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The influence of aggregate gradation properties on the characteristics of cold mix asphalt emulsion

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ABSTRACT

Cold Mix Asphalt Emulsion (CMAE) has the potential to serve as an environmentally friendly, efficient, and accessible alternative for road construction, as it eliminates the need for heating during production and can be compacted at low temperatures. One of the key factors affecting CMAE performance is the aggregate gradation used in the mixture. This study aims to analyze the effects of aggregate gradation on the volumetric characteristics, mechanical properties, and durability of CMAE. Laboratory experiments were conducted using several aggregate gradation types. The results indicate that the middle-limit gradation (G. L2) produced the highest dry density, while the lowest air void content was found in gradation G. L1. The mechanical properties, including soaked stability and Indirect Tensile Strength (ITS), were positively correlated with dry density, as they are influenced by aggregate structure, the asphalt emulsion content, and its asphalt adhesion quality. CMAE durability measured through moisture susceptibility (TSR) and mass loss (Cantabro loss test) was affected by the gradation type, asphalt–aggregate bonding, and water content in the mixture. Overall, aggregate gradation plays a critical role in determining CMAE performance. Notably, optimal performance is achieved when the mixture has fully lost its moisture, allowing for maximum asphalt binding efficiency. These findings highlight the importance of selecting appropriate aggregate gradation in CMAE design to enhance performance outcomes.

Keywords: aggregate gradation; cold mix asphalt emulsion; durability properties; mechanical properties; volumetric properties

1 Introduction

Types of asphalt mixtures based on mixing and compaction temperatures consist of Hot Mix Asphalt (HMA), Warm Mix Asphalt (WMA), and Cold Mix Asphalt (CMA). CMA is an asphalt mixture produced at a low mixing temperature so that it does not require heating and energy consumption to reduce asphalt viscosity than WMA and HMA [1], [2], [3], [4]. HMA is mostly produced with a mixing temperature above 140°C [5], [6], while the mixing temperature of WMA is lower, around 20°C - 40°C compared to HMA, using additives to reduce the viscosity of the asphalt [4], [7]. CMA is produced at low temperatures, thus significantly reducing the impact of global warming and CO_2 emissions due to the asphalt heating process and providing a good working environment for production staff [6], [8]. CMA can be classified into several types, namely asphalt mixtures using cutback asphalt (cold lay macadam), foam asphalt, and Cold Mix Asphalt Emulsion (CMAE) [1], [4], [6], [9]. CMAE is an alternative asphalt mixture solution that is environmentally friendly and economical compared to Hot Mix Asphalt (HMA) [1], [10].

CMAE uses asphalt emulsion as a binding material, which has advantages including low energy consumption and reduced pollution due to reduced greenhouse gas emissions, reduced risk of health and safety hazards at work, and applications carried out at low temperatures and adjusting to environmental temperatures. CMAE is an alternative road pavement construction material that is more environmentally friendly because it reduces energy use and reduces pollution due to emissions from the asphalt heating process which is generally carried out on low WMA and HMA [11], [12], [13]. CMAE can be mixed and

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compacted at low temperatures or ambient temperatures, allowing work to be carried out in various weather conditions without the need for special heating equipment, as well as increasing the flexibility of work in the field [11], [14]. In general, the CMAE mixing temperature ranges between 0°C - 40°C, due to the nature of asphalt emulsion which is liquid at low temperatures or adjusts to the ambient temperature to achieve the desired asphalt viscosity during the asphalt mixture production process [3]. The use of recycled material technology can be applied together with CMAE, so that it can reduce construction costs, energy costs, and environmental sustainability [15], [16], [17]. CMAE can be used as a road pavement construction material and also as a road maintenance material such as maintaining potholes by patching holes using CMAE.

Several aspects that affect the mechanical performance of CMAE include: CMAE has low initial strength at the start of construction because the mixture still contains water, volumetric properties of the mixture including the density of the asphalt mixture and air voids/Void in Mix (VIM), aggregate properties, quality of asphalt emulsion, additive materials [18], [19], [20], [21], [22]. CMAE has low initial strength, this is because the asphalt emulsion still contains water so it needs curing time until the water content in the mixture disappears [23], [24], [25], [26]. One way to strengthen the performance of CMAE at an early age after compaction is by adding additives such as cement, epoxy, styrene butadiene styrene block polymer (SBS), etc [27], [28], [29], [30]. Because there is water content in CMAE, compaction must be carried out as optimally as possible, when the water content in CMAE disappears, the space will be filled with air so that there are air voids in the asphalt mixture. One of the aggregate properties that has an effect on the performance of the asphalt mixture is aggregate gradation, aggregate gradation will affect the performance of CMAE [22], [31], [32]. The properties of asphalt emulsion will determine the quality of asphalt emulsion as an asphalt binder. Based on particle charge, asphalt emulsion is divided into cationic asphalt emulsion and anionic asphalt emulsion so that the type of asphalt emulsion that will be used for the asphalt mixture will be adjusted to the type of rock material from the aggregate [33]. The additives added to CMAE function to improve the performance of CMAE at an early age. In addition, additives can also be added to improve the performance of CMAE properties [34].

Aggregate gradation is one aspect of aggregate properties that affect the performance of asphalt mixtures from volumetric properties, mechanical properties, and durability properties. Aggregate gradation will affect the volumetric properties of the mixture, and the composition of the particle size distribution in the aggregate, asphalt, and air will affect the weight and volume aspects of asphalt [31], [35]. Aggregate gradation can affect volumetric parameters such as air void, Void in Mineral Aggregate (VMA), Void Filled with Asphalt (VFA), and asphalt mixture density. One aspect that affects the mechanical performance of asphalt mixtures is aggregate gradation, mechanical parameters such as deformation/rutting resistance, fatigue, stiffness, and indirect tensile strength can be affected by aggregate distribution [36], [37], [38], [39]. The durability properties of asphalt mixtures can be affected by aggregate gradation because aggregate gradation will affect water voids and asphalt content, proper aggregate gradation will increase the durability of asphalt mixtures against loads and environmental conditions. Proper aggregate gradation with controlled aggregate distribution will achieve optimal water voids and asphalt content, maximum mechanical performance against rutting and fatigue, and resistance to loads and environmental conditions.

Several studies related to gradation and CMAE research have been conducted to determine the effect on CMAE performance. Research conducted by Xu et al. [31] that aggregate gradation and asphalt content on the properties of asphalt emulsion mixtures with cement, the results of the ITS value are influenced by the correct gradation and asphalt content, the cantabro loss value depends on the aggregate gradation in addition to being influenced by the content of asphalt emulsion and cement and the balance of the fractal dimension value of the aggregate, the density and adhesion of asphalt are the main factors in increasing the mixture of asphalt emulsion with cement. Research conducted by Zhu et al. [22], [32] on asphalt emulsion cold recycled mixture resulted in coarser aggregate gradation will produce higher bulk density while finer gradation will increase asphalt content and long-term durability. Research on aggregate gradation on CMAE performance and CMAE applications in Indonesia is still limited because there are more HMA applications, and the specifications used use special specifications [40], so that it is necessary to conduct research on aggregate gradation on the influence of volumetric properties, mechanistic properties, and durability properties. This study aims to analyze the effects of aggregate gradation on the volumetric characteristics, mechanical properties, and durability of CMAE.

To achieve the research objectives of analyzing the effect of aggregate gradation characteristics on CMAE properties, a series of systematic stages were carried out. The first stage begins with examining the properties of aggregate and asphalt emulsion and making several CMAE samples with variations in aggregate gradation. Testing of volumetric properties parameters, such as dry density, air voids, VMA, and VFA play an important role in showing the balance between air voids and asphalt in the mixture. The mechanical properties tested include marshall stability and ITS. The durability properties tested were the TSR value of the ratio of soaked ITS to dry ITS, as well as the mass loss value of the cantabro loss test conducted to evaluate the wear resistance or loss of aggregate particles in dry conditions. The findings of this study are expected to provide information on the correct aggregate gradation that plays a role in determining the performance of CMAE. The results obtained are expected to provide a scientific contribution in the form of a deeper understanding of the relationship between aggregate gradation and CMAE properties.

2 Data and Methods

This research was conducted through a systematically designed laboratory experiment to analyze the effect of aggregate gradation properties on CMAE characteristics. All data collection procedures, data processing, and analysis refer to technical standards such as ASTM and special specifications of Ministry of Public Works of the Republic of Indonesia (MPW-RI) [40], as well as additional references from the technical guidelines of the Asphalt Institute. Data collection techniques using laboratory experimental methods. Data collection is carried out through a series of laboratory testing stages involving standard equipment and materials that have been prepared. All test data are collected and then processed using quantitative methods.

2.1 Aggregate Gradation

The research process began with the material preparation stage, which included the selection and characterization of both aggregates and asphalt emulsion. Once the material properties were identified, CMAE samples were prepared using several aggregate gradation variations based on the target gradation curve. The Dense Graded Emulsion Mixture (DGEM) Type IV gradation, as specified by the Ministry of Public Works of the Republic of Indonesia (MPW-RI)[40], and field gradation obtained from aggregate bleeding observations were adopted. DGEM Type IV gradation was selected because it is typically applied in surface course asphalt pavement. The aggregate gradations used in this study comprised the lower limit (G.L3), middle limit (G.L2), and upper limit (G.L1) of the DGEM Type IV specification, along with two field gradations, G.B1 and G.B2. The latter were obtained by adjusting aggregate mixtures to match the specification range between the upper and lower limits. In total, five aggregate gradation variations were evaluated in the CMAE mixtures, as illustrated in Figure 1. Finer gradations generally lie above the G.L2 curve, while coarser gradations tend to fall below it.

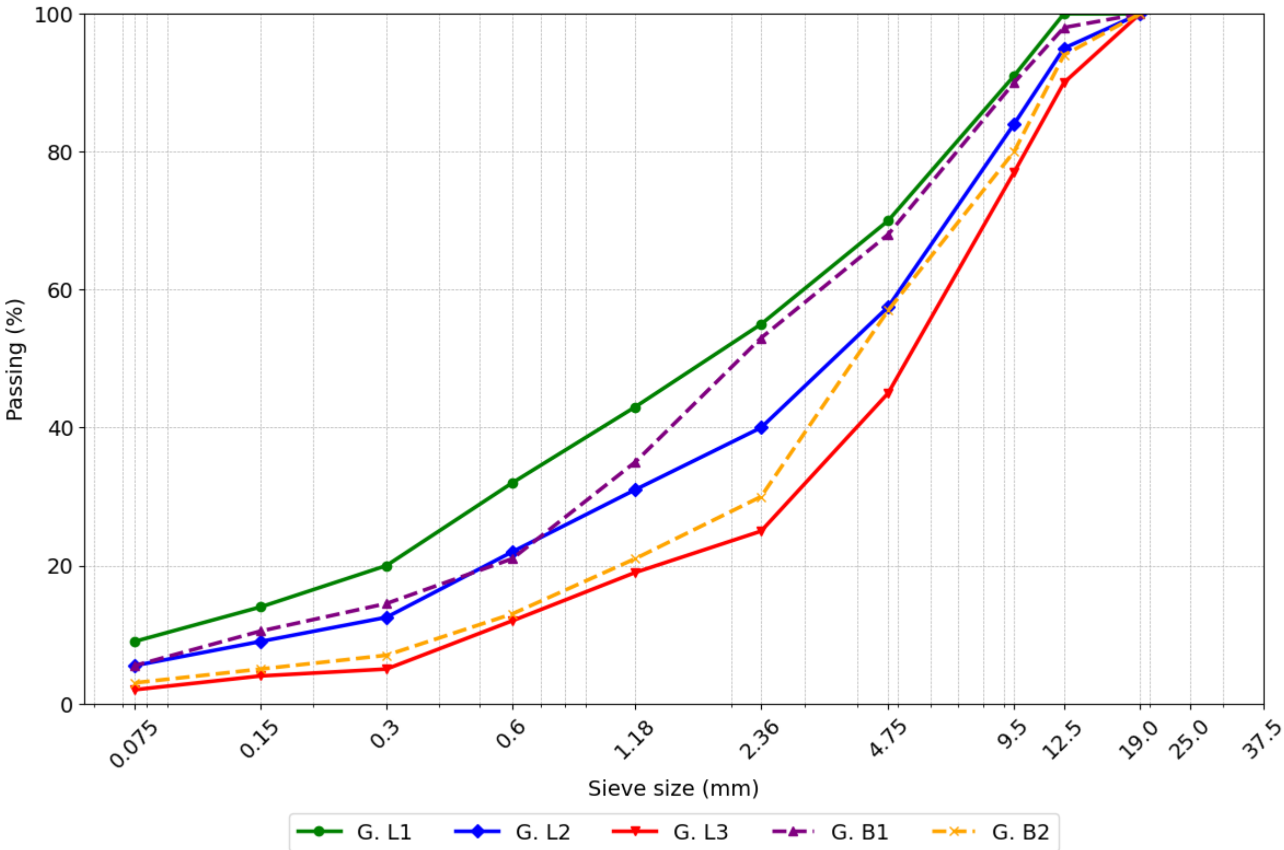

Figure 1. Aggregate gradation of CMAE

2.2 Estimation of Residual Asphalt Content and Asphalt Emulsion

Estimation of residual asphalt content and initial emulsion asphalt content is an important step in the CMAE design process. The main purpose of this stage is to estimate the amount of residual asphalt that will remain after the water in the emulsion asphalt evaporates and to determine the initial emulsion asphalt content that is in accordance with the characteristics of the mixture and the implementation method. The residual asphalt content is needed as a basis for calculating the initial emulsion asphalt content, because the residual content will affect the final performance of the asphalt mixture, especially at the aggregate coating stage, determining the compaction energy, and as a reference in determining the Optimum Residual Asphalt Emulsion Content (ORAC). The initial residual asphalt content is calculated using Equation 1 and the emulsion asphalt content is calculated using Equation 2 developed by the Asphalt Institute with the modification that the aggregate limits used, namely coarse aggregate is aggregate retained 4.75 mm while fine aggregate is aggregate that passes the 4.75 mm sieve and retained 0.075 mm, and filler is aggregate that passes the 0.075 mm sieve.

$$P = (0.05A + 0.1B + 0.5C) \text{ x } (0.7) \tag{1}$$

$$EAC = (P/X)\% \tag{2}$$

where P is the percentage of residual asphalt emulsion (%), A is the percentage of coarse aggregate (%), B is the percentage of fine aggregate (%), C is the of percentage filler (%), EAC is the percentage asphalt emulsion (%), and X is the percentage residual of asphalt emulsion (%).

After the initial asphalt content is determined, several variations of residual asphalt content are made. Variations in residual asphalt content are made to make samples in determining the ORAC value. Each variation of gradation made will be determined by the ORAC value so that each variation of gradation with the ORAC value will be searched for CMAE properties. Residual asphalt is the residue of asphalt emulsion and is the asphalt content without any water content in the asphalt emulsion. ORAC needs to take into account the effective asphalt content that covers the aggregate and the absorbed asphalt content absorbed by the aggregate. The effective asphalt content is the percentage of asphalt that covers the aggregate calculated from the difference between the total asphalt content and the aggregate absorbed asphalt content calculated using Equation 3 and Equation 4.

$$P_{ba} = 100 \frac{SG_{agg.eff} - SG_{agg.bulk}}{SG_{agg.bulk} \text{ x } SG_{agg.eff}} SG_{b} \tag{3}$$

$$P_{be} = P - \frac{P_{ba}}{100} P_s \tag{4}$$

where P_{ba} is the asphalt absorption (%), $SG_{agg.eff}$ is the effective specific gravity of aggregate, $SG_{agg.bulk}$ is the bulk specific gravity of aggregate, SG_b is the specific gravity of residual asphalt from asphalt emulsion, P is the total residual asphalt content (%), and P_s is the percentage of aggregate to the total mixture (%).

Asphalt Film Thickness (AFT) is the thickness of the asphalt layer that covers the surface of the aggregate in the asphalt mixture. The role of this film thickness is very important because the layer protects the aggregate from water attack and oxidation, which ultimately has a direct effect on the service life and resistance of the mixture to premature damage. The ideal film thickness can maintain the flexibility of the mixture without sacrificing its strength. The asphalt film thickness is calculated using Equation 5.

$$AFT = \frac{P_b}{100 - P_b} \text{ x } \frac{1}{SG_b} \text{ x } \frac{1}{ASA} \text{ x } 100 \tag{5}$$

where AFT is the asphalt film thickness, P_b is the residual asphalt content, SG_b is the specific gravity of the residual asphalt, and ASA is the aggregate surface area.

2.3 Coating Test of Asphalt Emulsion with Aggregates

The coating test was conducted to determine the optimum water content required in the CMAE mixing process. The optimum water content plays an important role in reducing the viscosity of the asphalt emulsion, thus facilitating the coating of the aggregate surface by the asphalt emulsion evenly and effectively. To find the optimum water content, the mixture was tested using variations in water content (3%, 4%, 5%, 6%, and 7%) of the total aggregate weight, this value was taken based on the research approach of Zhu et al. [22]. The evaluation process was carried out visually on the mixing results at each variation of water content. Determination of the optimum water content was carried out by visual assessment, namely when the asphalt emulsion could evenly cover the aggregate surface without looking too thin due to excess water, or too stiff due to lack of water.

2.4 Determination of Compaction

Determination of compaction energy in CMAE is carried out to ensure that the compaction process is able to produce optimal mixture density so that it meets the technical requirements related to porosity and immersion stability [24]. The right compaction energy is very important to achieve structural stability and durability of the mixture against environmental conditions to achieve the required performance parameter specifications of the mix. In laboratory activities, compaction is carried out using a Marshall compactor because the sample-making method uses the Marshall method, with two variations in the number of impacts, namely: first, 2 x 50 impacts (each side of the sample), 2 x 75 impacts and 2 x (2 x 75) impacts. This variation is designed to evaluate the effect of the compaction level on the physical characteristics of the mixture. The amount of compaction 2 x (2 x 75) was selected as the optimal compaction based on the combination that showed the best results in good mixture characteristics by considering the value of air voids and dry density.

2.5 Preparation of CMAE Samples

The CMAE mixture is made with variations in aggregate gradation. The mixture is arranged through the proportion between aggregate, filler, and asphalt emulsion, by adding the optimum water content that has been previously determined through the blanket test. This process is designed to produce a homogeneous mixture that can represent field conditions representatively. After the mixing is complete, the mixture is inserted into the test specimen mold and compacted using the compaction method and the amount of compaction that has been previously determined. After the compaction process is complete, the sample is not immediately removed from the mold. The sample is first left in a room at room temperature for approximately 24 hours to allow the bonding process and water evaporation to take place naturally. After the conditioning period is complete, the sample is released from the mold and is ready to be used for the mechanical and volumetric characteristics testing stage of the mixture as illustrated in Figure 1.

Before testing the CMAE specimens, the samples undergo a curing stage intended to stabilize the physical and chemical properties of the mixture and ensure that their condition reflects actual field conditions. The curing process allows sufficient time for the asphalt emulsion to react and bond effectively with the aggregates. This conditioning stage consists of three methods: oven curing, capillary soaking, and full curing, which are carried out as follows:

1. Oven curing
   After the compaction process is complete and the samples are released from the test specimen mold, each sample is then conditioned in an oven at a controlled temperature of 40°C for approximately 24 hours. This stage aims to accelerate the evaporation of free water and assist the initial bonding process between the residual asphalt and the aggregate. After drying in the oven, the samples are not tested immediately but are left in an open space at room temperature for approximately 24 additional hours. This conditioning time is intended to allow the internal temperature and humidity of the sample to reach stability, which is important to ensure accurate and representative test results.
2. Capillary soaking
   After the oven curing stage, the sample then enters the capillary immersion stage. This process is carried out by immersing half the height of the sample thickness into a room temperature water bath for about 24 hours. After that, the sample is turned over and the other side is immersed again for 24 hours with the same procedure. The purpose of this capillary immersion is to simulate humid field conditions and to test the resistance and performance of the mixture against water penetration from the surrounding environment. Capillary soaking is carried out to find the water absorption value.
3. Full curing
   In this process, the sample is cured at room temperature 25°C until it reaches a constant sample weight, which indicates that all the water in the mixture has evaporated and the mixture is in a perfectly dry condition.

Figure 1. Preparation of samples for curing

2.6 Determination of ORAC

ORAC determination is one of the important stages in the CMAE mix design process, which aims to obtain the optimal residual asphalt content that can produce a good-performing asphalt mix and meet the established technical standards. ORAC selection is carried out through an evaluative approach to several parameters such as immersion stability and air voids in the mix which are the main indicators in assessing the quality and resistance of the mix to environmental influences and traffic loads. In addition to these two main parameters, the analysis also includes additional characteristics of the mix such as the level of mix density, aggregate water absorption, and the thickness of the asphalt film formed around the aggregate grains. These three supporting parameters are evaluated based on the relevant specification limits, to ensure that the mix is not only structurally stable but also has adequate durability against wet conditions or temperature changes. ORAC value determination is carried out by identifying the Residual Asphalt Content (RAC) range that can meet all of these technical parameters, and then determining the optimal value at the midpoint of the CMAE properties range that meets the specifications.

2.7 Volumetric Properties of CMAE

Some volumetric properties that can be searched include: dry density, air voids, VMA, and VFA. Density is the ratio of the weight of the asphalt mixture to the volume of the asphalt mixture. For CMAE, the density parameter used is the dry density when the mixture does not contain water, which is calculated using Equation 6. The water content used when calculating dry density is the water content of the compacted mixture. Air voids are the air spaces between aggregate particles covered by asphalt in a compacted mixture and are expressed as a percentage of the total volume of the mixture, which can be calculated using Equation 7. VMA is the space between aggregate particles in a compacted asphalt mixture, expressed as a percentage of the total volume of the mixture, which can be calculated using Equation 8. VFA is the percentage of space between aggregate particles/VMA filled with asphalt and does not include asphalt absorbed by the aggregate, expressed as a percentage of VMA calculated using Equation 9.

$$D_{dry} = \frac{(100 - P_{RBC})}{(100 + P_{RBC} + w)} D_{wet} \quad (6)$$

$$VIM = \left(1 - \frac{D_{dry}}{SG_{mix}}\right) x\ 100 \quad (7)$$

$$VMA = 100 - \left(\frac{P_s}{SG_{agg.bulk}}\right) x\ D_{dry} \quad (8)$$

$$VFA = \frac{VMA - VIM}{VMA} x\ 100 \quad (9)$$

where D_{dry} is the dry density of the asphalt mixture (gr/cm^3), D_{wet} is the wet density of the mixture where the mixture still contains water after compaction (gr/cm^3), P_{RBC} is the residual asphalt content (%), w is the water content of the mixture after compaction (%), VIM is the air voids (%), SG_{mix} is the specific gravity of the mixture (%), $SG_{agg.bulk}$ is the bulk specific gravity of the aggregate (%), VMA s the percentage of space between aggregate particles in an asphalt mixture (%), and VFA is the percentage of space between aggregate particles/VMA that is filled with asphalt and does not include asphalt absorbed by the aggregate (%).

The proportion of aggregate fraction sizes plays a key role in determining aggregate gradation and its corresponding fineness modulus. The fineness modulus is an empirical factor of how coarse or fine the aggregate gradation [31]. The higher the value of the aggregate gradation fineness modulus, the coarser the aggregate shows. Finer aggregate gradation will tend to have a higher aggregate surface area so that the asphalt content required in the asphalt mixture will increase [41], [42]. The asphalt content plays a role in coating the aggregate surface and filling the cavities between aggregate particles, with changes in aggregate gradation, the surface area and cavities between particles change. The aggregate surface area increases with increasing aggregate fineness, so fine aggregates require high asphalt content. The aggregate fineness modulus can be calculated using Equation 10.

$$F_m = (A_i + \cdots + A_{0.15})/100 \quad (10)$$

where F_m s the fineness modulus of aggregates and A_i s the cumulative percentage of aggregates retained on the sieve size (the cumulative percentage of aggregates retained on the sieve size is calculated up to the one retained on the 0.15 mm sieve).

2.8 Mechanical Properties of CMAE

Mechanical properties of asphalt mixtures are physical and structural properties of asphalt mixtures that show the asphalt mixture responds to external forces (loads), temperature changes, and time. Some of the mechanical characteristics of asphalt mixtures that were tested include: Marshall stability, indirect tensile strength, stiffness modulus, dynamic modulus, resistance to permanent deformation/rutting, fatigue, etc. Testing the mechanical parameters of asphalt mixtures is very important to ensure pavement performance, identify potential problems with asphalt mixture properties, and determine the optimal mixture design.

2.8.1 Marshall Test

Marshall testing is one of the methods in evaluating the performance of asphalt mixtures, especially to determine the stability and flow values of the mixture [43], [44]. Stability parameters describe the resistance of the mixture to permanent deformation due to traffic loads, while the flow value indicates the flexibility of the mixture when receiving pressure. In the context of the CMAE mixture, this test is directed to obtain the immersion stability value and dry stability as a basis for determining the mechanical quality of the mixture. Before the test is carried out, all test specimen samples must undergo a suitable conditioning process (curing) to describe the field conditions representatively [24]. Marshall testing is carried out concerning AASHTO T 245-22 [45] as illustrated in Figure 2, but CMAE has its sample conditioning or curing, the sample is conditioned at room temperature ranging from 25°C in a dry state or in a water-immersed condition. In addition to the Marshall test, data from Marshall samples such as weight and volume can be used to calculate the volumetric properties of the mixture [46].

Figure 2. Marshall stability test

2.8.2 ITS Test

ITS testing is one of the important methods in evaluating the mechanical characteristics of asphalt mixtures, especially to determine the ability of the mixture to withstand horizontal tensile forces due to traffic loads. ITS is used to evaluate the resistance of the mixture to horizontal tensile strains under the pavement layer that cause internal tensile stress [47], [48]. The indirect tensile strength value is an indicator of the mechanical characteristics of the mixture against crack resistance and durability of the asphalt mixture, especially in assessing the performance of the material against tensile stress that occurs during road service [49]. The ITS value can increase along with the hardening period for all mixtures which may be caused by the strength obtained due to the hydration process [48]. ITS testing refers to ASTM D6931-17 [50] as illustrated in Figure 3 and is adjusted to the curing of the CMAE sample and can be calculated using Equation 11.

$$S_t = \frac{2000 \text{ x } P}{\pi \text{ x } t \text{ x } D} \quad (11)$$

where S_t is the indirect tensile strength (kPa), P is the maximum load (N), t is the height of the sample (mm), and D is the diameter of the sample (mm).

Before the ITS test is carried out, the test specimen samples first undergo a conditioning process (curing) to ensure that the water content in the mixture is at a stable level, and so that the test results can reflect the actual conditions when the mixture is applied in the field. This conditioning process includes two conditions:

1. Oven curing
   The sample was placed in an oven at a constant temperature of 40°C for approximately 24 hours to gradually reduce the water content in the mixture.
2. Full curing
   In this process, the sample is cured at room temperature 25°C until it reaches a constant sample weight, which indicates that all the water in the mixture has evaporated and the mixture is in a perfectly dry condition.

Figure 3. ITS test

2.9 Durability Properties of CMAE

Asphalt mixture durability properties are the ability of asphalt mixtures to withstand damage due to load and environmental influences without experiencing significant performance degradation. Durability reflects the mixture's resistance to moisture, extreme temperatures, and oxidation that can cause cracking, raveling, stripping, or loss of bond between asphalt and aggregate.

2.9.1 Moisture Susceptibility

Moisture susceptibility test is a laboratory evaluation method that aims to measure the resistance of asphalt mixtures to damage due to the influence of water or humidity. Water entering the asphalt mixture structure can weaken the bond between asphalt and aggregate, causing various types of damage such as stripping and loss of structural strength. One of the parameters used to conduct moisture susceptibility checks is the Tensile Strength Ratio (TSR) parameter [51], [52], TSR can be calculated using Equation 12. TSR is the ratio of indirect tensile strength after and before moisture immersion which is used as an evaluation indicator for the resistance of asphalt mixtures to damage due to moisture [52], [53], [54], [55].

$$TSR = \frac{S_{t2}}{S_{t1}} \text{ x } 100 \quad (12)$$

where TSR is the tensile strength ratio (%), S_{t2} is the ITS of the conditioned test sample (kPa), and S_{t1} is the ITS of the unconditioned test sample or dry condition without immersion (kPa).

2.9.2 Mass Loss

The mass loss value is determined by the cantabro loss test also known as Cantabro Abrasion Loss (CAL) which is a laboratory test method designed to evaluate the level of resistance of asphalt mixtures to the release of aggregate grains from the asphalt matrix as a result of decreased adhesion between asphalt and aggregate [44], [53]. The main purpose of this test is to determine the level of wear resistance (abrasion) of asphalt mixtures to working conditions that simulate traffic loads in the field, especially on asphalt mixtures that are porous or do not use large amounts of mineral fillers. The durability of asphalt mixtures to evaluate asphalt mixtures due to grain release is calculated as the percentage difference between the initial weight and the final weight of the sample after testing [31], [53]. The implementation of the cantabro loss test refers to the technical guideline principles of ASTM 7064/D7064M–21 [56] as illustrated in Figure 4 and is adjusted to the curing of the CMAE sample and the cantabro loss value can be calculated using Equation 13.

$$P_{CAL} = \frac{P_1 - P_2}{P_1} \text{ x } 100 \quad (13)$$

where P_{CAL} is the percentage cantabro abrasion loss (%), P_1 is the initial weight of the sample (gram), and P_2 is the weight of the sample after testing cantabro loss test (gram).

Figure 4. Cantabro loss test

Before testing the CMAE properties, the test specimen samples must first go through a conditioning stage to ensure that the mixture has reached a certain physical stability, especially related to the water content that can affect the integrity of the bond between asphalt and aggregate. Conditioning is carried out in two stages:

1. Oven curing
   The samples were dried in an oven at 40°C for approximately 24 hours to slowly reduce the water content in the mixture.
2. Full curing
   The samples were cured at room temperature 25°C until they reached a constant sample weight, which indicates that all the water in the mixture has evaporated and the mixture is in a perfectly dry condition.

3 Results and Discussion

3.1 Materials Properties

Examination of aggregate and filler materials and asphalt emulsion is intended to find the value of material properties. For CMAE mixtures, the study of aggregate specifications required is still limited in Indonesia, but if following the aggregate requirements for hot asphalt mixtures, the aggregate properties meet the specifications based on the Indonesian Ministry of Public Works with the results summarized in Table 1. Asphalt emulsion specifications if based on ASTM D2397/SD2397M-20 [57], the asphalt emulsion properties meet the specifications for the type of cationic asphalt emulsion CSS-1h with the results summarized in Table 2.

Table 1. Properties of aggregate and filler

Properties	Results
Specific gravity and absorption of coarse aggregate	
a. Bulk specific gravity	2.355
b. Aggregate absorption (%)	2.323
Specific gravity and absorption of fine aggregate	
a. Bulk specific gravity	2.367
b. Aggregate absorption (%)	2.030
Specific gravity of filler	2.542
Abrasion loss angeles (%)	32.460
Clay lump	
a. Coarse aggregate (%)	0.634
b. Fine aggregate (%)	0.699
Angularity of coarse aggregate (%)	100/98.6
Sand equivalent (%)	88.4
Soundness test	
a. Coarse aggregate (%)	7.455
b. Fine aggregate (%)	6.320
Aggregate flakiness index (%)	8.3

Table 2. Properties of asphalt emulsion

Properties	Results
Storage stability after 24 hours (%)	0.361
Sieve test No.20 (%)	0
Cement mixing test (%)	0
Residual of asphalt emulsion (%)	59.2
Viscosity saybolt furol, 25°C (s)	26
Specific gravity of residual asphalt	1.024
Penetration of of residual asphalt (0.1 mm)	60.95
Ductility of residual asphalt (cm)	104

3.2 Volumetric Properties of CMAE

Volumetric properties are properties that describe the volume relationship between aggregate, asphalt, and air voids in an asphalt mixture. The volumetric properties sought include: dry density, air voids, VMA, VFA, water absorption, and AFT as shown in the graph in Figure 5. Based on the graph in Figure 5, it is shown that each gradation variation produces different volumetric properties because the aggregate particle distribution of the variations made is different, this is also by research that gradation affects volumetric properties on air voids parameters [58], [59]. Each variation of aggregate gradation has a different RAC variation because each variation of aggregate gradation has a different composition of coarse aggregate, fine aggregate, and filler based on the calculation of residual asphalt content using Equation 1. Variations in aggregate gradation will produce optimum water content for aggregate coating that is different from the results of gradation G. L1 and G. B1 as much as 5% while in gradation G. L2, G. B2, and G. L3 as much as 5.5% of the total aggregate weight. The finer the aggregate gradation, the higher the water content in the asphalt coating process with aggregate [31]. The high water content will affect the air voids parameter [31], but if the water content used is optimal for CMAE, it will provide good mixture properties such as density and air voids [24].

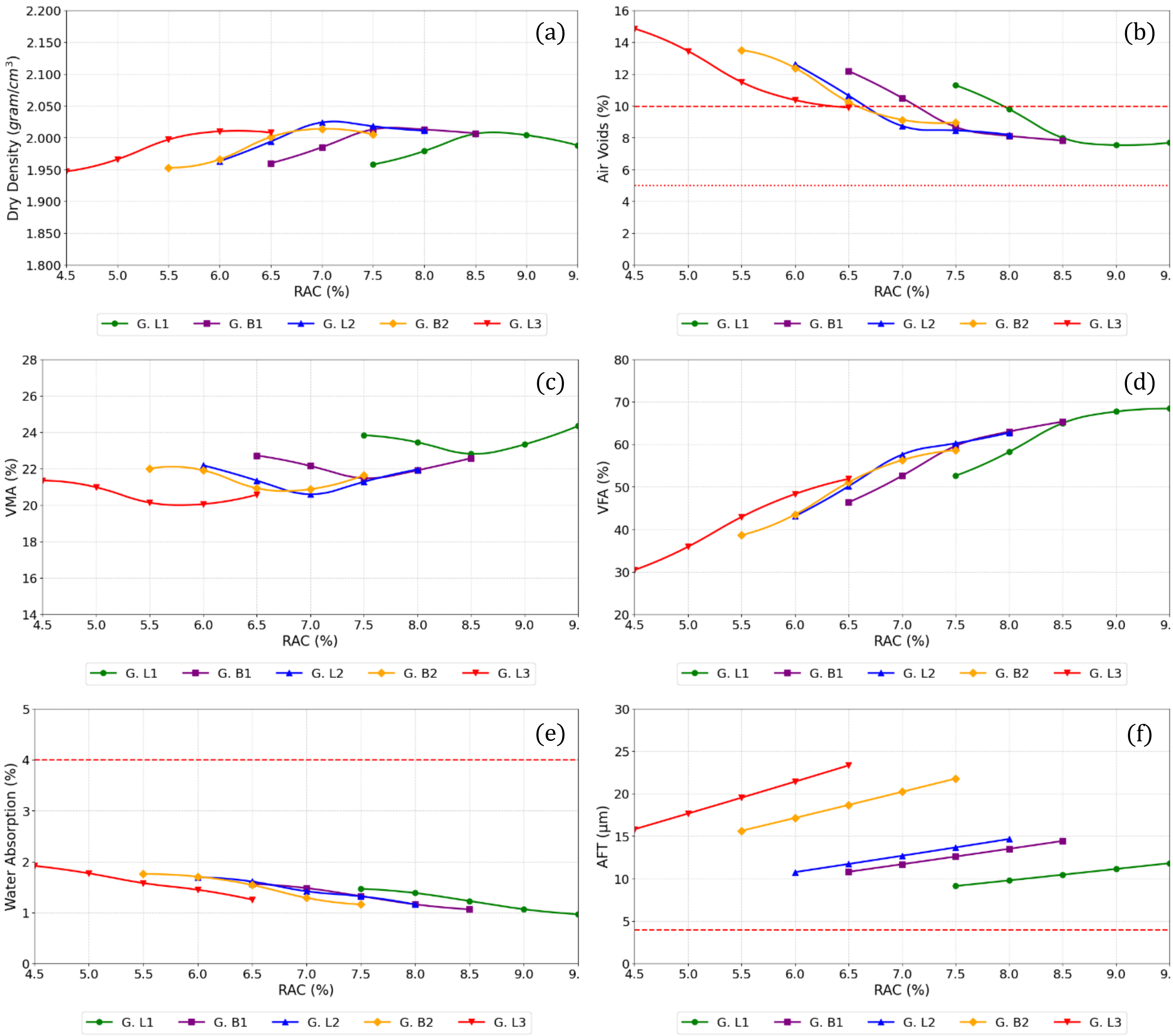

Figure 5. Volumetric properties (a) dry density, (b) air voids, (c) VMA, (d) VFA, (e) water absorption, (f) AFT

Based on the specific specifications set by MPW-RI, the required CMAE volumetric properties include air voids of 5%–10%, maximum water absorption of 4%, and minimum AFT of 8 µm. Based on the graphical data in Figure 5, not all RAC variations in each gradation meet these criteria. This is influenced by aggregate gradation characteristics, particularly the aggregate proportions and the amount of asphalt emulsion filling the voids. A summary of CMAE volumetric properties is presented as follows:

1. Dry density can be affected by aggregate gradation because the distribution and composition of aggregate fractions will affect the density of the aggregate density structure in CMAE. Finer continuous aggregate gradation will require a lot of asphalt content, so that in sufficient quantities it will fill the mixture cavity that has been filled with air and the mixture density will increase. Based on the graph in Figure 5 for the maximum dry

density value at gradation G. L2 (middle limit gradation) is 2.024 gram/cm^3, because the distribution of aggregate particle size is even, small and fine aggregates fill the gaps in the coarse aggregate space in the mixture and sufficient asphalt can fill the void space which causes the maximum G. L2 mixture density.

2. Air voids are related to the density of the mixture which is influenced by aggregate gradation and asphalt content [60]. Based on Figure 5, each increase in asphalt content can reduce air voids because asphalt will fill the gaps in the mixture. The lowest air voids value in the CMAE variation of G. L3 is 7.686% with an RAC 9.5%, while the highest air voids value is 14.849% with an RAC value of 4.5%. In addition to aggregate gradation and asphalt content in CMAE, air voids can also be influenced by water content. The higher the water content used for aggregate coating, the more it will cause an increase in air voids and a decrease in mixture density.
3. VMA can be affected by air voids, the lower the air voids value, the higher the VMA value because the aggregate is evenly distributed and fills the voids between the aggregate grains in the mixture. Based on Figure 5, the lowest VMA value is in CMAE gradation G. L3 with a value of 20.056% at RAC 4.5% while the highest VMA value is in gradation G. L1 with a value of 24.341% at RAC 9.5% this is influenced by the type of aggregate gradation which is a finer gradation. Well-distributed dense gradation will produce a low VMA value.
4. VFA is affected by the gradation and content of asphalt emulsion in the CMAE mixture. Based on Figure 5, the lowest VFA value in CMAE gradation G. L3 with a value of 30.453% at RAC 4.5% while the highest VFA is 68.425% at RAC 9.5%. If the aggregate gradation is evenly distributed with a low air voids value with a high asphalt content, the VFA value will increase [61]. At the same gradation in one variation, the lower the asphalt content in the mixture will produce a low VFA.
5. Water absorption is affected by air voids, aggregates with evenly distributed gradation and have low air voids values will produce low water absorption values. Based on the graph in Figure 5, the lowest water absorption value in CMAE gradation G. L1 is 0.969% with RAC 9.5% while the highest value in gradation G. L3 is 1.918% with RAC 4.5%. The lower the air voids value, the lower the voids in the mixture so that the percentage of water absorbed is lower.
6. AFT is influenced by the surface area of the aggregate and the asphalt content absorbed by the aggregate. Based on the graph in Figure 5, the G. L1 gradation is a finer gradation compared to other gradations, the lowest AFT value is 9.133 μm at RAC 9.5% while the highest value is in the G. L3 gradation with a value of 23.334 μm at RAC 4.5%. The aggregate has a lot of fine aggregate fractions, so the surface area of the aggregate increases, and the AFT decreases because the asphalt covering the aggregate becomes thinner. If the conditions of different aggregate gradation variations are different, then to achieve ORAC, the asphalt content required will increase and the ORAC value on the finer aggregate gradation will be higher than the ORAC on the coarser aggregate gradation, so the AFT value will also be influenced by ASA and RAC.

Based on the results of volumetric properties shown in Figure 5, aggregate gradation will affect the parameters of volumetric properties the finer the aggregate gradation as in G. L1 continuous gradation type will produce lower air voids but requires more asphalt content. Aggregate gradation at the middle limit as a control as in G. L2 is a continuous gradation type that will produce maximum dry density. Aggregate gradation will also affect the value of aggregate fineness modulus, ASA, and AFT as shown in the graphs of Figure 6 and Figure 7.

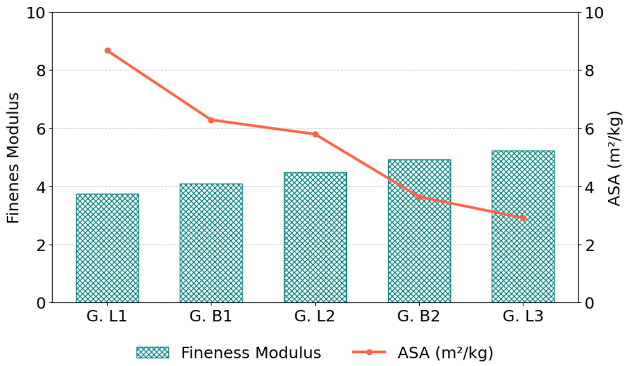

Figure 6. The effect of aggregate gradation on fineness modulus and ASA

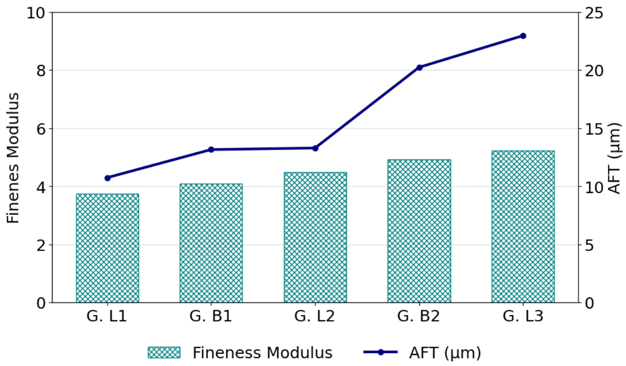

Figure 7. The effect of aggregate gradation on fineness modulus and AFT

Fineness modulus will provide an overview of the level of coarseness or smoothness of the aggregate based on the value of the aggregate sieve analysis results. Based on the analysis results and graph Figure 6, the CMAE fineness modulus value of gradation G.L1 is 5.23 and has the highest level of aggregate fineness among other aggregate gradation variations. Aggregate gradation G. L3 has a fineness modulus value of 3.73 and is the lowest among other aggregate gradation variations. A lower fineness modulus value indicates a finer aggregate gradation, while a higher fineness modulus value indicates a coarser gradation. Based on the graph Figure 6, the fineness modulus is related to ASA, the higher the fineness modulus value, the lower the ASA value will be because in fine gradation the composition of fine aggregate is high and has high contact plane rupture and ASA.

Fineness modulus and ASA have an effect on AFT because they are related to RAC in CMAE. Based on the analysis results and graphs in Figure 7, a low fineness modulus value correlates with AFT, the lower the fineness modulus level, the lower the AFT value. ASA refers to the total surface area of aggregate in a mixture volume and is greatly influenced by particle size. ASA will determine the amount of RAC needed to evenly coat the particle surface. When the fineness modulus value is high, the aggregate gradation tends to be coarse, the aggregate surface area is lower than the finer aggregate gradation so that the asphalt film covering the aggregate becomes thicker. The fineness modulus has an impact on the volumetric properties, particularly air voids and the effective asphalt content [62]. Similarly, aggregate gradation influences AFT [63], which is also affected by the amount of asphalt in the mixture [64].

Table 3. Volumetric properties and Marshall test of CMAE

Properties of CMAE	Variation of gradation aggregate					Spec.
	G. L1	G. B1	G. L2	G. B2	G. L3	
Optimum residual asphalt emulsion content (%)	9.2	7.8	7.4	6.9	6.3	-
Dry density (gram/cm^3)	2.005	2.013	2.020	2.014	2.008	-
Air voids (%)	8.173	8.336	8.570	9.125	9.992	5%-10%
VMA (%)	23.022	21.739	21.006	20.874	20.468	-
VFA (%)	66.078	61.654	59.188	56.296	51.169	-
Water absorption (%)	1.163	1.227	1.361	1.291	1.295	Max. 4%
AFT ((µm)	10.735	13.150	13.284	20.224	22.952	Min. 8 µm
Effective residual asphalt emulsion content (%)	7.770	6.819	6.304	5.975	5.341	Min 5.5%
Absorbed residual asphalt emulsion content (%)	1.018	1.064	1.075	1.102	1.131	Max. 1.7%
Soaked stability (kg)	1153.9	1241.7	1356.6	1243.1	978.2	Min. 300 kg
Flow (mm)	6.672	6.316	5.639	5.165	4.995	-

Based on the results of volumetric properties and marshall tests summarized in Table 3 if using special specifications from MPW-RI then CMAE on ORAC meets the specifications on gradations G. L1, G. B1, G. L2, and G. B2 while CMAE on gradation G. L3 does not meet the specifications on the effective residual asphalt emulsion content parameter. Aggregate gradation greatly affects RAC, the finer the aggregate gradation, the higher ORAC value on CMAE. Based on Table 3, the finer the gradation used on CMAE will produce a lower air voids value because, in fine gradations on continuous types, the aggregate is evenly distributed with finer particles filling the gaps of larger aggregates and sufficient asphalt to fill the air voids, this applies because all gradation variations made are continuous gradations. The lowest air voids value on CMAE gradation G. L1 with a value of 8.173% at RAC 9.2%. The highest soaked stability value is at gradation G. L2 at RAC 7.4% which is correlated with the dry density value.

3.3 Mechanical Properties of CMAE

3.3.1 Marshall Stability

The mechanical properties in the Marshall test that are sought include soaked stability and flow parameters. The soaked stability and flow parameters are depicted in the graphs of Figure 8 and Figure 9. CMAE samples for Marshall test were made at various gradations G. L1, G. B1, G. L2, G. B2, and G. L3. with a range of RAC variations.

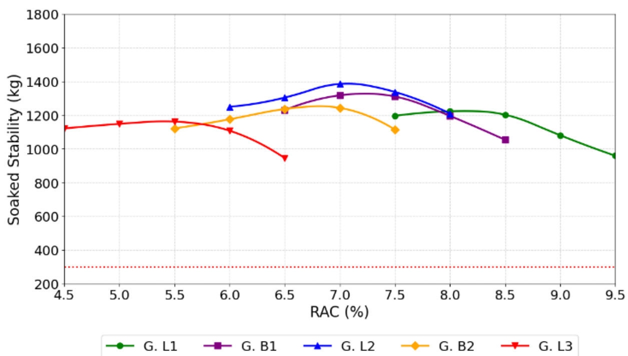

Figure 8. The correlation between RAC and soaked stability

Based on Figure 8, the highest soaked stability value is in CMAE gradation G. L2 with a soaked stability value of 1384.9 kg at RAC 7% while the lowest value is in CMAE gradation G. L3 with a soaked stability value of 945.8 kg at RAC 6. 5%. At ORAC 7.4%

conditions, CMAE gradation G. L2 produces a soaked stability of 1356.6 kg. Based on the variation of CMAE gradation, the soaked stability value increases with increasing RAC, until it reaches its peak before then decreasing and has a correlation with dry density. This shows that in the maximum soaked stability condition with sufficient RAC, there is an optimal bond balance between the aggregate and the asphalt emulsion, and has a good dry density value, which can provide maximum resistance to loads. Marshall stability can increase with increasing asphalt content to the optimal asphalt content and can then decrease, the increase in marshall stability is also influenced by the adhesion properties between the asphalt and the aggregate [65]. Research conducted by Gul et al. [66] and Althoey et al. [67] with machine learning approach analysis shows that marshall stability can be influenced by the percentage of aggregate and air voids.

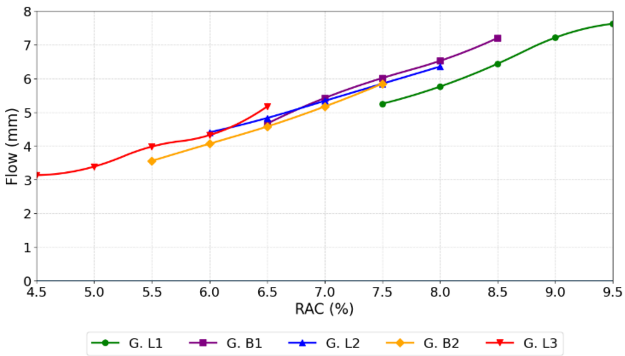

Figure 9. The correlation between RAC and flow

Based on Figure 9, the flow value shows an increase with increasing asphalt content, which means that the mixture becomes more flexible and plastic at all variations of CMAE gradation. Marshall stability can also be affected by air voids and the maximum specific gravity of the mixture [68], but excessive asphalt content, can also affect the marshall stability and flow values [65], [69]. Excessive RAC content in CMAE leads to an excess of binder, as the required asphalt is already sufficient to fill the air voids. This surplus asphalt makes the mixture more plastic and prone to deformation. As RAC increases, the flow value of CMAE also rises, but only up to a certain point beyond which the soaked stability begins to decline.

3.3.2 ITS

Mechanical properties in ITS testing are indirect tensile strength values of CMAE. CMAE samples for the ITS test were prepared using various aggregate gradations: G.L1, G.B1, G.L2, G.B2, and G.L3, along with ORAC. ITS parameters are depicted in the graph of Figure 10 and Figure 11. The ITS test is performed under both oven curing and full curing conditions, in which the full curing state ensures that no residual water content remains in the CMAE mixture after the entire curing process is completed.

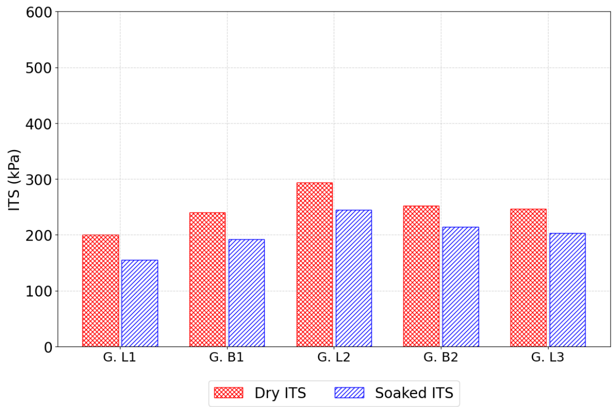

Figure 10. ITS of ORAC mixtures with varying aggregate gradations under oven curing conditions

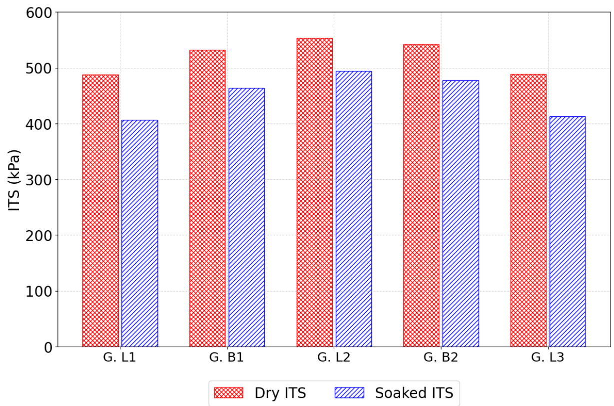

Figure 11. ITS of ORAC mixtures with varying aggregate gradations under full curing conditions

Based on the results of the ITS oven curing conditions graph Figure 10 and full curing conditions graph Figure 11, the maximum ITS value is at CMAE gradation G. L2. With ORAC 7.4% ITS value has the same correlation on dry density where dry density CMAE gradation G. L2 at ORAC 7.4%. The dense aggregate structure allows the formation of stronger bonds between aggregate particles and asphalt matrix so that it can withstand greater tensile stress. High-density mixtures have better interlocking between aggregates and more even asphalt distribution. Excessive increases in RAC can weaken the bonding strength between aggregate and asphalt so it affects ITS [31]. High air voids in asphalt mixtures can reduce the ITS value[31].

Based on the results of ITS oven curing conditions, the highest dry ITS value was 293.4 kPa and the soaked ITS value was 244.4 kPa, while full curing conditions obtained the highest dry ITS value of 553.3 kPa and soaked ITS value of 493.8 kPa on CMAE gradation G. L2. With ORAC 7.4. In dry ITS, the ITS value of full curing conditions is 1.8 times greater than oven curing conditions. In soaked ITS, the ITS value of full curing conditions is 2 times greater than oven curing conditions. The increase in ITS value from the beginning of compaction to full curing conditions occurs due to the curing process in the asphalt mixture using asphalt emulsion as a binder [18], [70]. The curing duration in the asphalt mixture using asphalt emulsion as a binder can affect the binding process between the aggregate and the asphalt so that it can affect the ITS value, long curing duration will increase mechanical properties [18], [70], [71].

3.4 Durability Properties of CMAE

3.4.1 Moisture Susceptibility

Moisture susceptibility was measured using the TSR parameter where TSR was obtained from dry ITS and soaked ITS. Moisture susceptibility was carried out on variations in CMAE gradation as seen in Figure 12.

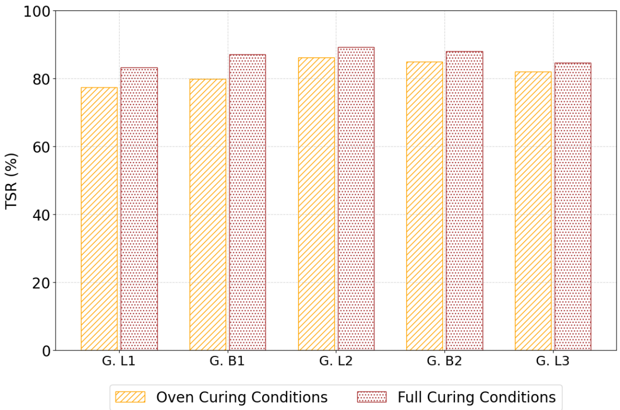

Figure 12. TSR of aggregate gradation variation on ORAC

Based on the analysis results displayed through the graph in Figure 12, the highest TSR results were obtained in CMAE gradation G. L2 at ORAC 7.4% in oven curing conditions and full curing conditions. The highest TSR value in oven curing conditions CMAE gradation G. L2 with ORAC 7.4% was obtained at 86% while the lowest in CMAE gradation G. L1 with ORAC 9.2% was obtained at 77%. The highest TSR value in full curing conditions CMAE gradation G. L2 with ORAC 7.4% was obtained at 89% while the lowest in CMAE gradation G. L1 with ORAC 9.2% was obtained at 82%. The TSR value under full curing conditions is higher than that under oven curing conditions because full curing allows the asphalt emulsion to achieve maximum adhesion strength between the asphalt and the aggregate.

Moisture susceptibility with TSR parameters can be influenced by several aspects, including aggregate gradation, mixture density, air voids, and adhesion properties of asphalt between asphalt and aggregate. Based on research conducted by Xu et al. [31], the TSR value in asphalt mixtures that utilize asphalt emulsion as a binder may be more affected by aggregate gradation and cement content rather than the amount of asphalt emulsion used. In cold mixtures using asphalt emulsion as a binder, the TSR value is influenced by the curing process [18].

3.4.2 Mass Loss

Mass loss was measured using the cantabro loss test parameters. The Cantabro loss test was made using various aggregate gradations: G.L1, G.B1, G.L2, G.B2, and G.L3, as well as ORAC. Cantabro loss was tested on various CMAE gradations with oven curing conditions and full curing conditions as seen in Figure 13.

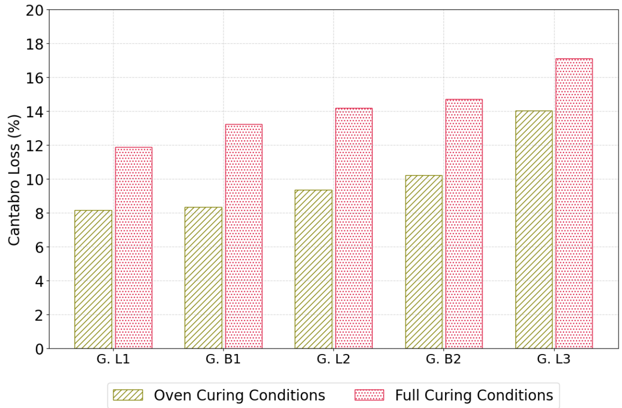

Figure 13. Cantabro loss of aggregate gradation variation on ORAC

Based on the analysis results displayed through the graph in Figure 13, the highest mass loss results for oven curing conditions and full curing conditions were obtained in CMAE gradation G. L3 at ORAC 6.3% while the lowest was in CMAE gradation G. L1 at ORAC 9.2%. The lowest mass loss value in oven curing conditions CMAE gradation G. L1 with ORAC 9.2% was obtained at 11.889% while the highest was in CMAE gradation G. L3 with ORAC 6.3% was obtained at 17.118%. The lowest mass loss value in full curing conditions CMAE gradation G. L1 with ORAC 9.2% was obtained at 8.142% while the highest was in CMAE gradation G. L3 with ORAC 6.3% was obtained at 14.041%. The low mass loss value indicates that CMAE is resistant to grain release and has strong asphalt and asphalt-aggregate adhesion. Low mass loss values are required for road pavements that are susceptible to spalling failure between asphalt mixture materials [72].

Based on Figure 13, dense gradation with a more dominant coarse aggregate fraction, such as in sample G. L3, tends to produce a higher mass loss value compared to a finer gradation type. Although coarse gradation can provide good structural stability, the tendency for surface particle peeling is higher due to the lack of finer aggregate filling the space between coarse aggregates, and the adhesion properties between aggregates and asphalt are not good. A finer dense gradation in the distribution of aggregate with asphalt becomes more even and the contact area between aggregates is wider, allowing asphalt to form a bond that covers the aggregate surface well. Mass loss with the cantabro loss test can be influenced by the type of aggregate gradation and asphalt adhesion strength [73]. In CMAE, the mass loss value can be influenced by the asphalt–aggregate adhesion or by the modification of the asphalt emulsion using additives, such as waterborne epoxy resin [74].

4 Conclusion

Based on the results of laboratory experiments, aggregate gradation significantly influences the properties of CMAE. It affects the volumetric, mechanical, and durability characteristics of the mixture. Aggregate gradation can be categorized by its fineness and coarseness using the fineness modulus parameter. A lower fineness modulus indicates finer aggregate gradation, which in turn increases the demand for asphalt emulsion as a binder. Finer aggregates tend to produce higher ASA values, requiring a greater percentage of asphalt emulsion.

The volumetric characteristics of CMAE are directly affected by aggregate gradation. Each gradation variation has a distinct material composition that influences parameters such as dry density, air voids, VMA, VFA, water absorption, and AFT. A well-distributed gradation such as G.L2 yields higher density due to the interlocking effect between coarse and fine aggregates and the sufficient presence of asphalt emulsion. Finer continuous gradations require higher asphalt content, which fills the voids more effectively. As a result, air voids decrease, while VMA and VFA increase with the rise in asphalt content.

The mechanical performance of CMAE, particularly in terms of soaked stability, increases significantly up to the optimum asphalt content, beyond which it declines due to asphalt excess. Soaked stability is positively correlated with the mixture's dry density. As asphalt content increases, so does the flow value, indicating greater plasticity that makes the mixture more prone to deformation. The ITS is determined by the compact and uniform aggregate structure, which enhances interlocking and bonding between particles. Adequate asphalt content also strengthens the mixture's resistance to tensile stress. ITS is influenced by aggregate gradation, binder–aggregate adhesion, and the curing process.

The durability of CMAE against moisture susceptibility, as measured by the TSR, is influenced by the bonding strength between the asphalt and aggregates. Under full curing conditions where no water remains in the mixture adhesion is optimized, resulting in higher TSR values. In contrast, mass loss is more pronounced during early curing stages (e.g., oven curing), when the presence of moisture and incomplete binder–aggregate bonding can lead to aggregate particle detachment.

Future research could explore the influence of aggregate shape and surface texture on gradation, particularly regarding the contact area between particles, using a Discrete Element Method (DEM) approach. Since this study used aggregate gradation variations with the same nominal aggregate size, subsequent studies should examine the effects of gradation involving different nominal sizes. Moreover, given that CMAE exhibits suboptimal properties at early ages, future work should investigate the influence of additives and curing time on improving its mechanical performance, durability, and chemical stability.

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