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BALANCING DAMPING GAINS AND STRENGTH LOSSES IN RUBBER-MODIFIED CEMENT ASPHALT MORTAR

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ABSTRACT: Cement asphalt mortar (CAM) serves as a damping layer on non-ballasted tracks. The development of the damping characteristics of the CAM suggests using rubber powder as a substitute for fine aggregate to improve the damping properties. Rubber powder problems stem from potential significant decreases in mechanical properties. Meanwhile, the rubber content must be limited to achieve optimal mechanical and dumping properties. This study aims to systematically investigate the mechanical and damping characteristics of rubber powder-modified CAM to balance damping gains and strength losses. Mechanical properties are determined by compressive strength characteristics. Damping properties are determined by the damping ratio. Results showed that the rubber powder-modified CAM at 0%, 10%, 15%, and 20% exhibited that at 10% slightly decreased the compressive strength of CAM compared to 0%, while 15% and 20% significantly decreased it. The rubber powder-modified CAM at 10% exhibits better performance in terms of increasing the damping ratio, which has a relatively slight influence on the compressive strength loss of CAM. The rubber powder-modified CAM at 10% with a low asphalt content of 0.2 shows an increase in ductility, whereas at a high asphalt content of 0.6, it decreases compared to the rubber powder-modified CAM at 0%. The elastic modulus and dynamic modulus decrease with the rubber powder-modified CAM and significantly decrease with increasing asphalt content. The damping properties increased with the rubber powder-modified CAM and rose considerably with increasing asphalt content. The natural frequency decreases with the rubber powder-modified CAM and significantly decreases with increasing asphalt content.

Keywords: Rubber powder, Cement asphalt mortar, Mechanical properties, Damping properties, Non-ballasted track.

1. INTRODUCTION

The railway track system of high-speed trains has been developing for 50 years worldwide [1]. There exist two categories of railway tracks: ballasted and non-ballasted [2,3]. Non-ballasted track has been widely used on China's high-speed railway [4]. The non-ballasted track system consists of a strong concrete slab firmly attached to a concrete base, with a layer of cement-asphalt mortar (CAM). The CAM provides elasticity and damping, which reduces the dynamic movement of the non-ballasted track system, as shown in Fig.1 [5] . The primary role of the interlayer CAM is to act as a dampening layer [6,7]. A higher damping ratio results in better vibration reduction and a more effective vibration isolation effect on a non-ballasted track, or the natural frequency of the structure should be as low as possible [7]. Li et al. [8] studied the damping characteristics of CAM, and the results show that the damping ratio varies from 2.75% to 3.5%.

The CAM provides an elasticity and damping layer, which requires the mechanical properties to follow the China Railway Specifications (2008) CN 18598016A, which requires a compressive strength of greater than 15.0 MPa for type CAM with a high elastic modulus and greater than 1.8 MPa for type CAM with a low elastic modulus [9]. A CAM with a low elastic modulus is better suited for structures that need higher damping performance. A CAM with a high elastic modulus is ideal for structures that prioritize strength over damping performance [10].

The CAM consists of cement, water, asphalt emulsion, fine aggregate, and various other mixtures [11,12]. Asphalt-to-cement ratios significantly affected the mechanical properties of CAM [10]. The development of the damping characteristics of the CAM proposes the utilisation of rubber powder as a substitute for fine aggregate to increase the damping properties due to its energy absorption effect [8][13]. On the other hand, rubber powder from used tires will contribute to environmentally friendly systems, sustainable development, and the infrastructure of green initiatives [14]. In the process, rubber powder is used as a substitute for the fine aggregate in CAM [14,15]. The rubber powder can increase the damping ratio [16]. On the other hand, the problem of rubber powder arises due to a possible reduction in compressive strength [16–19].

Therefore, the rubber content must be limited to balance damping gains and strength losses [17]. Faizah et al. [18] reported that crumb rubber-modified aggregate on mortar with a ratio of 0.6 significantly improves the damping behaviour of mortar while reducing the compressive strength. Xunhao et al. [20] stated that replacing natural aggregate with rubber content should be limited to 20%–30%. Anin et al. [21] reported that, based on the workability of mortar, the rubber content is limited to a maximum proportion of 25%. Roychand et al. [16] suggested that rubber powder should not exceed 20% of the total aggregate volume. Davoodi et al. 2021 stated that a rubber-modified aggregate of 5% performs the best in terms of fluidity, flexural strength, compressive strength, and elastic modulus, and drying shrinkage of concrete [22]. The modification of concrete with rubber powder to improve its dynamic performance is well-established. However, the specific contribution of rubber powder modification to CAM applications in non-ballasted track remains limited. Therefore, further investigation is needed.

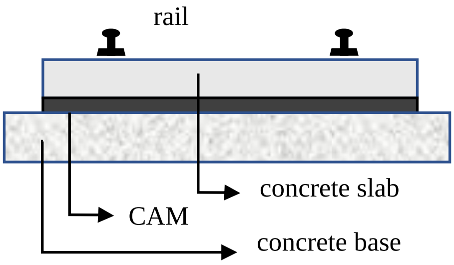

Fig.1. CAM interlayer on non-ballasted track

This study aims to investigate the mechanical and damping properties of rubber-powder-modified CAM to balance damping gains and strength losses. The mechanical properties of CAM studied include compressive strength characteristics, static modulus elasticity, dynamic modulus, damping ratio, and natural frequency. Compressive strength to confirm the balancing damping gains and strength losses of CAM. The logarithmic decrement method was used to analyse the damping properties of the rising free vibration dynamics of CAM, determined by pulse velocity.

Table 1 Properties of asphalt emulsion

Properties	Value
Viscosity, say bolt furol (25°C)	31
Storage stability 24 hours %	0.71
Distillation residue %	59.43

2. RESEARCH SIGNIFICANCE

This study provides novel insights into the dual role of rubber powder in cement asphalt mortar (CAM), balancing mechanical strength and damping performance for non-ballasted high-speed train tracks. Unlike previous studies focusing primarily on strength reduction, this research systematically investigates compressive strength, elastic and dynamic modulus, damping ratio, and natural frequency under varying asphalt contents and rubber powder dosages. The originality lies in identifying an optimal dosage (10%) that enhances damping properties with minimal strength loss, establishing a theoretical basis for performance-based CAM design. These findings contribute to developing durable, vibration-resistant, and sustainable non-ballasted track systems.

3. EXPERIMENTAL STUDY

3.1. Material

The cationic asphalt emulsion CSS-1h used in this study complies with ASTM D2397, and its properties are presented in Table 1. Styrene-butadiene rubber (SBR) polymer pH 10,0 was used to improve the compatibility between asphalt and cement according to Erlangga et.al [12]. Ordinary portland cement, as specified in ASTM C 150. The fine aggregate was river sand, falling within gradation II as specified in ASTM C 33, with a fine grain modulus of 3.0. The antifoaming agent, with a specific gravity of 0.85 g/cm³, solids content of 98%, and viscosity of 1000 mPa·s, was used to reduce foam bubbles during the asphalt emulsion mixing process. The expansive agent, a 320 mesh with 98.4% content, was developed to minimise shrinkage. To lower high water levels in the mix, superplasticizer polycarboxylate ether polymers, a water-reducing high-range type F as specified in ASTM C494/C494M (2008), were used. This study utilised rubber powder from car tire crumb rubber, classified as class 40-1 according to ASTM D5603-01, with its chemical composition in Table 2.

Table 2 Rubber powder chemical compositions (wt/%)

Chemical composition	Index mass %
C	83.73
SiO_2	6.34
SO_3	5.64
Cl	1.483
CaO	0.936
Fe_2O_3	0.136
NiO	12.0

3.2. The CAM mixing method

The mixing of CAM utilized a Hobart N50 brand mixer, following the ASTM C 305-99. The mixing method for cement asphalt mortar is briefly outlined as follows: a) In the initial stage, rubber powder and fine aggregate are blended in dry conditions for 1 minute. b) Modified aggregates mixed with rubber powder and cement are classified as dry components and are blended in dry conditions for 1 minute. c) The liquid (asphalt emulsion, SBR polymer, water, superplasticizer, antifoam) is mixed with the dry components and blended for 2 minutes. In the final stage, an expansive agent is added and blended for 1 minute. Mixing speed: 60 rpm, at room temperature (24 °C). The CAM specimens were stored in a moist room at a relative humidity of 50% in the environment (laboratory curing) until they reached the age of 28 days.

3.3. Composition of CAM

CAM type I represents the high elastic modulus CAM; the asphalt to cement ratio (A/C) was 0.2, while the ratio of fine aggregate to cement (FA/C) was set at 1.0, and the water cement factor (W/C) was fixed at 0.34. CAM type II represents the low elastic modulus CAM; the (A/C) ratio was 0.6, while that of the (FA/C) ratio was set at 1.5, and the W/C ratio was fixed at 0.44. For both CAM types I and II, the water-to-cement ratio does not include the water content of the fine aggregate, rubber powder, or asphalt emulsion. The fine aggregate and rubber powder are in a saturated surface dry condition. For both CAM type I and II, the ratio of SBR polymer to asphalt (SBR/A) is set at 5 %, the ratio of superplasticizer to cement (SP/C) is set at 1 %, antifoam to asphalt emulsion (AF/A) was set at 0.1%, and expansive agent to cement is set at 0.013%. The fine aggregate proportion, substituted with rubber powder to enhance the damping properties of CAM, is indicated with rubber contents of 0%, 10%, 15% and 20%, respectively. Table 3 shows the composition of CAM used in this study.

Table 3 Composition of CAM

Code	C	A/C	W/C	FA/(C+AE)	
				FA	RP
CAM type I					
A1	1	0.2	0.34	1.0 x100%	1.0x0%
A2	1	0.2	0.34	1.0x90%	1.0x10%
A3	1	0.2	0.34	1.0 x85%	1.0x15%
A4	1	0,2	0,34	1.0x80%	1.0x20%
CAM type II					
A5	1	0.6	0.44	1.5x100%	1.5x0%
A6	1	0.6	0.44	1.5x90%	1,5x10%
A7	1	0.6	0.44	1.5x85%	1.5x15%
A8	1	0.6	0.44	1.5x80%	1.5x20%

Description: C = cement; AE = asphalt emulsion; W = water; FA = fine aggregate, RP = rubber powder.

3.4. Method

3.4.1. Compressive strength test

The CAM compressive strength test samples consisted of cube specimens measuring 50 mm. The average compressive strength test results from 3 specimens were used to discuss the compressive strength at 28 days. The maximum permissible range between the CAM specimens is 8.7%, as specified in ASTM C109/C109M-99. The result of the ultimate load for confirmation acceptance of CAM material is based on the China Railway Specifications (2008) CN 18598016A.

3.4.2. Static modulus of elasticity test

The static modulus of elasticity test specimen was 3 cylinder measuring 100 mm in diameter and 200 mm in height. The modulus of elasticity of CAM applies to the stress range of 40% of the ultimate concrete strength, as specified in ASTM C469–02. The result was used to confirm the mechanical characteristics of CAM.

3.4.3. Dynamic modulus

The dynamic modulus of CAM was determined using pulse velocity, as specified in ASTM C 597. The Ultrasonic Pulse Velocity test produced the ultrasonic pulse of the CAM beam. The CAM beam specimens, with dimensions of 53 mm × 63 mm × 400 mm, conform to AASHTO T321-07. The specimen replication consists of 3 specimens.

3.4.4. Damping properties test

The damping properties test is conducted in accordance with ASTM E756-05. The simple laboratory adopted a beam-supported clamp-free design. The beam specimen is 50 x 63 x 400 mm. Three identical specimens were prepared. A 0.5 kg load was suspended at the center of each beam using a string. Once the string was cut, the beam entered a state of free vibration. The Dewesoft program converted the analogue signals into digital signals in the frequency domain and installed them on the computer. The free vibration test scheme is illustrated in Fig. 2. The amplitude, natural frequency (f), and number of cycles were measured using the Dewesoft program, and the damping ratio (ξ) is subsequently calculated. Fig. 3 shows the schema of logarithmic decay of the ratio of two (or more) successive amplitudes.

The damping ratio (ξ) is a function of the logarithmic decay of the ratio of two (or more) successive amplitudes of single-frequency oscillations, which can be expressed in the following Equation (1) [23]:

$$\xi = Ln\left[\frac{y1}{y2}\right] x\ 100\ x\ \frac{1}{n\ x\ 2\pi} \qquad (1)$$

Where:
ξ = damping ratio (%),
$y1$= amplitude maximum (g),
$y2$ = amplitude approximately at half of $y1$,
n = the number of cycles between $y1$ and $y2$, π = 3.14.

3.4.5. Microstructure of CAM

Investigation of the CAM microstructure uses a scanning electron microscope (SEM).

4. RESULTS AND DISCUSSIONS

4.1. Effect of rubber powder on compressive strength CAM

The effect of rubber powder on the compressive strength of CAM is shown in Fig. 4. CAM with A/C 0.2 shows a decrease in compressive strength at 7 and 28 days when fine aggregate is substituted with rubber powder at proportions of 0%, 10%, 15%, and 20%. The strength values at 7 days are 12.22 MPa, 11.88 MPa, 7.4 MPa, and 7.15 MPa, respectively. At 28 days, they are 16.36 MPa, 16.26 MPa, 9.1 MPa, and 8.8 MPa, respectively. Similarly, for CAM with an A/C ratio of 0.6, the compressive strength decreases to 4.62 MPa, 4.38 MPa, 4.19 MPa, and 3.86 MPa at 7 days, and to 6.24 MPa, 5.98 MPa, 5.18 MPa, and 4.71 MPa at 28 days.

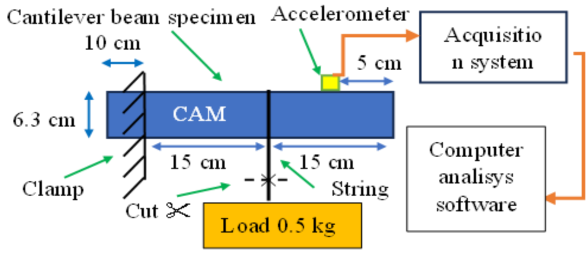

Fig.2. Free vibration test scheme

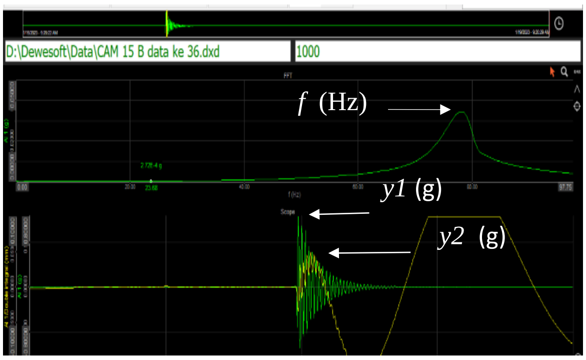

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Fig.3. The logarithmic decay of successive amplitudes

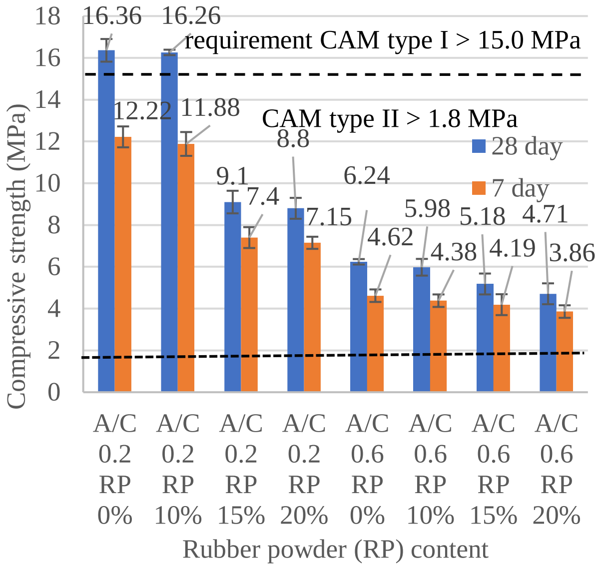


Fig.4. Compressive strength of the CAM with various A/C ratios and rubber powder (RP)

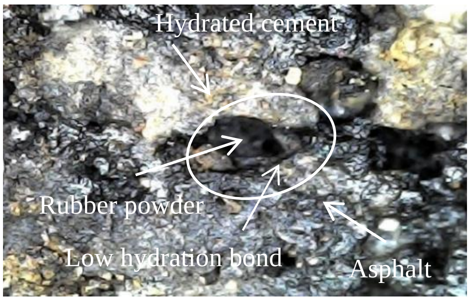


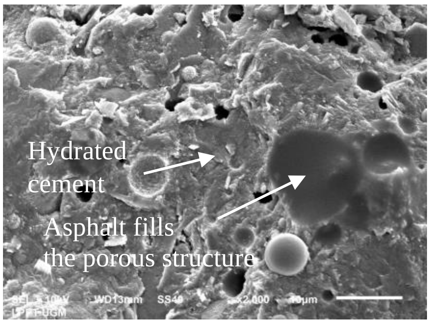
Fig.5. Rubber powder bond failure on the CAM (x100)

Fine aggregate is substituted with rubber powder at 10% resulting in a slight decrease in the compressive strength of CAM compared to that at 0%. In contrast, substitution at 15% and 20% leads to a more significant decrease in CAM. A decrease in the compressive strength of CAM is suggested due to the low hydration bond between cement and rubber particles in CAM. As shown in Fig. 5, the investigation of the CAM microstructure reveals that the rubber particles fail to bond with the cement paste. The impermeable characteristics of rubber powder result in poor adhesion between the rubber powder and the cement paste in CAM, which affects the hardened mortar's properties, rendering it porous and non-rigid. It leads to a compressive strength of mortar [16][24]. The deformation of the rubber particles is relatively larger than that of the cement particles, which results in a weak interfacial bond between the rubber powder and the cement matrix, and crack initiation results in decreased compressive strength [16][19].

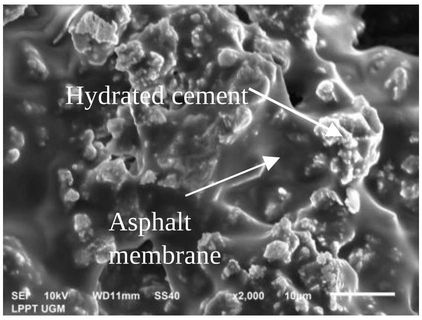
Recent results show that increasing asphalt emulsion content in rubber powder-modified CAM decreases its compressive strength, as shown in Fig. 4. The mechanical strength of CAM is enormously affected by the asphalt content [25,26]. Asphalt emulsion has a significant retarding effect on cement hydration, and this retarding effect increases significantly with increasing A/C ratio. The decrease in mechanical strength can be attributed to the effect of slowing cement hydration due to being blocked by emulsified asphalt granules [27].

Fig. 6. a) shows the CAM with a low asphalt content; the main structure of the CAM is formed by cement hydration, and asphalt bound to hydrated cement fills the porous structure of the CAM. This agrees with the statement by Qiang et al. 2011 that the functioning cement paste forms the main structural framework responsible for strength. Meanwhile, the asphalt phase is shown as a filling phase, resulting in a weak phase in the system structure [26].

Fig. 6. b) shows the CAM with a high asphalt content; the network created by the asphalt membrane and the framework built by the cement paste work together to contribute to the overall strength. However, these two structural frameworks are equally weak. As additional asphalt emulsion is incorporated, the function of asphalt in the CAM transitions from serving as a secondary binder to functioning as a primary binder. Increasing the asphalt content to A/C 0.6 results in the hydrophobic characteristic of the asphalt emulsion gradually becoming the primary phase in CAM, slowing down the hydration of the cement, and reducing the stiffness of the mortar [26].



a) CAM with A/C 0.2



b) CAM with A/C 0.6

Fig.6. Microstructure of the CAM with various asphalt content (x2000)

Fig. 7 shows the compressive strength and strain of the CAM with various A/C ratios and rubber powder (RP). Regarding the CAM A/C 0.2 and A/C 0.6, the substitution of 10% rubber powder resulted in a decrease in compressive strength. The CAM A/C 0.2 with rubber powder substitutions at 0% and 10% exhibits strain ductility of 1.44 and 6.69, respectively. The CAM A/C 0.6 with rubber powder substitutions at 0% and 10% exhibit strain ductility of 26.36 and 11.69, respectively. However, the CAM A/C 0.2 with 10% substituted rubber powder exhibits greater ductility compared to the control specimen. It is related that the elastic properties of rubber adhere to Hooke's law; rubber's elasticity enables it to retain its shape after deformation while absorbing mechanical energy, demonstrating its ductility [28].

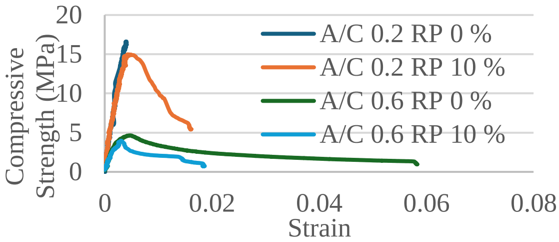


Fig.7. Compressive strength and strain of the CAM with various A/C ratios and rubber powder (RP)

The CAM A/C 0.6 with 0% rubber powder substitution is more ductile than CAM A/C 0.6 with 10% rubber powder substitution. It indicates that rubber powder affects the ductility of CAM at a low asphalt content (A/C 0.2). Still, it does not affect the increase in CAM ductility at a high asphalt content (A/C 0.6). Increasing the asphalt content more significantly improves the ductility of CAM. The stress gradually increases with axial strain during the early stage. However, after reaching the peak load of the CAM, the stress decreases slowly even as the strain continues to grow. The microstructure formed by cement and asphalt in CAM prevents a rapid drop in stress after the peak and enhances the fracture ductility [29]. It is related that asphalt emulsion is a viscoelastic material [30]. The viscoelastic material follows Newton's law and exhibits an increase in response strain to increasing stress. Therefore, applying stress increases the strain rate [28].

Increasing the ductility of CAM low asphalt content (A/C 0.2), substituted with 10% rubber powder, is related to the fact that rubber powder has elastic properties. Rubber has elastic properties that enable it to retain its shape after deformation while absorbing mechanical energy. The elastic properties of rubber follow Hooke's law and grow stronger with increased strain [28]. On the other hand, increasing the asphalt content more significantly increases the ductility of CAM. It is related that asphalt emulsion is a viscoelastic material [30]. The viscoelastic material follows Newton's law and exhibits a linear increase in response to increasing strain. Therefore, applying strain increases stress with the strain rate [28].

4.2. Effect rubber powder on the static modulus of elasticity CAM

Fig. 8 shows the modulus elasticity of the CAM with various A/C ratios and rubber powder (RP). On the CAM A/C 0.2 and A/C 0.6, which were substituted with 10% rubber powder, the modulus of elasticity of CAM decreased. It indicates that the addition of rubber powder decreases the elastic modulus of CAM. It relates to the ability of rubber to exhibit elastic properties, allowing it to maintain its original shape after deformation while absorbing mechanical energy and losing its modulus. Rubber exhibits elastic properties that enable the absorption of mechanical energy and a loss modulus [28].

On the other hand, Fig. 8 shows that the CAM A/C 0.6 results in a modulus of elasticity lower than CAM A/C 0.2. It indicates that increasing the asphalt content significantly reduces the elastic modulus of CAM, which is related to the asphalt emulsion as a viscoelastic material [30]. The viscoelasticity of a material is that the material can be elastic and viscous simultaneously under small stresses. It has the characteristics of dissipated energy and the loss modulus [7].

Fig. 9. a) shows the brittle failure characteristic of the CAM A/C 0.2 under compression, where the specimens were split into two halves, and the rapid failure is characterised by no plastic yield in the material and rapid crack propagation. Fig. 9. b) shows the failure mode of CAM A/C 0.2 with rubber powder 10%, which has a slightly ductile characteristic. More cracks were developed before failure, separating the specimen into many halves. This indicates that rubber powder results in a slightly ductile failure characteristic of CAM. Rubber exhibits elasticity properties that enable it to maintain its original shape after deformation while absorbing mechanical energy. It relates to the slightly ductile characteristic of CAM [28].

Fig. 9. c) illustrates a mode failure in the CAM A/C 0.6, whereas Fig. 9. d) depicts a mode failure in the CAM A/C 0.6 with 10% rubber content powder. Both exhibited the ductile characteristics of CAM under compression, with numerous cracks developing in the specimen before failure. Although the specimens experienced severe damage due to the development of multiple cracks, they remain intact and show no signs of separation. The specimens with a ductile failure mode show a high energy absorption capability. It indicates that increasing asphalt content results in the ductile failure characteristic of CAM. It is related that asphalt emulsion is a viscoelastic material [30]. The viscoelasticity of a material is that the material can be elastic and viscous simultaneously under small stresses. It exhibits characteristics of dissipated energy and a loss modulus. It relates to the ductile characteristic of CAM [7].

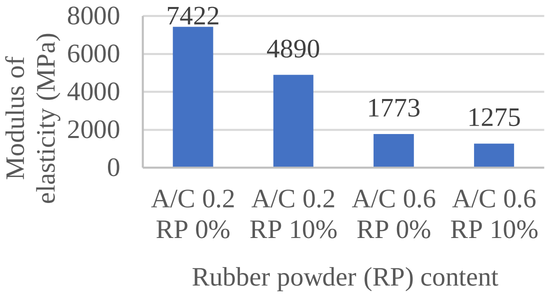


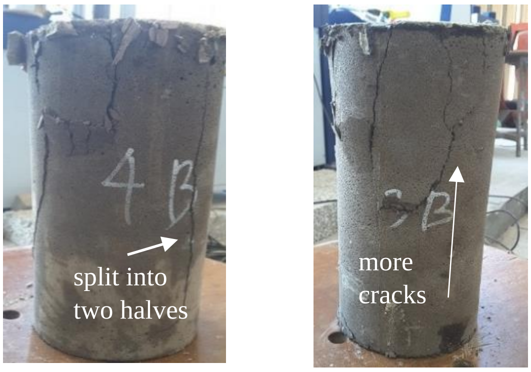
Fig.8. Modulus of elasticity of CAM with various A/C and rubber powder (RP)

4.3. Effect of rubber powder on the dynamic modulus of elasticity CAM

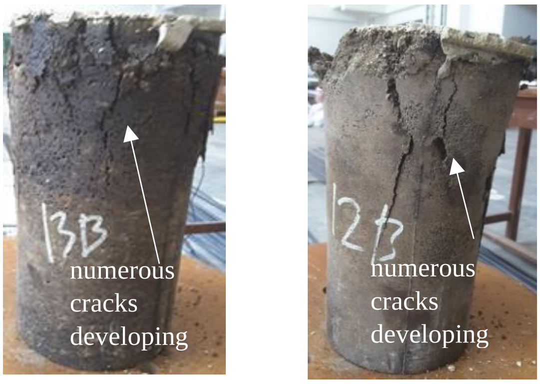
Fig. 10 shows the dynamic modulus of the CAM with various A/C ratios and rubber powder (RP). In the CAM A/C 0.2 and CAM A/C 0.6 samples, which were substituted with 10% rubber powder, the dynamic modulus of CAM decreased. This substitution with 10% rubber powder led to a reduction in the dynamic modulus of CAM. The CAM A/C 0.6 has a lower dynamic modulus than the CAM A/C 0.2. This indicates that rubber powder decreases the dynamic modulus of CAM. Meanwhile, increasing the asphalt content significantly reduces the dynamic modulus of CAM. This is related to the presence of rubber powder, resulting in a decrease in CAM density, as seen in Fig. 11. The density of CAM directly affects the resulting differences in UPV [31]. Rubber exhibits elastic properties that enable the absorption of mechanical energy and a loss modulus [28]. On the other hand, increasing the asphalt content significantly reduces the dynamic modulus of CAM, which is related to the asphalt emulsion as a viscoelastic material [30]. The viscoelasticity of a material is that the material can be elastic and viscous simultaneously under small stresses. It has the characteristics of dissipated energy and the loss modulus [7].

4.4. Damping properties of rubber powder-modified CAM

Fig. 12 shows the logarithmic decrement signal of CAM with various A/C ratios and rubber powder (RP). The damping ratio (ξ) is a function of the logarithmic decay of the ratio of two or more consecutive amplitudes of a single frequency oscillation [23]. The damping ratio can be calculated using Equation 1.



a) A/C 0.2 RP 0% b) A/C 0.2 RP 10%



c) A/C 0.6 RP 0% d) A/C 0.6 RP 10%

Fig.9. Compression failure mode of the CAM with various A/C and rubber powder (RP)

Fig. 13 shows the damping ratio of CAM with various A/C ratios and rubber powder (RP). When the fine aggregate is substituted at 10% with rubber powder, the damping ratio of CAM A/C 0.2 increased from 2.23% to 2.76%, and the CAM A/C 0.6 rose from 3.29% to 3.56%. It shows that rubber powder can increase the damping ratio in CAM at low (A/C 0.2) and high (A/C 0.6) asphalt content. However, the CAM at a high asphalt content (A/C 0.6) results in a higher dumping ratio than at a low content (A/C 0.2). The damping ratio of CAM increases significantly with the substitution of rubber powder and with the increase of asphalt content. It relates to the ability of rubber powder to fill the pores in the CAM structure, as shown in Fig. 5. The rubber powder-modified CAM becomes elastic, as illustrated in Fig. 7. The elastic properties of rubber adhere to Hooke's law and increase with greater strain. Rubber's elasticity allows it to keep its shape after deformation while absorbing mechanical energy, showcasing its damping ability [28].

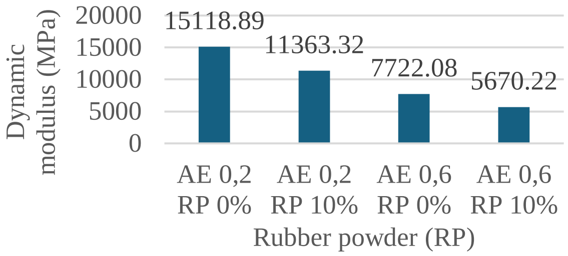


Fig.10. The dynamic modulus of CAM with various A/C ratios and rubber powder (RP)

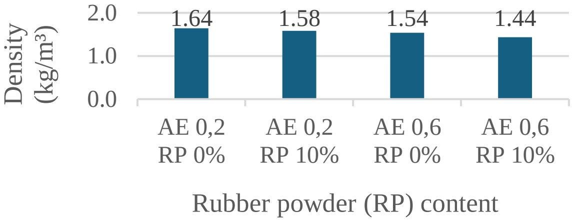
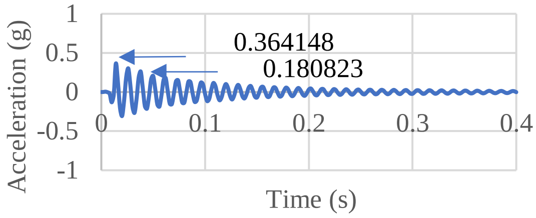


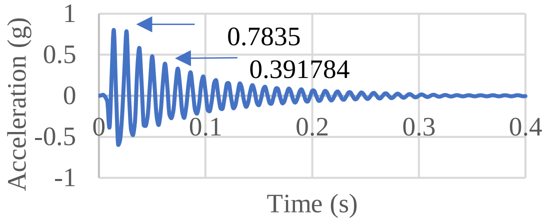
Fig.11. The density of CAM with various A/C ratios and rubber powder (RP)

Meanwhile, based on recent studies, increasing the asphalt content has a more significant impact on the dumping ratio of CAM. Asphalt emulsion is a viscoelastic material that can improve the phase angle between stress and strain, which reflects the damping ability of the viscoelastic material [30]. Viscoelastic materials experience a time delay in strain compared to stress [32]. The viscoelasticity of a material is that the material can be elastic and viscous simultaneously under small stresses. It exhibits characteristics of dissipated energy and a loss modulus. The dissipation energy and the loss modulus show the damping performance. [7].

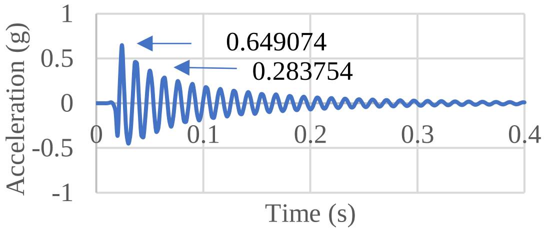
Rubber powder increases the damping ratio and decreases the elastic modulus of CAM [16]. Meanwhile, recent results show that asphalt content can significantly increase the damping ratio and decrease the elastic modulus of CAM. The damping ratio increases with a decrease in the elastic modulus of the CAM, as shown in Fig. 14. This phenomenon is attributed to the elastic properties of rubber, which allow for the absorption of mechanical energy and a loss of modulus [28]. Meanwhile, increasing the asphalt content increases the dumping ratio and reduces the elastic modulus of CAM. Asphalt emulsion is a viscoelastic material that can improve the phase angle between stress and strain. It reflects the damping ability of the material [30]. The damping ratio rises as the magnitude of cyclic shear strain increases [33]. Leiben. 2018 reported that the higher the loss modulus and energy dissipation, the better the damping performance [7].



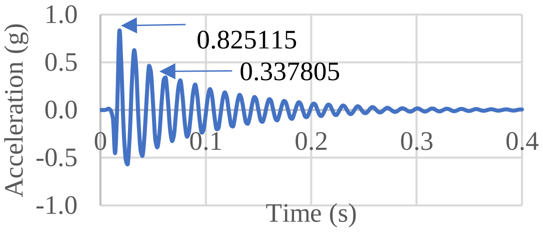
a) AE 0.2 PR 0%



b) AE 0.2 PR 10%



c) AE 0.6 PR 0%



d) AE 0.6 RP 10%

Fig.12. The logarithmic decrement signal of the CAM with various A/C and rubber powder (RP)

Fig. 15 illustrates the correlation between the damping ratio and the elastic modulus of CAM, following an exponential trend represented by Equation (2) :

$$y = 20.53\, x^{-0.244} \quad (2)$$

where: y = damping ratio, x = modulus of elasticity

The vibration decay in the damping graph is not strictly exponential, and a minor fluctuation exists. However, the exponential approach is based on the theoretical conceptualisation of the vibration decay in the damping curves [34].

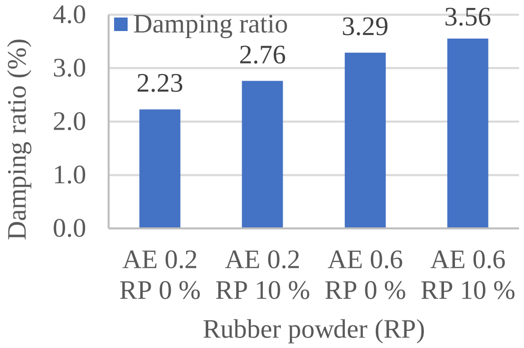


Fig.13. The damping ratio of the CAM with various A/C and rubber powder (RP)

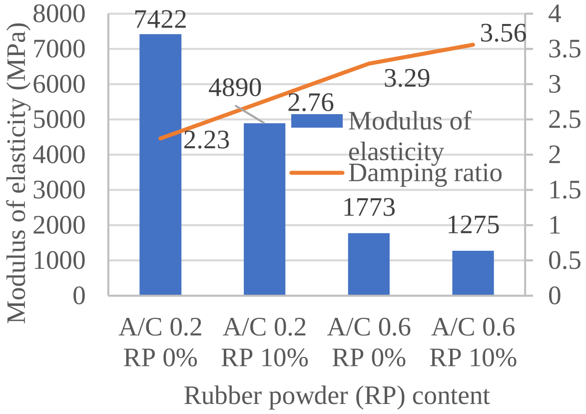


Fig.14. Modulus of elasticity and damping ratio of CAM with various A/C and rubber powder (RP)

Fig. 16 shows the results of the effect of rubber powder on the natural frequency of CAM with A/C 0.2 and A/C 0.6. When the fine aggregate is substituted with rubber powder 10%, the natural frequency of CAM A/C 0.2 decreases from 83.25 Hz to 80.08 Hz, and CAM A/C 0.6 decreases from 76.90 Hz to 70.56 Hz. The natural frequency of CAM decreases with the substitution of rubber powder and an increase in asphalt content. The decreasing natural frequency of CAM indicates a decrease in the stiffness of the CAM. According to Faizah 2019, the decreasing natural frequency of the beam concrete indicates the decreasing stiffness of the beam concrete [18]. Rubber has elastic properties that enable it to retain its original shape after deformation, absorb mechanical energy, and decrease in modulus. [28]. Meanwhile, based on recent studies, increasing the asphalt content has a more significant effect on decreasing the natural frequency of CAM. It is related that asphalt emulsion is a viscoelastic material [30]. The viscoelasticity of a material has characteristics of dissipated energy and the loss modulus [7].

Ridengaoqier (2021) reported that a quadratic function of modulus elasticity can express the natural frequency of concrete, based on both theoretical and experimental evidence. A decrease in the elastic modulus of concrete represents a decrease in the natural frequency [35].

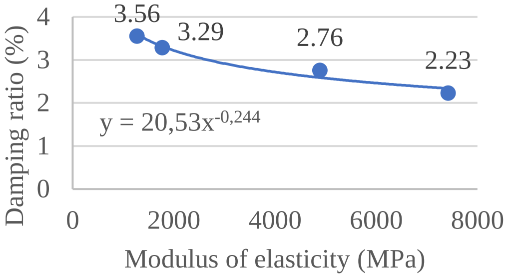


Fig.15. Damping ratio and modulus of elasticity of the CAM

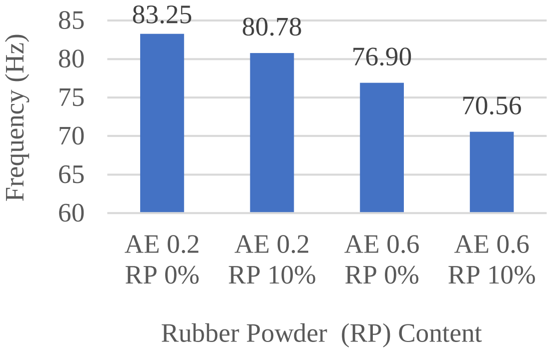


Fig.16. Natural frequency of CAM with various AE and rubber powder (RP)

5. CONCLUSIONS

Based on studies of the mechanical and damping characteristics of rubber-powder-modified CAM used as interlayers on non-ballasted tracks in high-speed trains. The results obtained include the compressive strength characteristics, modulus of elasticity, dynamic modulus, damping ratio, and natural frequency of CAM. The rubber powder content of 15% and 20% significantly decreases the compressive strength of CAM. Meanwhile, the rubber powder content of 10% results in a slight decrease in compressive strength compared to that at 0%. The rubber-modified aggregate at 10% in CAM exhibits better performance in terms of balancing compressive strength loss, and increased damping ratio. The rubber powder increases the ductility of the CAM with low asphalt content. Nevertheless, on the CAM with high asphalt content, the asphalt content significantly increased the ductility more than the rubber powder. The rubber powder decreases the CAM's elastic modulus and dynamic modulus, which significantly decreases with increasing asphalt content. By incorporating the rubber powder and increasing the asphalt content, the CAM's elastic modulus decreases. The rubber powder decreases the dynamic modulus of the CAM and significantly decreases with increasing asphalt content. The damping ratio of CAM increases with the substitution of rubber powder and significantly increases with increasing asphalt content. By incorporating the rubber powder and increasing the asphalt content, the damping ratio of CAM increases. The natural frequency of the CAM decreases with the substitution of rubber powder and significantly decreases with increasing asphalt content.

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