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# Volumetric Assessment of Hot Mix Asphalt Incorporating Petroleum Bitumen and High-Calcium Fly Ash for Binder Courses: A Case Study

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**ABSTRACT**

The qualities and amount of filler have a big impact on how well asphalt mixtures work. The purpose of this study is to evaluate the possibility of using industrial waste powder, such as fly ash in place of conventional rock ash filler in asphalt mixture compositions. One measure to evaluate this potential is the volumetric asphalt mixture. To find out if this industrial waste might be utilized in the asphalt mixture, SEM and XRD experiments were first conducted. The AC-BC (Asphalt Concrete Binder Course) type of asphalt is produced by mixing petroleum bitumen with aggregate and fly ash. Three volumetric characteristics—void in mix (VIM), void in mineral aggregate (VMA), and void filled bitumen (VFB)—are discussed in this study. The variations of fly ash usage in the asphalt mixture of this research are 0%, 25%, 50%, 75%, and 100%. The density value is not substantially changed by changing the fly ash level from 0% to 100%, according to the volumetric values of VIM, VMA, and VFB. Generally speaking, adding fly ash to the mixture has no discernible effect on density, but at higher asphalt levels (6.5% and 7%), the density does considerably decrease as the fly ash level increases from 25% to 50%. This suggests that adding a certain quantity of fly ash has no negative effects on the asphalt mixture's density; nevertheless, a higher fly ash content could result in a slight decrease in cohesion. The construction industry, waste management, and the environment can all profit from the use of industrial waste in the production of asphalt mixtures, particularly binder asphalt, according to the findings of volumetric characteristics.

## 1. INTRODUCTION

Road pavements are exposed to the environment. The bitumen's behavior has a major impact on how well asphalt road pavements work. Bitumen is a complicated substance that behaves differently at different temperatures. It behaves similarly to a Newtonian fluid at high temperatures, a viscoelastic liquid at intermediate temperatures, and a viscoelastic solid at low temperatures. As a result, issues brought on by climate change will unavoidably affect pavement service life. The most impacted failure criterion is rutting (permanent deformation) performance [1]. Over a 20-year period, a study on climate change in the USA revealed that rutting rose by 9–40% and weariness increased by 2–9%. A transportation network must always be in operation since it is a vital piece of infrastructure that underpins social and economic activity. The availability and accessibility of transportation networks were specifically mentioned in the Sustainable Development Goals (SDG 9.1) of the UN. High direct and indirect expenses result from weather-related disruptions to the transportation sector. The life cycle cost (LCC) analysis of the pavement is greatly impacted by climate change.

Sustainability is the ability to meet technical and human requirements while minimizing negative effects on the environment and the economy. Since transportation is the most basic human necessity, creating sustainable transportation infrastructure should be a high priority. In Indonesia, asphalt dominates the road network assets, accounting for around 83.5% of the entire pavement [1-5]. When creating a sustainable pavement, it is imperative to take performance, economic advantages, and environmental effects into account.

Researchers have looked for ways to reduce air pollution and the use of natural resources to make asphalt from an environmental standpoint. A recent measurement of $CO_2$ at the Indonesian Observatory exceeded 410 parts per million (ppm) for the first time in 2022 [6, 7]. With so much at stake, reducing greenhouse gas (GHG) emissions is imperative across all industrial sectors in order to combat the rapidly approaching catastrophic phenomenon of global warming. Energy use and greenhouse gas emissions happen in the industrial sector of manufacturing asphalt pavement during the stages of material manufacture, construction, servicing, maintenance, and end-of-life. The two most important ones are the phases of building and material production [8]. Purchasing raw materials, transporting raw materials, and producing asphalt mixtures are all part of the materials manufacturing process [9].

With cleaner manufacturing and viable development as the primary goals, the use of trash is an interesting trend with high potential for many highway researchers due to the modernization of the building industry. The main objective of these researchers is to provide sustainable, smooth, safe, and affordable roads so that the anticipated loads may be carried. Due to these conditions, there is a greater need to find road materials that can delay structural deterioration and enhance asphalt pavement performance. One of the components of asphalt mixtures, filler has a significant impact on the behavior and characteristics of the mixtures, particularly the impacts of aggregate binding.

The components of asphalt mixtures are bitumen, mineral aggregates, filler, and additives (if needed). The very fine aggregate, or filler, is produced by industrial processes or natural rocks. The most common filler is limestone powder. Standard National Indonesia [10] states that fillers can be in different powder forms, with a maximum particle size of 0.063 mm. The properties of bituminous or hydraulic mixtures are determined by the addition of these fillers. Because they have a major impact on the mechanical and physical qualities of the mixture, fillers are crucial in the creation of asphalt mixes [11, 12]. Even while fillers are widely used in asphalt mixtures, it is difficult to provide a broad category that includes all of their uses [13, 14]. The finest portion of the aggregate structure in an asphalt mixture is represented by the fillers, which complete the granulometry and help to lower the mixture's air void content. Its main purpose is to fill the voids left by the aggregates in the mixture; the inert component makes the mixture denser and impermeable. Fillers can assist lessen the heat sensitivity of asphalt mixtures or enhance the mechanical qualities of the mastic that covers the coarse aggregates, according to a number of experimental applications and studies [15, 16]. The fillers must meet specific chemical and physical requirements in order to ensure that the bituminous binder and aggregates function properly together [17-19]. The mixture's behavior at the various temperatures it will encounter throughout its lifetime must also be guaranteed by these characteristics.

The sustainability of the environment has always been severely hampered by Indonesia's large industrial waste output. Due to the nation's continued reliance on steam power plants (PLTU), fly ash trash output is rising in tandem with the nation's quick economic development. Fly ash waste is a byproduct of burning coal. The specifications of the coal requirements for the national PLTU in 2021 are estimated by the Electricity Supply Business Plan (RUPTL) to be around 113.6 million tons, and they are projected to increase by approximately 37.6% to 156.3 million tons in 2030. This could lead to an increase in the generation of fly ash waste.

Fly ash is known to include a variety of dangerous materials, including heavy metals and poisonous chemical compounds, according to numerous scientific investigations. Fly ash management gone wrong can pollute the environment, especially when it comes to contaminated soil and water. Fly ash should not be disposed of improperly since this can lead to major issues like respiratory ailments, soil and water pollution, and biological cycle disturbance [20]. Since the tiny particles in fly ash can lead to respiratory issues and other health issues, the hazard to human health is also very serious. But if we are inventive and creative, we can turn this garbage into a useful resource. For example, the industry uses the fly ash from burning coal as a replacement or filler in combinations used for road paving. Fly ash is frequently regarded as an environmental issue in PLTU plants. However, through earlier development and research, scientists and researchers have learned that fly ash may be reused in other industries, most notably in the production of road pavement mixtures.

As a filler, fly ash helps lessen reliance on natural raw materials like sand. The detrimental effects on the environment can be lessened by decreasing the mining of natural resources. Utilizing fly ash waste as a filler enhances the stability, compressive strength, and deformation resistance of mixtures used in road pavement, claims [21]. Fly ash additionally aids in minimizing damage and cracks brought on by compaction and expansion.

These days, blended cement is produced by adding fly ash and other byproducts from national cement mills to Portland cement clinker. One kind of blended cement is Portland composite cement, which is produced in accordance with national standards (SNI). The development of Portland composite cement aims to decrease fly ash dumping, minimize mined raw material use, and optimize kiln fuel utilization.

Fly ash has been studied by Jaber et al. [22] as a filler for asphalt mixtures. The Marshall characteristic approach was then used to conduct laboratory studies in which we varied the percentage of fly ash utilization to 0%, 20%, 40%, 60%, 80%, and 100%. To determine the tensile strength of the asphalt mixture, we performed an indirect tensile strength (ITS) test after the Marshall test. The outcomes demonstrated that the addition of fly ash significantly enhanced the asphalt mixture's stiffness, stability, resistance to moisture damage, and rut resistance.

The use of alternative binding styles is crucial for raising the standard of road pavements. Quicklime and Portland Composite Cement (PCC) binders were used in the Laston Intermediate Layer (AC-BC) mixture in study [23]. PCC binder improves the mixture's effectiveness over quicklime, according to Rangan et al. [24]. PCC has a suitability rating of 98.69%, but Quicklime has a score of 98.47%. The Laston Intermediate Layer (AC-BC) mixture with fly ash waste binder is used as a reference in this study.

Included are volumetric characteristics. The determining factors in a compacted asphalt mixture are void in mix (VIM), void in mineral aggregate (VMA), and void filled bitumen (VFB). This study looks at the VIM, VMA, and VFB of asphalt mixtures made with high-calcium fly ash and petroleum bitumen.

## 2. RESEARCH SIGNIFICANCE

Utilizing fly ash as a filler in asphalt mixtures has been shown in multiple earlier experiments to improve the stability and durability of the asphalt. This might solve the problem of using fly ash waste as a binding material and offer approaches for enhancing the sustainability and performance of Indonesian road pavements with a different approach.

Drawing on a number of earlier investigations, this study seeks to clarify and measure the improvement in road pavement performance that results from the Asphalt Concrete Binder Course (AC-BC) mixture's usage of fly ash waste as a binder material. In this study, the volumetric values VIM, VMA, and VFB are tested as part of the Marshall characteristics to help with data analysis and optimization of the composition of variations in asphalt content and fly ash waste content.

Because fly ash can assist lessen deformation and cracking and increase resistance to changes in temperature and environmental conditions, asphalt mixes containing fly ash often have higher durability. The incorporation of fly ash into asphalt mixtures has the potential to enhance road performance by augmenting stability, strength, and longevity. The consistency and quality of fly ash can differ according on the source, much like with other applications for fly ash waste. The asphalt mixture's consistency and quality may be impacted by these variations. Using fly ash as an asphalt mixture can be a sustainable and practical way to cut waste, enhance road performance, and lessen the environmental impact of the coal-fired power generation industry, taking into account the advantages and associated concerns. When using the practice of employing fly ash in asphalt mixtures, it is crucial to carry out thorough research and consider these variables.

## 3. MATERIALS AND METHOD

### 3.1 Physical properties of aggregate

The majority of the ingredients in an asphalt mixture are aggregates, hence the study looked at aggregate features to assess their feasibility. Tables 1-4 show the findings of tests conducted on the properties of coarse aggregates, fine aggregates (sand and stone ash), and fillers (aggregates that pass sieve No. 200) derived from stone ash. Aggregates retained by sieve No. 8 (2.36 mm), aggregates passing sieve No. 8 and retained by sieve No. 200 (0.075 mm), and aggregates passing sieve No. 200 are the coarse aggregate, fine, and filler aggregates that are utilized.

**Table 1.** Physical properties of coarse aggregate

| No. | Properties | Results of Testing | Unit |
|---|---|---|---|
| | Water absorption | | |
| 1 | **Crushed stone 5-10 mm** | 1.52 | % |
| | **Crushed stone 10-20 mm** | 0.70 | % |
| | Specific gravity | | |
| | **Crushed stone 5-10 mm** | | |
| | Bulk | 2.42 | - |
| | Saturated surface dry | 2.46 | - |
| 2 | Apparent | 2.51 | - |
| | **Crushed stone 10-20 mm** | | |
| | Bulk | 2.57 | - |
| | Saturated surface dry | 2.60 | - |
| | Apparent | 2.61 | - |
| | Flatness index | | |
| 3 | **Crushed stone 5-10 mm** | 19.18 | % |
| | **Crushed stone 10-20 mm** | 9.56 | % |
| | Abrasion | | |
| 4 | **Crushed stone 5-10 mm** | 25.87 | % |
| | **Crushed stone 10-20 mm** | 25.77 | % |

**Table 2.** Physical properties of fine aggregate (stone dust)

| No. | Properties | Results of Testing | Unit |
|---|---|---|---|
| 1 | Water absorption | 1.68 | % |
| | Bulk specific gravity | 2.63 | - |
| 2 | Saturated surface dry specific gravity | 2.67 | - |
| | Apparent specific gravity | 2.75 | - |
| 3 | Sand equivalent | 89.66 | % |

**Table 3.** Physical properties of fine aggregate (sand)

| No. | Properties | Results of Testing | Unit |
|---|---|---|---|
| 1 | Water absorption | 2.72 | % |
| | Bulk specific gravity | 2.37 | - |
| 2 | Saturated surface dry specific gravity | 2.43 | - |
| | Apparent specific gravity | 2.53 | - |
| 3 | Sand equivalent | 76.69 | % |

**Table 4.** Physical properties of filler (stone dust)

| No. | Properties | Result of Testing | Unit |
|---|---|---|---|
| 1 | Water absorption | 2.28 | % |
| | Bulk specific gravity | 2.60 | - |
| 2 | Saturated surface dry specific gravity | 2.65 | - |
| | Apparent specific gravity | 2.76 | - |
| 3 | Sand equivalent | 69.57 | % |

The aggregate utilized in Table 1 to Table 4 satisfies the Bina Marga standards in Indonesia requirement from Standard National Indonesia for the necessary road materials, according to tests conducted on the qualities of coarse aggregate (crushed stone), fine aggregate (stone ash and sand), and filler manufactured from stone ash.

### 3.2 Physical properties of fly ash

The fly ash characteristic test results are displayed in Table 5. The fly ash size distribution graph is displayed in Figure 1. Fly ash is used in the AC-BC combination to partially replace fly ash filler. Pozzolanic substance is what fly ash, a fine material, belongs to.

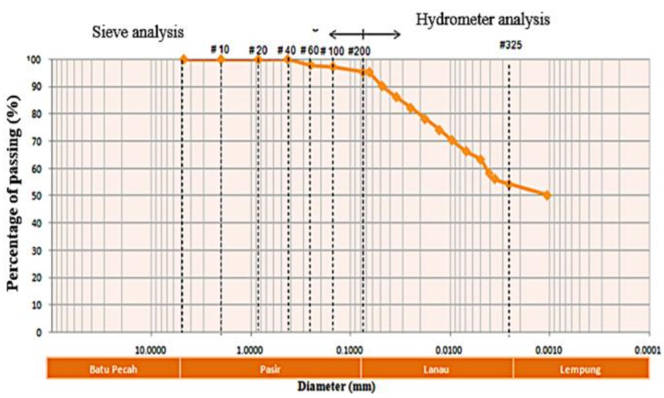


**Figure 1.** Fly ash size distribution

The findings of the fly ash specific gravity analysis are 2.88 in Table 5, which is higher than the specific gravities of slaked lime and laterite soil. This is because fly ash contains fine grains, notably those that pass-through sieves No. 200 (>90%) and No. 325 (45 millimicrons) (5-27%), according to the explanation given by ACI Committee 226. Typically, fly ash is shaped like solid or hollow balls. Fly ash has a water content of about 4% and a density of 2.23 gr/cm$^3$. Fly ash has a specific gravity that ranges from 2.15 to 2.6 and even up to 2.9. It is coloured a dark Gray. Particle size of fly ash from bituminous coal burning is less than 0.075 mm. The specific area of fly ash is 170-1000 m$^2$/kg. Sub-bituminous coal fly ash has an average particle size of 0.01 to 0.015 mm, a surface area of 1-2 m$^2$/g, and a mostly spherical, or ball-shaped, particle form that improves flowability.

**Table 5.** Physical properties of fly ash

| No. | Properties | Result of Testing |
|---|---|---|
| 1 | Specific gravity | 2.88 |
| 2 | Sieve analysis | > 90% lolos No.200 |

### 3.3 Physical properties of petroleum bitumen

Petroleum bitumen serves as the study's binder. To ascertain the physical parameters of asphalt and how they relate to its performance, we looked at its features. The results of the petroleum bitumen tests are shown in Table 6. The properties of petroleum bitumen were examined in Table 6. This research demonstrate that the asphalt utilized in this investigation complied with the 2018 General Specifications Revision 2, Section 6 asphalt pavement requirements.

**Table 6.** Physical properties of petroleum bitumen

| No. | Properties | Results of Testing |
|---|---|---|
| 1 | Penetration before weight loss (mm) | 78.60 |
| 2 | Soft point (°C) | 58 |
| 3 | Ductility at 25°C, 5 cm/min (cm) | 114 |
| 4 | Flash point (°C) | 280 |
| 5 | Specific gravity | 1.12 |
| 6 | Weight loss (%) | 0.3 |
| 7 | Penetration after weight loss (mm) | 86 |

### 3.4 Research design

This study substitutes fly ash waste for petroleum bitumen in the Asphalt Concrete Binder Course (AC-BC) blend and uses a laboratory experimental method on coarse aggregate and fine aggregate test objects.

The next stage is to create samples by calculating the Optimum Asphalt Content (OAC) using a combination of fly ash content variations (0%, 25%, 50%, 75%, and 100%) as a filler substitute and asphalt content variations (5.0%, 5.5%, 6.0%, 6.5%, and 7.0%). Variations in the use of fly ash levels used are based on research conducted by Rangan, et al. [7], where the use of fly ash as a filler is able to substitute filler and rock ash by 25% in AC-WC mixtures [9]. The SNI 06-2489-1991 standard serves as the procedural guide for sampling. In order to assess the performance of the mixture, we also test for Marshall characteristics such as stability, flow, MQ, VMA, VFB, VIM, and density. We can learn more about the properties of the asphalt mixture through this test.

### 3.5 AC-BC mixture preparation

After heating the petroleum bitumen to around 165°C, we combined it with the heated filler and aggregate. The mixing temperature between petroleum bitumen, filler, and aggregate is 150°C. Using a typical Marshall hammer, 75 blows were applied to each side of a 100 mm diameter by 60 ± 5 mm height cylindrical specimens with varying petroleum bitumen contents (5.0%, 5.5%, 6.0%, 6.5%, and 7.0%).

### 3.6 Unconditioned specimens and immersed specimens

To determine the specimens' resistance to moisture damage, we subjected them to three different treatments. The specimens were initially stored in a laboratory environment with a temperature of 30°C and a relative humidity of 65%. The specimens were submerged in the laboratory room for 24 hours at 30°C for the second and third treatments. For every treatment, we prepared the specimens in triplicate.

### 3.7 Volumetric assessment of asphalt mixture

The most popular and widely utilized test in use today is the Marshall testing. This is because the gadget is easy to mobilize due to its usefulness and simplicity. Marshall testing attempts to quantify aggregate and stability to flow. Flow is defined as the change in a mixture's deformation or strain from zero load to its maximum load, expressed in millimetres, or 0.01. The following features of asphalt concrete mixtures are revealed by the Marshall test parameters, especially the volumetric one:

3.7.1 Void in mix (VIM)

The air voids (Va) or volatile asphalt mixtures (VIM) are the spaces between asphalt-covered aggregate particles in asphalt pavement mixtures. The amount of air spaces in the mixture can be calculated using the following formula:

$$\text{VIM} = 100\% \times \frac{Gmm - Gmb}{Gmm} \quad (1)$$

where,

*VIM*: Air voids in solid mixture, percent of total volume;
*Gmm*: Maximum specific gravity of the mixture;
*Gmb*: Bulk specific gravity of solid mixture.

3.7.2 Void in mineral aggregate (VMA)

The gaps between aggregate particles in a pavement, including air voids and the effective asphalt volume (which does not include the volume of asphalt the aggregate absorbs), are referred to as "voids between aggregates" (VMA). The following formula can be used to compute the combination's VMA if the composition of the mixture is ascertained as a weight % of the entire mixture:

$$VMA = 100\% - \left(\frac{Gmb \times Ps}{Gsb}\right) \quad (2)$$

where,

*VMA*: Voids in mineral aggregate (percentage of bulk volume);
*Gsb*: Bulk specific gravity of aggregate;
*Ps*: Aggregate, percent of total weight of mixture;
*Gmb*: Bulk specific gravity of solid mixture (ASTM D 2726).

3.7.3 Void filled bitumen (VFB)

Voids filled with asphalt (VFB) is the percentage of voids between aggregate particles (VMA) that are filled with asphalt, excluding asphalt absorbed by the aggregate.

$$VFA = 100\% \times \frac{VMA - VIM}{VMA} \quad (3)$$

where,

*VFB*: Air voids filled with asphalt, percentage of VMA (%);
*VMA*: Air voids in mineral aggregate, percentage of total volume (%);
*VIM*: Air voids in the mixture after compaction (%).

## 4. RESULTS AND DISCUSSION

### 4.1 Chemical characteristics of fly ash

The chemical properties of the filler derived from fly ash and fly ash are shown in Table 7, which represents the material's XRF test findings. The SEM test findings for the fly ash utilized in this investigation are displayed in Figure 2 on a 10-micron scale. The fly ash particles employed as filler in this study have extremely diverse particle sizes and are spherical, generally spherical, as shown in Figure 2.

**Table 7.** Chemical characteristics of fly ash

| Element | Contents (%) |
|---|---|
| $SiO_2$ | 44.69 |
| $Al_2O_3$ | 15.73 |
| $Fe_2O_3$ | 10.25 |
| CaO | 14.12 |
| MgO | 2.78 |
| $K_2O$ | 0.73 |
| $Na_2O$ | 0.49 |

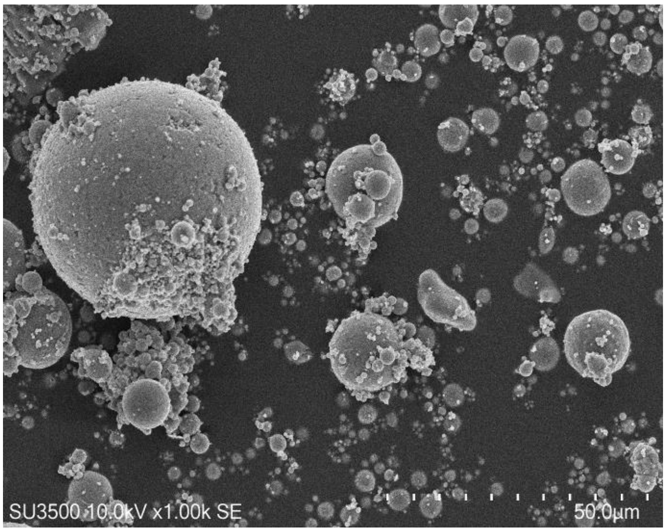


**Figure 2.** SEM test of fly ash

Fly ash is classified into three classes (class N, class F, and class C) by ASTM C618-03 [24]. For fly ash in the class N and class F categories, the minimum content of $SiO_2$, $Al_2O_3$, and $Fe_2O_3$ compounds is 70%; in the class C category, the value ranges from 50% to 70%. As a result, class N and F fly ash have comparatively lower CaO contents than class C fly ash, which has a CaO content of more than 10% (ASTM C618-03). Fly ash in the class F category has less than 20% CaO element content [25]. According to ASTM C618-03 and Woszuk et al. [25], type F fly ash (low calcium fly ash) is the fly ash employed in this study. A snapshot of the SEM test findings with a particle size of 50 μm. This suggests a solid link between the aggregate and the binder, improving the asphalt mixture's performance.

The fly ash particles utilized as filler in this study ranged widely in particle size from 484 nm to 1.24 μm, as revealed by the results of SEM examination with a particle size of 10 μm. This suggests a solid link between the aggregate and the binder, improving the asphalt mixture's performance.

### 4.2 Aggregate gradation and mixture design

Both stone dust and coarse aggregates were supplied by the same stone-crushed operation. Stone dust is produced during the crushing process of stone. In this investigation, the coarse and fine aggregate utilized to make the asphalt mixes were crushed and sharp-edged river stone and stone dust. There was a continuous aggregate grade with a 20 mm maximum size. As a filler, we used stone dust that passed through the No. 200 sieve. Filler is a product of the crushed stone process; it is a particle that passes through screen No. 200 (0.0075 mm).

Multiplying the comparative value of the intended aggregate composition by the percentage value of passing the sieve analysis yields the proportion of combined aggregates. After that, the results for every component—that is, every fraction satisfying the graduation requirements of the AC-BC mixture—were in compliance with Section 6 of Bina Marga's 2018 General Specifications for Road Works, Revision 2, regarding asphalt mixtures as AC-BC.

The resulting percentage of the combined aggregate is then adjusted to the specification interval value. The current combined aggregate gradation is then established by plotting the combined aggregate and the specification interval onto a graph, as shown in Table 8.

**Table 8.** Aggregate gradation and mixtures design (6.0% asphalt content)

| Filter Size | | Pass the Filter | | | | Stuck the Filter | | | Mixed Composition (%) | |
|---|---|---|---|---|---|---|---|---|---|---|
| Inchi | mm | Specification (%) | | | Mixed Gradation (%) | Weight (%) | Weight in Mixture (%) | Weight in Mixture (gr) | | |
| 1½ | 37,500 | | | | | | | | | |
| 1 | 25,000 | 100 | | | 100.00 | | | | | |
| 3/4 | 19,000 | 90 | - | 100 | 95.95 | 4.05 | 3.50 | 42.05 | 47.20 | Coarse Aggregate |
| 1/2 | 12,500 | 75 | - | 90 | 88.38 | 7.57 | 7.02 | 84.29 | | |
| 3/8 | 9,500 | 66 | - | 82 | 75.79 | 12.59 | 12.04 | 144.53 | | |
| No.4 | 4,750 | 46 | - | 64 | 50.62 | 25.17 | 24.62 | 295.49 | 42.30 | Fine Aggregate |
| No.8 | 2,360 | 30 | - | 49 | 35.51 | 15.11 | 14.56 | 174.77 | | |
| No.16 | 1,180 | 18 | - | 38 | 26.45 | 9.06 | 8.51 | 102.17 | | |
| No.30 | 0,600 | 12 | - | 28 | 18.89 | 7.56 | 7.01 | 84.17 | | |
| No.50 | 0,300 | 7 | - | 20 | 12.84 | 6.05 | 5.50 | 66.05 | | |
| No.100 | 0,150 | 5 | - | 13 | 7.03 | 5.81 | 5.26 | 63.17 | | |
| No.200 | 0,075 | 4 | - | 8 | 5.05 | 1.98 | 1.43 | 17.21 | | |
| Pan (filler) | | | | | | 5.05 | 4.50 | 54.05 | 4.50 | Filler |
| Asphalt | | | | | 6.00 | | 6.00 | 72.00 | 6.00 | Asphalt |
| Total | | | | | | 100.00 | 100.00 | 1200 | 100 | |

Only the mixture design for a 6.0% asphalt concentration is displayed in Table 8. Divide Table 8 according to each filter to find the proper mixture design for asphalt contents of 5.0, 5.5, 6.5, and 7.0%. The by-sieve proportion method is used in this study's combined aggregate gradation and mixing design.

Table 8 of Bina Marga's 2018 General Specifications for Road Works shows that the combined aggregate design, or combined aggregate gradation, satisfied the surface layer requirements and fell inside the standard specification interval, enabling the development of an ideal mix design in binder course mixture.

**4.3 Volumetric properties of asphalt mixture**

Using a Marshall compactor and varied amounts of petroleum bitumen, each field is tested and subjected to 75 impacts. Parameters including stability, flexibility, and flow that gauge a test object's resistance to load are obtained from the Marshall test analysis. The volumetric value of VMA, VFB, and VIM are among the Marshall features that are reviewed and analysed in this study.

4.3.1 Void in mix (VIM)

Following the volume measurement, Figure 3 shows the relationship between the petroleum bitumen content and the VIM value, with varying quantities of fly ash (0%, 25%, 50%, 75% and 100%) used as a filler. According to the 2018 General Specifications, a VIM value of 3% to 5% is necessary.

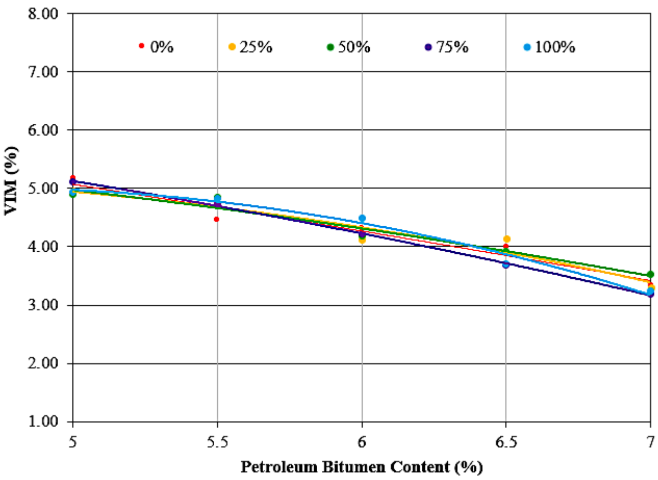


**Figure 3.** Relationship of Petroleum bitumen with VIM

The similar tendency may be found by looking at the VIM values for all fly ash contents for each bituminous petroleum content. Without employing fly ash as a filler, the test specimen's VIM value at asphalt content 5.0%, 5.5%, 6.0%, 6.5%, and 7.0% is 5.17%, 4.46%, 4.31%, 4.00%, and 3.37%, respectively. The 25% contents in test specimens containing fly ash are 4.96%, 4.71%, 4.13%, 4.14%, and 3.31%. It is 4.91%, 4.84%, 4.19%, 3.92%, and 3.52% in test specimens with a 50% fly ash content. It is 5.11%, 4.74%, 4.21%, 3.69%, and 3.18% in test specimens with a 75% fly ash content. The figures for the test specimen with a 100% fly ash content are 3.70%, 3.24%, 4.93%, 4.83%, and 4.49%. VIM dropped within the 3-5% range at without fly ash, from 5.169% at 5% to 3.336% at 7%. VIM fixed in the range of 3-5% for 25% fly ash, dropping from 4.965% at 5% asphalt content to 3.306% at 7% content. According to the range of 3-5% requirements at 50% fly ash content, VIM dropped from 4.908% at 5% asphalt content to 3.522% at 7%. As per 3-5% standards at 75% fly ash concentrations, VIM dropped from 5.109% at 5% asphalt content to 3.181% at 7%. VIM dropped to 3.241% at 7% from 4.934% at 5% asphalt percentage, per 3-5% requirements at 100% fly ash.

4.3.2 Void in mineral aggregate (VMA)

In accordance with Division 6 of General Specification 2018, Revision 2, asphalt pavement, asphalt mixtures must have a VMA value of at least 15%. A volumetric parameter called VMA shows whether there are any voids in between the aggregate binding. Figure 4 illustrates the relationship between the VMA value and the quantity of petroleum bitumen at various fly ash replacement contents for filler minerals. They are 25%, 50%, 75%, 100%, and 0%.

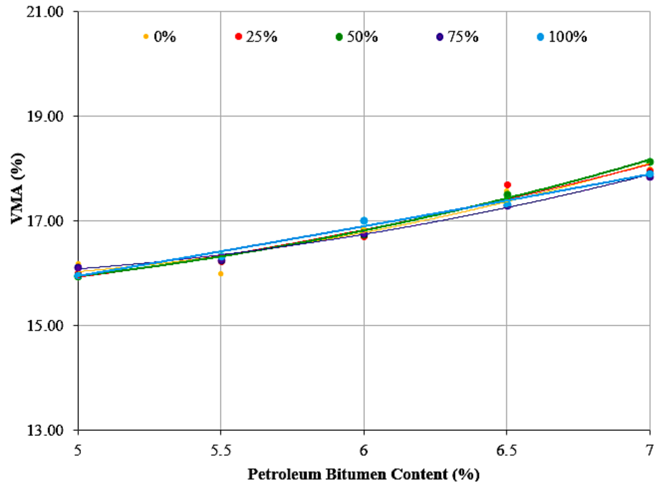


**Figure 4.** Relationship of Petroleum bitumen with VMA

The VMA value in the test specimen without fly ash increases as bitumen petroleum contents rise. The test samples with bitumen petroleum contents of 5%, 6%, 7%, 6%, 6%, and 5% with fly ash instead of stone ash filler have visible VIM values of 16.18%, 16.86%, 17.58%, and 17.98%, respectively. The experiment sample containing 25% fly ash yields VMA values of 16.22%, 16.71%, 17.70%, and 17.96%. With a fly ash content of 50%, the test specimen's VMA values are 15.95%, 16.33%, 16.75%, 17.50%, and 18.14%. The VMA values of each bitumen petroleum content are 15.97%, 16.33%, 17.01%, 17.32%, and 17.90% for test specimens with fly ash contents of 75%, 16.13%, 16.25%, 16.78%, 17.31%, and 17.85% for test specimens with 100% fly ash.

With the addition of asphalt without fly ash, VMA and VFB rise, and they all satisfy the requirements of ≥15% and ≥65%. MQ drops at the 7% content, below the minimal limit of 250 kg/mm, and peaks at 6% asphalt contents (482.62 kg/mm). Density fluctuates but remains within the tolerance of ≥2.2 $kg/mm^3$. The results indicate that 6% asphalt contents are ideal for optimum performance.

When the amount of asphalt increases with 25% fly ash, so do VMA and VFB; both must fulfil the minimum requirements (≥15% for VMA and ≥65% for VFB). At 6% asphalt concentration, the maximum Marshall Quotient (MQ) is 557.67 kg/mm; however, at 6.5% and 7%, the MQ falls short of the requirements. At 7%, it is less than the maximum MQ. Although mixed density fluctuates, it always falls within the ≥2.2 $kg/mm^3$ range. The optimal ratio of performance and stability is found at 6% asphalt content. As the amount of asphalt increases at 50% fly ash, VMA and VFB also rise to fulfil the respective requirements of ≥15% and ≥65%. At 6% asphalt concentration, the Marshall Quotient (MQ) is at its maximum (629.23 kg/mm), but it falls at 6.5% and 7% content, reaching a value below specifications at 7%. The mixture density satisfies the requirements ≥2.2 kg/mm$^3$ and is steady in the range of 2.262 to 2.276 kg/mm$^3$. Overall, 6% asphalt content is ideal for maximum performance.

4.3.3 Void filled bitumen (VFB)

The relationship between petroleum bitumen content and VFB value at each fly ash content—that is, 0%, 25%, 50%, 75%, and 100%—that is used to replace a portion of the fly ash filler is depicted in Figure 5. The 2018 General Specification, Revision 2, Division 6 on Asphalt Pavement states that asphalt mixtures must include 65% or more VFB.

The test specimen lacking fly ash had a higher VMA value as bitumen petroleum contents rise. In the case of test samples prepared without the use of fly ash in place of stone ash filler and bitumen petroleum contents of 5%, 6%, 7%, 6%, 6%, and 5%, the visible VIM values are 16.18%, 16.86%, 17.58%, and 17.98%, respectively. The VMA values of 16.00%, 16.22%, 16.71%, 17.70%, and 17.96% are obtained from the test material containing 25% fly ash. 15.95%, 16.33%, 16.75%, 17.50%, and 18.14% are the VMA values in the test specimen with a fly ash content of 50%. Test specimens with 75% fly ash yield VMA values of 16.13%, 16.25%, 16.78%, 17.31%, and 17.85%, whereas test specimens with 100% fly ash yield VMA values of 15.97%, 16.33%, 17.01%, 17.32%, and 17.90% for each bitumen petroleum content.

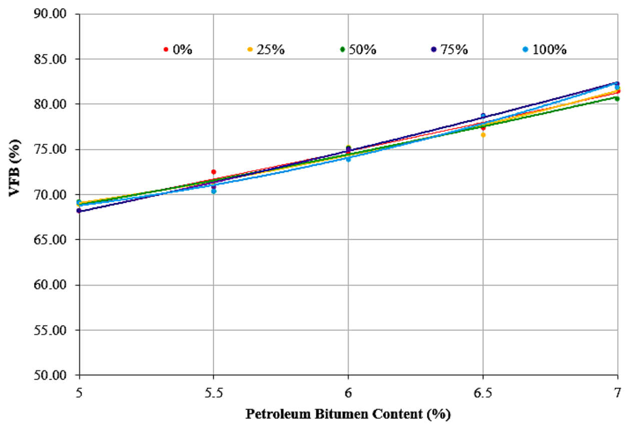


**Figure 5.** Relationship of Petroleum bitumen with VFB

Both VMA and VFB rise as the amount of asphalt increases with 75% fly ash, reaching minimum limitations of roughly 15% and 65%, respectively. With a value of 696.10 kg/mm, the highest Marshall Quotient (MQ) is found at 6% asphalt content. The MQ falls at 6.5% and 7% asphalt content, and it is below specifications at 7% content. Density satisfies the minimal requirements of ≥2.2 kg/mm$^3$ and falls between 2.269 and 2.278 kg/mm$^3$. According to these findings, 6% asphalt concentration is ideal for optimum performance. Both VMA and VFB rise as the amount of asphalt increases with 100% fly ash, reaching the minimum limitations of roughly 15% and 65%, respectively. The Marshall Quotient (MQ) reaches its maximum value of 770.73 kg/mm at a 6% asphalt content. But at 6.5% and 7% contents, it starts to decline and at 7% content, it reaches a value that is below the requirements. Density meets the requirements of ≥2.2 kg/mm$^3$, falling between 2.269 and 2.276 kg/mm$^3$. The ideal asphalt content for maximum performance is 6%.

### 4.4 Volumetric assessment of asphalt mixture

The volumetric assessment for the VIM, VMA, and VFB characteristics is shown in Figures 6 to 8, where different filler percentages (0%, 25%, 50%, 75%, and 100%) are substituted with high calcium fly ash and petroleum bitumen as binder. Fly ash is anticipated to increase the density of the AC-BC mixture and, naturally, provide good Marshall properties and a volumetric cavity that satisfies Indonesian road condition requirements by Standard National Indonesia.

The VIM graph at 0% fly ash content demonstrates how the VIM value decreases as the amount of asphalt increases. The decrease is 5.17% at 5.0% asphalt content, 4.46% at 5.0% to 5.5% asphalt content, 4.31% at 5.0% to 6.0% asphalt content, 4.00% at 5.0% to 6.5% asphalt content, and 3.34% at 5.0% to 7.0% asphalt content. The VIM value decreases as the amount of asphalt increases at a fly ash content of 25%. This decrease is 4.96% at 5.0% asphalt content, 4.71% at 5.0% to 5.5% asphalt content, 4.13% at 5.0% to 6.0% asphalt content, 4.14% at 5.0% to 7.0% asphalt content, and 3.31% at 5.0% to 7.0% asphalt content.

The VIM value drops with an increase in asphalt content at 50% fly ash percentage. 5.0% asphalt content results in a decrease of 4.91%, 5.0% to 5.5% asphalt content results in 4.84%, 5.0% to 6.0% asphalt content results in 4.19%, 5.0% to 6.5% asphalt content results in 3.92%, and 5.0% to 7.0% asphalt content results in 3.18%. The VIM value decreases with increasing asphalt content at a fly ash content of 75%. This decrease is 5.11% at 5.0% asphalt content, 4.75% at 5.0% to 5.5% asphalt content, 4.21% at 5.0% to 6.0% asphalt content, 3.69% at 5.0% to 6.5% asphalt content, and 3.18% at 5.0% to 7.0% asphalt content. The VIM value at 100% fly ash content decreases as the amount of asphalt increases; this decrease is 4.93% at 5.0% asphalt content, 4.83% at 5.0% to 5.5% asphalt content, 4.49% at 5.0% to 6.0% asphalt content, 3.70% at 5.0% to 6.5% asphalt content, and 3.24% at 5.0% to 7.0% asphalt content.

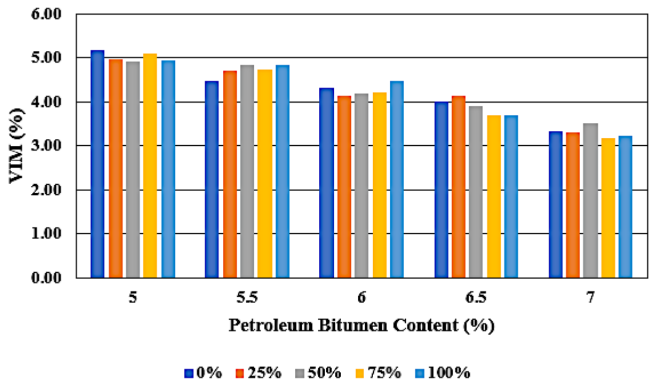


**Figure 6.** Volumetric assessment of VIM

The VMA graph shows that as the asphalt content increases, the VMA value increases, even at 0% fly ash content. The increase is 16.18% at 5.0% asphalt content, 16.87% at 5.0% to 5.5% asphalt content, 17.58% at 5.0% to 6.5% asphalt content, and 17.98% at 5.0% to 7.0% asphalt content. We see an increase in the VMA value when the asphalt content rises when the fly ash concentration approaches 25%. Starting at 5.0% asphalt content, this increase increases to 16.22% at 5.0% to 5.5% asphalt content, 16.71% at 5.0% to 6.0% asphalt content, 17.70% at 5.0% to 6.5% asphalt content, and 17.96% at 5.0% to 7.0% asphalt content.

We see an increase in the VMA value when the asphalt content rises when the fly ash concentration hits 50%. This increase begins at a 5.0% asphalt content and increases to 16.33%, 16.75%, 17.50%, and 18.14% at various asphalt content levels. A 5.0% asphalt content is the starting point for this increment. We see an increase in the VMA value as the asphalt content rises when the fly ash concentration hits 75%. Starting at 5.0% asphalt percentage, this increment increases to 16.13%, 16.25%, 16.78%, 17.31%, and 17.85% at 5.0% asphalt content, respectively. We see an increase in the VMA value as the asphalt content rises when the fly ash concentration hits 100%. At 5.0% asphalt content, the increase is 16.33%; at 5.0% to 5.5% asphalt content, it is 17.02%; at 5.0% to 6.0% asphalt content, it is 17.32%; and from 5.0% to 7.0% asphalt content, it is 17.90%.

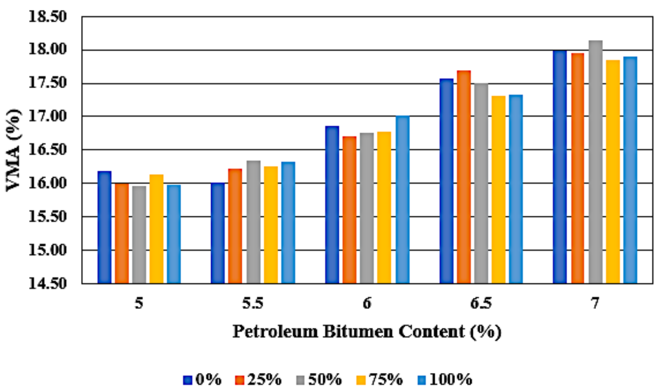


**Figure 7.** Volumetric assessment of VMA

The VFB graph shows that as the asphalt content increases, the VFB value increases, even at 0% fly ash content. The increase is 68.34% at 5.0% asphalt content, 72.50% at 5.0% to 5.5% asphalt content, 74.63% at 5.0% to 6.0% asphalt content, 77.38% at 5.0% to 6.5% asphalt content, and 81.56% at 5.0% to 7.0% asphalt content. We see an increase in the VFB value when the asphalt content rises when the fly ash concentration is 25%. for 5.0% asphalt content, this increase is 71.21%, 75.64%, 76.64%, and 81.83%, respectively, for 5.0% to 6.0%, 5.0% to 7.0%, and 5.0% to 6.0% asphalt content.

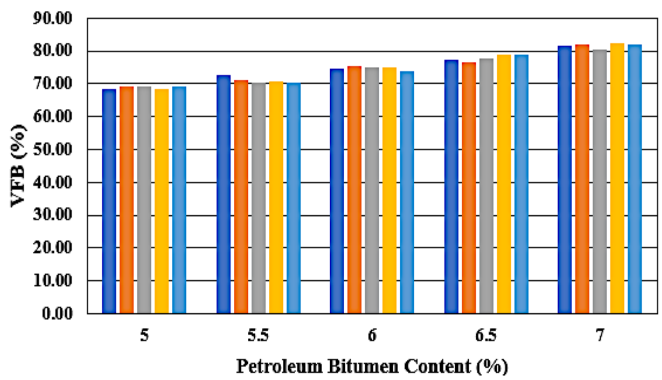


**Figure 8.** Volumetric assessment of VFB

We see an increase in the VFB value when the asphalt content rises when the fly ash concentration hits 50%. This increase is 75.19% at 5.0% to 6.0% asphalt content, 77.65% at 5.0% to 6.5% asphalt content, 80.61% at 5.0% to 7.0% asphalt content, and 69.31% at 5.0% to 5.5% asphalt content. The VFB value increases with the amount of asphalt at a fly ash content of 75%. At 5.0% asphalt content, the increase is 68.33%; at 5.0% to 5.5% asphalt content, it is 70.82%; at 5.0% to 6.0% asphalt content, it is 75.03%; at 5.0% to 6.5% asphalt content, it is 78.77%; and at 5.0% to 7.0% asphalt content, it is 82.25%. The value of the VFB at 100% fly ash content grows with the amount of asphalt; this climbs to 69.13% at 5.0% asphalt content, 70.43% at 5.0% to 5.5% asphalt content, 73.91% at 5.0% to 6.0% asphalt content, 78.69% at 5.0% to 6.5% asphalt content, and 81.97% at 5.0% to 7.0% asphalt content.

Fly ash filler seems to have a major impact on raising the heat mixture's stability value utilizing AC-WC gradations. A number of studies have shown how adding fly ash as a filler to a pavement mixture can improve its stability and emphasize its potential as a filler material to improve resilience modulus and stripping resistance [26]. Using materials that pass through a 0.075-m filter, Amoni et al. [27] introduced different amounts of flying ash (0, 10, 50, and 100%) in place of mineral fillers in 2005. The materials were put to the test for fatigue, rutting, dynamic creep, resilient modulus, stripping resistance, and indirect tensile strength. The best percentage for enhancing mechanical qualities was found to be 10% fly ash added to mineral fillers. Tumpu and Lapian [28] used fly ash contents of 25%, 50%, 75%, and 100% and discovered that the addition of fly ash content raised the stability value and may be used as a mineral filler in asphalt concrete.

The pozzolanic activity in the Laston AC-BC combination was induced by two oxides, $SiO_2$ and $Al_2O_3$, which were 44.69% and 15.73% present in the flying ash in this investigation, respectively. Furthermore, a tiny percentage of this oxide crystallizes, creating a solid link between the aggregate and the binder that is being utilized [20].

Because the indirect tensile strength of the asphalt mixture employing this fly ash filler is rising in tandem with the application of more fly ash filler, the mixture's performance is good. This is corroborated by the research by Dulaimi et al. [29], which carried out fatigue testing, water sensitivity tests, static and dynamic creep tests, and indirect tensile tests. The mixture made with flying ash has superior mechanical qualities than the mixture made with limestone fillers, as the data show. Therefore, using flying ash as a mineral filler in the asphalt mixture shows great promise.

Some coal and lime ash combinations satisfy the minimum tensile strength standards established by the South Carolina Department of Transportation [30]. Sedimentative fillers are typically successful in lowering the moisture sensitivity of HMA mixes [31]. Based on the collected results, flying ash from all four groups is suitable to employ in a BC combination; group 4 performed the best [32]. The Fly Ash BC mixture has a superior nature than the usual mixture, and 7% filling content is the ideal amount.

OPC and limestone are the two fillers used in Kuwait [33]. The findings show that utilizing OPC as a filler raises the fixed strength value. Both hydrated lime and fly ash, according to Abdel-Wahed et al. [34], help to lessen moisture damage, suggesting that utilizing fly ash as an alternative additive could result in significant cost savings. Consequently, it is strongly advised to use flying ash as a filler in paved mixtures.

## 5. CONCLUSIONS

It is a highly complicated issue to employ bitumen petroleum in different types of road pavement building. Thus, further investigation is required to examine the use of bitumen petroleum in conjunction with high-calcium fly ash for road pavement. Numerous studies have been carried out to investigate the efficacy of high-calcium fly ash and petroleum bitumen in road pavement. They all agree that these materials improve the performance of road pavement by acting as a binder and a replacement for fillers made of cement or stone ash. Thus, the following are the study's conclusions:

1. The content of petroleum bitumen reaches its optimal density when it is combined with high-calcium fly ash. At this point, the proper amount of asphalt is used to hold the aggregate together without going overboard and reducing density.
2. 100% does not significantly alter the density value, as indicated by the volumetric values of VIM, VMA, and VFB, in the variation of the 0% fly ash level. In general, the addition of fly ash to the mixture does not significantly alter density; however, when the fly ash level rises to 25% to 50%, density does somewhat drop at higher asphalt levels (6.5% and 7%). This indicates that a specific amount of fly ash addition does not adversely affect the density of the asphalt mixture; nevertheless, a larger fly ash level may cause a little drop in cohesiveness.
3. The best amount of flying ash to partially replace the stone ash filler in the AC-BC combination, which employs petroleum bitumen as a binding agent, is 50%, according to the results of the AC-BC asphalt volumetric test, which blended bitumen petroleum with high calcium fly ash. The performance of the AC-BC asphalt combination is also highly influenced by MQ, flow, and stability, therefore these studies have not produced representatives that match Marshall's qualities.

The study's findings are in favour of using high calcium fly ash as an AC-BC mixture filler and bitumen petroleum as a binder. This strategy is anticipated to decrease the quantity of flying ash and boost the application of hot mix, which contains bitumen petroleum.

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## REFERENCES

[1] Mahan, H.M., Ajam, H.K.K., Jassim, H.S.H. (2023). Enhancing Marshall properties through the integration of waste plastic water bottles in dry process asphalt production. Mathematical Modelling of Engineering Problems, 10(5): 1817-1823. https://doi.org/10.18280/mmep.100534

[2] Al Qadi, A.N.S., Khedaywi, T.S., Haddad, M.A., Al-Rababa'ah, O.A. (2021). Investigating the effect of olive husk ash on the properties of asphalt concrete mixture. Annales de Chimie - Science des Matériaux, 45(1): 11-15. https://doi.org/10.18280/acsm.450102

[3] Tian, P., Peng, K.X., Dong, H.N., Li, Y., Dong, W.Z. (2021). The effect of mineral powder on the surface/interface of aggregates and asphalt. Annales de Chimie - Science des Matériaux, 45(4): 281-290. https://doi.org/10.18280/acsm.450403

[4] Tumpu, M., Rangan, P.R. (2024). Silica quartz characteristics from local silica sand on compressive strength of mortar. Civil Engineering Journal, 10(8): 2588-2600. https://doi.org/10.28991/CEJ-2024-010-08-010

[5] Bhatt, A., Priyadarshini, S., Mohanakrishnan, A.A., Abri, A., Sattler, M., Techapaphawit, S. (2019). Physical, chemical, and geotechnical properties of coal fly ash: A global review. Case Studies in Construction Materials, 11: e00263. https://doi.org/10.1016/j.cscm.2019.e00263

[6] Nasir, N.H.M., Usman, F., Saggaf, A. (2022). Development of composite material from Recycled Polyethylene Terephthalate and fly ash: Four decades progress review. Current Research in Green and Sustainable Chemistry, 5: 100280. https://doi.org/10.1016/j.crgsc.2022.100280

[7] Rangan, P.R., Tumpu, M., Mansyur. (2023). Marshall characteristics of quicklime and Portland Composite Cement (PCC) as fillers in Asphalt Concrete Binder Course (AC-BC) mixture. Annales de Chimie - Science des Matériaux, 47(1): 51-55. https://doi.org/10.18280/acsm.470107

[8] Liu, F., Liu, H.Q., Wei, G.X., Zhang, R., Zeng, T.T., Liu, G.S., Zhou, J.H. (2018). Characteristics and treatment methods of medical waste incinerator fly ash: A review. Processes, 6(10): 173. https://doi.org/10.3390/pr6100173

[9] Saing, Z., Mairuhu, D., Tumpu, M. (2024). Characteristics of asphalt concrete wearing course mix incorporating recycled tire rubber as an additive. GEOMATE Journal, 26(115): 34-43.

[10] Sutradhar, D., Miah, M., Chowdhury, G.J., Sobhan, M.A. (2015). Effect of using waste material as filler in bituminous mix design. American Journal of Civil Engineering, 3(3): 88-94. https://doi.org/10.11648/j.ajce.20150303.16

[11] Diab, A., Enieb, M. (2018). Investigating influence of mineral filler at asphalt mixture and mastic scales. International Journal of Pavement Research and Technology, 11(3): 213-224. https://doi.org/10.1016/j.ijprt.2017.10.008

[12] Mabui, D., Tumpu, M., Widodo, S., Rusmin, M., Rangan, P.R. (2024). Optimization of asphalt content through Marshall characteristics using modified asbuton. GEOMATE Journal, 26(117): 116-123.

[13] Joshi, A.R., Patel, S. (2023). Investigation into sustainable application of class C Fly ash layer in flexible pavement. Journal of Hazardous, Toxic, and Radioactive Waste, 27(1): 04022033. https://doi.org/10.1061/(ASCE)HZ.2153-5515.0000727

[14] Tomar, R., Jain, R.K., Kostha, M.K. (2013). Effects of fillers on bituminous paving mixes. International Journal of Engineering Research and Science & Technology, 2(4): 2391-2397.

[15] Mirković, K., Tošić, N., Mladenović, G. (2019). Effect of different types of fly ash on properties of asphalt mixtures. Advances in Civil Engineering, 2019(1): 8107264. https://doi.org/10.1155/2019/8107264

[16] Al Nageim, H., Dulaimi, A., Al-Busaltan, S., Kadhim, M.A., Al-Khuzaie, A., Seton, L., Croft, J., Drake, J.

(2023). The development of an eco-friendly cold mix asphalt using wastewater sludge ash. Journal of Environmental Management, 329: 117015.
[17] ASH, U.H.V.F. (2024). Mechanical properties of foamed concrete (FC). International Journal of GEOMATE, 26(118): 141-148. https://doi.org/10.21660/2024.118.g13323
[18] Parung, H., Tumpu, M., Tjaronge, M.W., Amiruddin, A.A., Walenna, M.A., Mansyur. (2023). Crack pattern of lightweight concrete under compression and tensile test. Annales de Chimie - Science des Matériaux, 47(1): 35-41. https://doi.org/10.18280/acsm.470105
[19] Joumblat, R., Al Basiouni Al Masri, Z., Elkordi, A. (2023). Dynamic modulus and phase angle of asphalt concrete mixtures containing municipal solid waste incinerated fly ash as mineral filler substitution. International Journal of Pavement Research and Technology, 16(5): 1196-1216. https://doi.org/10.1007/s42947-022-00190-x
[20] Joumblat, R., Elkordi, A., Khatib, J., Al Basiouni Al Masri, Z., Absi, J. (2023). Characterisation of asphalt concrete mixes with municipal solid waste incineration fly ash used as fine aggregates substitution. International Journal of Pavement Engineering, 24(2): 2099855.https://doi.org/10.1080/10298436.2022.2099855
[21] Gusty, S., Ahmad, S.N., Tumpu, M. (2024). Assessing open-graded asphalt’s resistance to degradation via cantabro test in hot-mix cold laid asbuton. GEOMATE Journal, 27(120): 60-68.
[22] Jaber, S.K., Aljawad, A.A., Pop, E., Prisecaru, T., Pisa, I. (2022). The use of bottom ash and fly ash from medical incinerators as road construction material. Scientific Bulletin-University Politehnica of Bucharest, 84(2): 43-54.
[23] Bieliatynskyi, A., Yang, S., Pershakov, V., Shao, M., Ta, M. (2022). The use of fiber made from fly ash from power plants in China in road and airfield construction. Construction and Building Materials, 323: 126537. https://doi.org/10.1016/j.conbuildmat.2022.126537
[24] Rangan, P.R., Tumpu, M., Arrang, A.T., Yunianta, A., Rachim, F. (2024). Effect of curing time and liquid alkaline activators on compressive strength development of fly ash and bamboo leaf ash-based geopolymer concrete. GEOMATE Journal, 27(119): 112-119.
[25] Woszuk, A., Bandura, L., Franus, W. (2019). Fly ash as low cost and environmentally friendly filler and its effect on the properties of mix asphalt. Journal of Cleaner Production, 235: 493-502. https://doi.org/10.1016/j.jclepro.2019.06.353
[26] Mistry, R., Roy, T.K. (2021). Performance evaluation of bituminous mix and mastic containing rice husk ash and fly ash as filler. Construction and Building Materials, 268: 121187. https://doi.org/10.1016/j.conbuildmat.2020.121187
[27] Amoni, B.C., Freitas, A.D., Bessa, R.A., Oliveira, C.P., Bastos-Neto, M., Azevedo, D.C., Lucena, S.M.P., Sasaki, J.M., Soares, J.B., Soares, S.A., Loiola, A.R. (2022). Effect of coal fly ash treatments on synthesis of high-quality zeolite A as a potential additive for warm mix asphalt. Materials Chemistry and Physics, 275: 125197. https://doi.org/10.1016/j.matchemphys.2021.125197
[28] Tumpu, M., Lapian, F.E. (2024). Asphalt mix compressive stress-strain behavior: An analytical and experimental study of variable influence. Civil Engineering Journal, 10(5): 1525-1542. https://doi.org/10.28991/CEJ-2024-010-05-011
[29] Dulaimi, A., Qaidi, S., Al-Busaltan, S., Milad, A., Sadique, M., Kadhim, M.A., Al-Khafaji, R., Sabri Sabri, M.M. (2023). Application of paper sludge ash and incinerated sewage ash in emulsified asphalt cold mixtures. Frontiers in Materials, 9: 1074738. https://doi.org/10.3389/fmats.2022.1074738
[30] Dulaimi, A., Al-Busaltan, S., Kadhim, M.A., Al-Khafaji, R., Sadique, M., Al Nageim, H., Ibrahem, R.K., Awrejcewicz, J., Pawłowski, W., Mahdi, J.M. (2022). A sustainable cold mix asphalt mixture comprising paper sludge ash and cement kiln dust. Sustainability, 14(16): 10253. https://doi.org/10.3390/SU141610253
[31] Bamigboye, G.O., Bassey, D.E., Olukanni, D.O., Ngene, B.U., Adegoke, D., Odetoyan, A.O., Kareem, M.A., Enabulele, D.O., Nworgu, A.T. (2021). Waste materials in highway applications: An overview on generation and utilization implications on sustainability. Journal of Cleaner Production, 283: 124581. https://doi.org/10.1016/J.JCLEPRO.2020.124581
[32] Baloochi, H., Aponte, D., Barra, M. (2022). Waste paper ash as a hydraulic road binder: Hydration, mechanical and leaching considerations. Journal of Environmental Management, 314: 115042. https://doi.org/10.1016/J.JENVMAN.2022.115042
[33] Al-Merzah, S., Al-Busaltan, S., Nageim, H.A. (2019). Characterizing cold bituminous emulsion mixtures comprised of palm leaf ash. Journal of Materials in Civil Engineering, 31(6): 04019069. https://doi.org/10.1061/(ASCE)MT.1943-5533.0002714
[34] Abdel-Wahed, T., Dulaimi, A., Shanbara, H.K., Al Nageim, H. (2022). The impact of cement kiln dust and cement on cold mix asphalt characteristics at different climate. Sustainability, 14(7): 4173. https://doi.org/10.3390/SU14074173