Improving strength of porous asphalt: a nano material experimental approach

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Abstract. Porous asphalt (PA) has potential to be utilized in many urban area in Indonesia which often faced high street runoff during rainy season. PA is an environmentally friendly tool for stormwater management. A typical porous pavement has an open-graded surface over an underlying stone recharge bed. The water drains through the porous asphalt and into the stone bed, then, slowly, infiltrates into the soil. However, despite of the benefit of porous asphalt, there is still weaknesses, such as less of service life than dense-graded asphalt due to its lower durability and strength. In order to improve durability and strength of PA, this study investigates the effect of using fly ash (FA) class F in porous asphalt (PA) mixture as replacement of common filler. Since asphalt pen 60/70 is mainly binder material in Indonesia, it is used as the default for all samples in this experiment. The optimum bitumen content (OBC) was determined for all the mix by Marshall mix design. In view of the nanomaterial approach, samples were then prepared for the same optimum bitumen content (5.85%) by using Bina-Marga’s PA standard in control mix as well as natural FA and treated FA as alternative filler in modified mixes. Treated FA itself has been milled using transversal ball mill machine for 3 to 6 hours. Experimental results indicated higher stability value and reduction of permeability with the same OBC for the mixture having treated FA as filler content in comparison with standard mix and natural FA mix. It is proposed that additional finer material of treated Fly ash as alternative filler added into asphalt mixture resulted in improvement strength. In order to do that, the required amount of treated Fly ash should be less than 200 grams.

1 Introduction

The application of porous asphalt has so many advantages for infrastructure. At the beginning steps, with proper design and installation, porous asphalt pavements can provide a cost-effective solution for stormwater management in an environmentally friendly way. Although it has limitations in terms of durability and strength, this research discussed the optimization of asphalt porous can be determined. For this research, fly ash was used as alternative filler for void reduction but still maintaining for drains. To satisfy fly ash as filler, modification in terms of size was conducted. Bituminous materials, such as asphalt, are used on a large scale road construction projects in Indonesia. There are three mainly types of pavement that has been used in Indonesia such as; dense-graded mixtures, open-graded mixtures (Porous Asphalt), and rigid pavement. Dense-grade mixtures and rigid pavement are the mainly used on road construction in Indonesia. However, number of flood on the surface of the pavement are extremely high during in wet season. Since dense-graded mixtures and rigid pavement has a characteristic that only drain the water to nearest drainage system through surfaces, it means that this type of pavement depend to another infrastructures such as drainage system. However, porous asphalt has something different than the other type of pavement. First used in 1950’s in the United States, and become popular in the 1980’s by more than 200 projects of porous asphalt designed by Cahill Associate, this type of pavement allow water to drain infiltrate through surfaces. This might be suitable in Indonesian road since the porous asphalt construction will gives more space for water to drain before reach the nearest drainage system. Despite of the benefit of porous asphalt, there is still weaknesses in porous asphalt such as less of service life than open-graded or rigid pavement, and its durability and strength. There are two type of modification to
improve it such as binder modification or aggregates modification. Since asphalt Pen 60/70 is the mainly used binder material in Indonesia, so Pen 60/70 become the default of all samples in this research. It will be easier to construct when all the material are the mainly used and available all across the country. Because of Pen 60/70 become the default, the modification will be in aggregate.

There are three kind of sample which will be use the gradation content specification of porous asphalt that has been standarized by Bina Marga (Ministry of Public Works in Indonesia) in 2012 (Syahputra, 2017). The three kind of samples are; with optimum bitumen content, 18% of fly ash (class F), and 3,6% of fly ash that has been milled using transversal ball mill machine for 3 to 6 hours. Using original fly ash and milled fly ash class F as a replacement in aggregate content will reduce its permeability and improve its durability. To investigate of sample characteristics, several test such as cantabro loss, marshall test and permeability test will be tested in transportation laboratorium. Another test will be held in physics laboratorium by using transversall ball mill machine and nano material laboratorium by using scanning electron microscope (SEM) and X-ray diffraction (XRD) facility.

2 Research Objectives
To improve strength and durability of porous asphalt, this research will identify how fly ash will react when it comes to the porous asphalt mixtures. Since fly ash will fill the pores between porous asphalt mixtures as a filler, this reaction will reduce the permeability and improve the strength of asphalt porous. However, amount of fly ash should be analyzed to get the optimum composition. Another objectives of this research is to analyze the impact of fly ash that has been milled for 3-6 hours. This research will gives the result of marshall test, cantabro test and permeability test of three samples that stated before.

3 Experimental Procedures
3.1 Asphalt Porous Mix Design
Mix design of porous asphalt has various standards depend on the availability of resources and the climate of a country that observed. In Indonesia, ministry of public works has established a standard in 2012 about guidance for porous asphalt. This research will use the specification of Indonesian standard with the gradation of aggregate shown below.

| Sieve Number | Spec Percent Pass | Percent Retained |
|--------------|------------------|-----------------|
| (ASTM)       | (mm)             | Avg             |     |
| 1"           | 25,000           | 100             | 0   |
| 3/4"         | 19,000           | 95 – 100        | 97,5| 2,5 |
| 1/2"         | 12,500           | 64 – 84         | 74  | 23,5|
| 4            | 4,750            | 10 – 31         | 20,5| 53,5|
| 8            | 2,360            | 10 – 20         | 15  | 5,5 |
| 200          | 0,075            | 3 – 7           | 5   | 10  |
| Pan          |                  | 5               |     |

To find the optimum asphalt content, there are 15 sample with various asphalt content from 4%, 5%, 6%, 7%, and 8%. Each sample will has weight about 1100 grams. After measuring the gradation, aggregates will be heat up until reach 164 °C, and will be mixed with asphalt in temperature of 154 °C. Several test will conduct based on the Indonesian specification of porous asphalt. There are three kinds of test that will be a criteria to find the optimum asphalt content. The three kinds test are:

1. Asphalt Draindown test
2. Cantabro Loss test
3. Marshall Stability test

Asphalt draindown test is a test to quantify amount of asphalt that has been dripped from the porous asphalt mixtures. For open gradation mixtures or asphalt porous this test is a special test. The sample of asphalt
mixtures will be put into a bucket without compacted before. After that, the bucket will be put into an oven for 65 minutes.

\[
\text{Asphalt Draindown} = \frac{A-B}{C} \times 100
\]

Where:
- \( A \) = Final weight of plate (gr)
- \( B \) = Initial weight of plate (gr)
- \( C \) = Initial total sample weight, g

Cantabro loss test is a test to quantify the abration loss of pavement mixtures. There are two type of this test which are with steel ball and without steel ball. First aggregate mixture was compacted with hammer for 50 times of blows each size. The sample will be put into abration loss Loss Angeless Machine with 300 revolutions.

\[
\text{CL} = \frac{A-B}{A} \times 100
\]

Where:
- \( \text{CL} \) = Cantabro Loss,
- \( % \ A \) = Initial weight of test sample,
- \( B \) = Final weight of test sample

The last test for finding optimum asphalt content is marshall stability test. This test will quantify the factor of mixtures and marshall factor. This test will show how much pores that created inside the sample with the same sample procedure with cantabro loss. The output of this test are such as:
1. Flow
2. Marshall Quotient
3. Void in Mixtures (VIM)
4. Voids in the Mineral Aggregate (VMA)
5. Voids Filled with Bitumen (VFB)

Stability of marshall is the maximum load that the sample can bear before it crushed with a constant load at 55mm/minute.

| Mixture Characteristics | 4 | 5 | 6 | 7 | 8 | Spec |
|-------------------------|---|---|---|---|---|-----|
| Asphalt Draindown (gr)  | 0,00 | 0,00 | 0,00 | 0,01 | 0,03 | < 0,3 |
| VIM                     | 22,1 | 21,1 | 19,4 | 17,04 | 15,8 | 17 - 23 |
| Cantabro Loss           | 23,3 | 14,8 | 11,9 | 6,64 | 6,88 | < 20 |
| Marshall Stability      | 506, 7 | 402, 7 | 383, 7 | 531,1 | 351, 5 | > 35 |

The amount of optimum asphalt content have to fulfill the specification that has been stated. For Indonesian specification have to fulfill criteria such as VIM, marshall stability, asphalt draindown and cantabro loss. Figure 1 will show the result of the test. From the test, the optimum asphalt content will be in 5,85% of total weight of the sample.
Figure 1 Result of Cantabro Loss (a), VIM (b), Asphalt Draindown (c), Marshall Stability (d) (e)
3.2 Fly Ash Replacement

The use of fly ash in Indonesia has been implemented in many construction site. This material can reduce the heat of hydration because of cementious material that can generates heat. In asphalt mixtures, fly ash will become a filler that can fill into a small pores inside it. This material is very cheap and available accross the country, because fly ash is a waste material from coal mining. However, to find the optimum composition, there are several test to conduct such as:

1. Ball Milling Process
2. Scanning Electron Microscope test
3. X-Ray Diffraction test

Since this research was conducted the modification of aggregate not the binder content, the replacement aggregate with fly ash would be investigated. Fly ash class F will be treated first before it pour to the asphalt porous mixtures. The treatment is to put some fly ash into a transversal ball mill machine. This process will take for 3-6 hours until the size of fly ash turns into smaller particles. There are 30 small balls which has 0.5 grams of weight and 3 big balls which has 1 grams of weight.

![Transversal Ball Mill](image1)

![Tube and Balls for Fly Ash Milling Process](image2)

After 3-6 hours the particle size of fly ash has been reduced until 200 nm. Before the milling process or the original size of the particle size is up to 30 μm. By using finer particle size, it will improve the durability of the porous asphalt because this finer particles will fill the pores between aggregates. To know the particle size has been reduced, further analysis need to conduct which is scanning electron microscope (SEM). The result of the SEM will be shown on figure below.
From the result of SEM, it was shown that the original fly ash has a round shape and bigger size than 3-6 hours fly ash that has been milled. The modified fly ash has a cracked form because there is a crushed reaction between balls, tube and the fly ash.

It’s better under 6 hours of milling process, because the more hours of milling process that fly ash gets will gives a hydration reaction. This reactions comes from the heat that generates between tube and balls. Fly ash should not react yet into another forms before it pour into an asphalt mixtures. In some cases, fly ash react each other and become a new shape because of heat that generates after 24 hours of milling process.

Another test to find the characteristics of nano particle is X-Ray Diffraction. X-ray diffraction is used for a wide variety of material characterization studies. Primarily, the technique identifies crystalline species in a material. The result from an XRD analysis is a diffractogram showing the intensity as a function of the diffraction angles. The upper graphic is a graphic for modified fly ash and the other one is a graphic. Quartz peaks from fly ash is at 26.
3.3. Permeability test

After findings the characteristics of fly ash in physics laboratorium, another test will conduct later. There are three main criteria to compare all of the sample which are Marshall stability, Cantabro Loss and permeability test. For permeability test, this research will conducting falling head permeability method. There are two method for permeability test, first constant head and the second one is falling head method. Constant head method is suitable for sample which has high permeability ability (k > 10^{-3} cm/s) This method is suitable for this sample because this material has a low permeable ability which has the value of k is about 10^{-3} cm/s to 10^{-5} cm/s.

\[ k = \frac{a \cdot L}{A \cdot \Delta t} \cdot \ln \left( \frac{h_1}{h_2} \right) \]

Where:
- k = Permeability coefficient
- L = height of sample
- h1 = initial height of water
- h2 = final height of water
- A = area of sample
- \( \Delta t \) = time that needs from h1 to h2

![Figure 7. Permeability Test](image)

The height of h1 is 13 cm above the sample surface, and h2 is 6 cm above the sample surface. First of all, water have to pour into the plastic tube until it has height higher than h1. Stopwatch starts when water starts to drain through the sample reach h1 point and finish when water reach h2 point, this is call \( \Delta t \). It is very recommended to seal the sample tightly. On our first trial, water runs through the gap between seal and sample. So, it’s very important to make sure that water runs through the sample for a precision result.

4. Result

After several test, there are three samples that has been tested. The three types of sample are:
1. With Optimum Bitumen Content (OBC)
2. With OBC + Natural Fly Ash F (OBC + FAF)
3. OBC + Fly Ash Modified (OBC + FAFM)

All the samples will be tested based on Indonesian asphalt porous Specification. Samples with optimum asphalt content has a proportion of asphalt content is 5.85%. The second samples is OBC with a replacement of fly ash in aggregate contents. With 18% of replacement of fly ash (200 gram), the gradation will be modified table.

4. The last type of sample is OBC + Fly Ash Modified. This fly ash has been milled in transversal balling machine for 3-6 hours and has been tested in SEM and XRD to make sure the particle size already finer than the original fly ash. The reduction of particle size will gives more durability to the sample since it can fill pores between aggregates. The proportion of aggregate content will be shown at table 5.
Table 3. OBC’s Aggregates Content

| Sieve Number (ASTM) (mm) | Percent Pass Avg | Percent Retained | Gram  |
|-------------------------|-----------------|-----------------|-------|
| 1"                      | 25              | 100             | 0     | 0    |
| 3/4"                    | 19              | 97.5            | 2.5   | 27.5 |
| 1/2"                    | 12.5            | 74              | 23.5  | 258.5|
| 4                       | 4.75            | 20.5            | 53.5  | 588.5|
| 8                       | 2.36            | 15              | 5.5   | 60.5 |

Table 4. OBC + Natural Fly Ash F Aggregates Content

| Sieve Number (ASTM) (mm) | Percent Pass Avg | Percent Retained | Gram  |
|-------------------------|-----------------|-----------------|-------|
| 1"                      | 25              | 100             | 0     | 0    |
| 3/4"                    | 19              | 97.5            | 2.5   | 27.5 |
| 1/2"                    | 12.5            | 74              | 14.41 | 158.5|
| 4                       | 4.75            | 20.5            | 44.41 | 488.5|
| 8                       | 2.36            | 15              | 5.5   | 60.5 |
| 200                     | 0.075           | 5               | 10    | 110  |

| Pan                     | 5               | 55              |       |
| Fly Ash Original        | 18,18           | 200             |       |
| Total Weight            | 1100            |                 |       |

Table 5. OBC + Modified Fly Ash Aggregates Content

| Sieve Number (ASTM) (mm) | Percent Pass Avg | Percent Retained | Gram  |
|-------------------------|-----------------|-----------------|-------|
| 1"                      | 25              | 100             | 0     | 0    |
| 3/4"                    | 19              | 97.5            | 2.5   | 27.5 |
| 1/2"                    | 12.5            | 74              | 23.50 | 258.5|
| 4                       | 4.75            | 20.5            | 50.59 | 556.5|
| 8                       | 2.36            | 15              | 5.5   | 60.5 |
| 200                     | 0.075           | 5               | 10    | 110  |

| Pan                     | 5               | 55              |       |
| Fly Ash Original        | 2,91            | 32              |       |
| Total Weight            | 1100            |                 |       |

All sample has the same procedure such as, mixing temperature and number of blown (50 blown hammered each side). After all the samples already mixed, all the samples has to be tested in cantabro loss, marshall test and permeability test. As mention above, the more use of fly ash replacement in aggregate content will improve its durability but reduce permeability. Tabel. 6 will show the impact of fly ash replacement in aggregate content.

Table 6. OBC’s Aggregates Content

| Testing Measure          | Unit       | Spec | Type          | OBC | OBC + FAF | OBC + FAFM |
|--------------------------|------------|------|---------------|-----|-----------|------------|
| Marshall Stability       | kg         | >350 | OBC           | 497 | 1079      | 779        |
| Cantabro Loss            | %          | <20  | OBC + FAF     | 10.47| 19.14    | 7.89       |
| VIM                      | %          | 17 - 23 | OBC + FAFM | 18.12| 9.67     | 17.06      |
| Permeability Test        | cm/s       | 0.001| OBC + FAFM    | 0.04942| 0.00045  | 0.186      |

The result shows that with OBC in 5.85 %, the sample only can bear 497 kg. However the result in OBC + FAF because can bear up to 1079 kg. In the middle range is OBC + FAFM with 779 kg. All the samples passed
the requirement of the specification. The percentage of VIM of all the sample are in linear line. Since the more finer particles was pour into the mixtures, the less permeable it gets. In VIM, OBC + FAF’s sample doesn’t have a requirement because it has lesser percentage than the specification with only 9.67%.

In cantabro loss, all the samples passed the requirement. The percentage of cantabro loss in OBC sample has 10.47% loss, and in OBC + FAF sample has 19.14% loss. However, the percentage has been reduce in OBC + FAFM sample. The reason why OBC + FAF has more percent loss than the other is because its gradation has more finer material than the other. This finer material fill in pores between aggregates so it can gives more strength in marshall stability test, but in cantabro loss test the finer aggregate can’t bear the impact of its revolutions especially for finer material that has located on the side of the sample. In OBC + FAFM the percent of loss is only 7.89%, it’s because of, amount of finer material has lesser and only 32 gram or 2.91% from the total weight. This modified fly ash has more finer particles and it has particle size up to 200nm. This particles can fill inside the pores in nano meter, not only in mikrometer like natural fly ash. This material gives more strenght since the more of surface area that can bind in nano meter scale.

In permeability test, OBC has the most absorbence than the other sample. it has coefficient of permeability 0.44cm/s. Only OBC + FAF that has not requirement into an asphalt porous specification because it has less value of permeability coefficient which is only 0.00045 and it’s below the specification. OBC + FAFM sample was passed the requirement of asphalt porous specification even has lesser value of permeability coefficient than OBC’s sample.

5. Conclusion
From the result, the more finer material pour into the asphalt mixture will gives more strength but it has to be less than 200 grams. In 200 grams of fly ash material replacement, when it comes to permeability test, the water still can drain through asphalt mixture it means that the sample still has a permeable characteristics, not impermeable.

The reduction of finer material from micro meter scale to nano meter scale is proved to improve more strength in porous asphalt mixtures. This material gives more strenght since the more of surface area that can bind in nano meter scale.

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