asphalt concrete ACO 11+.

Figures 5 and 6 show clearly that the influence of contained bituminous or hydraulic binder in a cold recycled mix has lower influence on the behavior of the two components of the complex modulus, than the fact that it is a cold recycled mix. In other words, all four cold recycled mixtures have relatively similar shape of master curves but they are all significantly different from the shape of the complex modulus master curves of hot mix asphalt. All cold recycled mixes have significantly lower viscous component of the complex modulus and thus also the phase angle. Their behaviour is therefore somewhere between the behaviour of elastic materials and the viscoelastic behaviour of conventional hot mix asphalt. The effect of bituminous binder type, contained in the cold recycled mixes, is almost negligible. The effect of contained hydraulic binder is, however, apparent from the graph. Mixtures A and B with 3 % of cement reach much higher values of the elastic component in the low frequencies and high temperatures. In the entire range of test temperatures and frequencies, mixtures A and B show lower values of the phase angle. Included cement causes a shift of the behaviour closer to the behaviour of an elastic material.
Overall, it is possible to describe the behaviour of cold recycled mixes under different conditions and the differences compared to the reference hot asphalt mix as follows. In the high test temperatures and low frequencies, both components of complex modulus are low for cold recycled mixes, which do not contain cement (mixture C and D), and the reference mix ACO 11+. Although in the case of mixes A and B the included cement results in higher values of the elastic component in the high test temperatures and low frequencies, they are still much lower than the values in the rest of the test
spectrum. Significant variation between the complex modulus components of different mixes under these conditions is interesting as well – in the mix ACO 11+ elastic modulus is almost equal to the viscous modulus and the phase angle therefore reaches around 45 °. In contrast, the phase angle of cold recycled mixes achieves approximately half of the ACO values, resulting in less viscous behaviour of the mix. This is a positive result. The mix will be less susceptible to permanent deformation under slow transport loading and exposure to high summer temperatures.

With increasing frequency and decreasing temperature, both complex modulus components of all five mixes are rising, however, the growth rate differs significantly. ACO 11+ shows more rapid increase in the elastic component and rapid reduction in the phase angle. On the other hand, the E1 and E2 master curves of cold recycled mixes are almost parallel and the phase angle of these mixtures remains almost unchanged at high temperatures and low frequencies. At medium temperatures and frequencies, the behavior of all five mixes is similar – both components of complex modulus are rising, phase angle decreases. Although the mix ACO 11+ generally achieves higher values of complex modulus at medium temperatures and frequencies, both of its components are in similar proportion as for the mix C and D. Hence, the phase angle of these three mixtures is also similar. Therefore, at the medium temperatures and frequencies, the behaviour of cold recycled mixes without added cement is the most similar to the behaviour of classic hot asphalt mixtures, which can be considered as an expected phenomenon. At the low temperatures and high frequencies there is a significant decrease in the loss modulus and the phase angle. This indicates that mixes lose their viscous behaviour and the material becomes completely elastic. The phase angle of the cold recycled mixes decreases faster than the phase angle of the mix ACO 11+. To conclude, in the low temperatures and high frequencies the cold recycled mixes show inferior qualities than the mix ACO 11+, therefore it can be assumed that they will be more susceptible to cracking.

![Figure 7. Master curves for the elastic and viscous component of the complex modulus of tested mixes E, F, G a H.](image-url)

Figures 7 and 8 show master curves for mixes E-H, again compared to the reference mixture ACO 11+. The graphs clearly show that the addition of 3% of pulverized concrete has no significant effect on the development of the measured characteristics as well. Further it was confirmed that the shapes of master curves are very similar, whether the mix comprises bituminous emulsion or foamed bitumen,
and that the different binder dosage also doesn’t bring any essential variance. From the group of four tested cold recycled mixes, the most different was the mix H, which contained RAP 0/11. The most distinct behaviour has again the reference mix ACO 11+.

**Figure 8.** Master curves for the phase angle of tested mixes E, F, G and H.

In the entire range of test temperatures and frequencies, both complex modulus components of mix F achieve higher values compared to mix E. Included pulverized concrete has according to the results similar effect as added cement, i.e. it increases the mixture stiffness and it increases the elastic component of the complex modulus. From the perspective of the entire spectrum of the viscoelastic behaviour of cold recycled mixes, mix F is closer to the purely elastic behaviour typical e.g. for concrete. On the other hand mix E behaves more viscous (achieves higher values of the phase angle), and therefore its behaviour is closer the behaviour of hot asphalt mixtures.

The graphs 7 and 8 show also that in the entire frequency spectrum, both complex modulus components of mix G are lower than for mixes E and F, and mix H achieves substantially lowest values of both complex modulus components. Besides that, the progress of elastic and viscous modulus of all tested cold recycled mixes is quite similar. As in mixtures A-D, with the increasing frequency and the decreasing temperature the real component of the master curve increases and its derivative gradually decreases till it almost reaches the zero value. This phenomenon correlates well with the transition of the material properties into the elastic area and reaching the equilibrium modulus. It was also confirmed that the cold recycled mixes and the reference mix ACO 11+ achieve similar phase angle values at middle frequencies and temperatures. The decline in the phase angle values in mixes E, F and G occur even at higher frequencies than in the mix ACO 11+, suggesting lower susceptibility of cold recycled mixes to cracking at low temperatures. The difference, however, is not significant and it does not correspond with the trend identified in mixes A-D.

Mix H shows the worst qualities also in terms of the phase angle at high frequencies and low temperatures – as the only one of the tested mixes, mix H shows inferior qualities than the reference mixture ACO 11+ (a decrease in the phase angle occurs already at much lower frequency values than in other cold recycled mixes). The behaviour of mix H is in this perspective closer to the behaviour of the reference mix ACO 11+, which is more temperature-dependent and frequency-dependent.
4. Conclusion
The main findings resulting from the investigation of the complex dynamic modulus and the subsequent master curves construction for the cold recycled mixes can be summarized in the following points:

- Cold recycled mixes are thermo-mechanically sensitive. However, the dependence on the test temperature and frequency is lower than in conventional hot asphalt mixes. This fact is evident from the flatter phase angle curve and the flatter elastic component curve of cold recycled mixes.
- At the lowest temperatures and highest frequencies, this material tends to behave almost elastically.
- The behaviour of cold recycled mixes is closest to hot asphalt mixtures behaviour at the medium temperatures and frequencies (similar value of the phase angle).
- At the highest temperatures and lowest frequencies, cold recycled mixes achieve roughly half lower phase angle values than the conventional hot asphalt mixes. The behaviour of cold recycled mixes is therefore closer to the behaviour of an elastic material. As a result the cold recycled mixes should be less susceptible to permanent deformation.
- Mixtures with 3 % of cement reach significantly higher values of the elastic complex modulus component at low frequencies and high temperatures. In the entire range of test temperatures and frequencies, they show lower phase angle than the mixes with no cement. Added cement causes a shift of the behaviour closer to the behaviour of an elastic material.

Acknowledgement
This paper was prepared under the funding of project TA04031256, supported by the Technology Agency of the Czech Republic, program Alfa.

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