Experimental Investigation: the optimum asphalt content and grading for PFC mixtures using local materials

Abdul-Kareem N. Abbood 1 Thair J M alfatlawi I Safa A. Hussein 2*
1&2 University of Babylon, Department of civil Engineering, Babylon, Iraq. Email: abdulkareemaji078@gmail.com, thairjm@yahoo.com & mcesafaali@gmail.com*

Abstract Permeable pavement is widely used to improve the water circulation systems in urban areas. The advantages of using permeable pavement include the storage of rainwater, reduction of runoff, out-flow delay and reduction of peak discharge. Permeable friction course (PFC) is mixed as a thin surface layer of asphalt pavement in order to achieve environmental and safety benefits. This mixture creates a surface course of a permeable compacted mix of aggregates, consisting of sand, binder, and asphalt, that is blended hot in the mixing stage. The aim of this research is to determine the best characteristics of such permeable mixtures. In this study, three aggregate distributions of minimum, medium, and maximum specifications are utilised to select the best proportions of asphalt cement for a porous asphalt surface. The results show that the medium gradation meets the requirements and can thus be considered the best gradient. The optimal binder content is found to be 6.3% for permeable asphalt mixtures.

Keywords: Permeable Asphalt Mixture, Optimum asphalt cement (OAC), Cantabro loss test, Permeable friction course (PFC).

I. Introduction

Pavement structures in highways mainly consist of layers of superimposed processed materials placed on natural sub-graded soil; these are characterised by their initial function and contribution to load distribution of vehicles on the sub-grade. The structure of pavement must be capable of supplying acceptable surface quality, with little sliding resistance, good reflective characteristics, and reduced noise pollution [1]. The ultimate aim is to ensure that the transmitted stresses from wheel load are reduced so that they will not exceed the bearing capacity of the sub-grade [2]. It is generally recognised that there are two types of pavements. Flexible pavements, also referred to as asphaltic concrete or hot mix asphalt (HMA) pavements, are often associated with the construction of highway facilities and, at present, constitute approximately 94 percent of surfaced roadways in the United States [3]. The other major pavement type is rigid, or Portland cement concrete (PCC) pavements, though composite pavements consisting of a PCC pavement overlaid with an HMA pavement do exist [4].

For both flexible and composite pavements, a common technique used by many agencies for preventive maintenance and/or rehabilitation is simply to construct a thin HMA overlay, normally somewhere between 1 and 2 inches thick, to protect the existing surface against water intrusion,
reduce roughness, restore skid resistance, increase structural capacity, and improve the overall ride quality [5]. Open-graded mixes use only crushed stone and a small percentage of manufactured sands. Permeable friction courses are defined as a thin, permeable layers of asphalt that integrate a skeleton of uniform aggregate size with a minimum of fines. The porous nature allows immediate drainage of water from the pavement surface, while the voids absorb sound energy to reduce surface noise [6]. Their open structure allows runoff to drain via the friction course to an impermeable intermediary course below, and thus out into roadside channels. This eliminates tire spray and hydroplaning, increasing the friction of wet pavement and the reflectivity of the surface, and decreasing the noise of traffic, producing a safer pavement [7-8].

Permeable pavements have been used since the 1970s, initially mainly in Europe after the Europeans had used U.S.-style open graded friction courses since the 1930s to that point. The Japanese later added modification to the European method to create another generation of permeable pavements now widely used in Asian countries. These improvements included the use of modified asphalt binders and fibres [9]. Open graded asphalt was utilised as a wearing surface in the 1950s in Australia, which is considered the first instance of such use. The technique was defined in 1973 and took on many names globally such as porous friction mix, asphalt, friction course, drainage asphalt, open graded asphalt, open textured asphalt, porous asphalt, and pervious macadam [10]. The environmentally sound nature of porous asphalt was assumed to solve excess soil percolation, replenish aquifers raises, decrease floods and water table and decrease the existing loads of storm water sewers.

The layering of impermeable surfaces because of the constructions of urban and concrete drainage system implementation required a fast solution for stormwater runoff and this was met by dual porous asphalt (PA). The use of porous asphalt as stormwater storage is served by the infiltration system [11], and in conditions of the wet driving, the skid resistance of porous asphalt wearing layers is usually very good, with spray and splash strongly decreased and an increased coefficient of skidding [12]. The specifications for porous asphalt in the United Kingdom (UK) were derived from trials over a period of 20 years starting from 1967, leading to the frequent adoption of a 5 cm thick course with 2 cm max size high aggregate quality. These trials also pointed out that the lifetime of porous asphalt is limited by clogging and hardening of the binder [13].

There are also some potential disadvantages associated with the use of PFCs, however The most obvious difference between PFCs and conventional dense-graded HMA is the decrease in the expected service life. Open graded porous asphalt cost in the 1970s was between 35 to 50 percent higher than cost of an equal amount of dense asphalt material, although the overall construction cost remained approximately the same for PFCs with higher binder contents and higher AV contents [14]. Many agencies thus sought mixing support to assess the binder content, laboratory density, gradation, and material segregation and variability by visual inspection. Satisfactory compaction is also required to avoid ravelling. Though a specified density in the field is not currently required, recent investigation has recommended the inclusion of a density specification for PFC construction, corresponding to the optimal content of asphalt. Generally, all agencies have a lowest smoothness for mix acceptance, and the aggregate type utilised and its surface features play an important role in an asphalt pavement's resistance to water action.
The purpose of this research is to find the best gradients and optimum asphalt content for PFC mixtures. The source of the aggregate utilised in the porous asphalt mixture examined, a crushed stone, is the Al-Najaf quarry. This aggregate is widely used in the middle and south of Iraq for construction. The aggregate tends to be of off white colour with angular surfaces, and it has both coarse particles and fine aggregate. The asphalt cement utilised was obtained from the south west of Baghdad.

II. Materials

The materials in this research are those generally used for asphalt paving in most of Iraq [15]. An asphalt cement with a 40 to 50 penetration grade was used; its characteristics meet the Corporation’s state specifications for Bridges and Roads (SCRB, R/9 2003) as presented in Table (1). The aggregate consisted of crushed aggregate; two types of fine aggregate, crushed sand at 75% and natural sand at 25% by weight of fine aggregate, were used. The selected gradation followed ASTM D7064 (2013) specifications for porous mixtures of asphalt paving from 19 mm maximum aggregate size to 0.075mm minimum aggregate size. These were recombined and sieved in suitable amounts to meet the required gradations for SCRB specifications (SCRB, R/9 2003) [16] as presented in Table (2). One mineral filler was utilised, this being ordinary Portland cement. The physical characteristics of the filler are listed in Table (3).

Table (1): Asphalt cement Physical Characteristics.

| Test                                      | Unit          | Specification   | Value of test | S.C.R.B 2003 specification |
|-------------------------------------------|---------------|-----------------|---------------|-----------------------------|
| Penetration (25 °C- 100g - 5sec)          | 1/10 mm       | (ASTM D5)       | 49            | (40-50)                     |
| Ductility (25 °C, 5 cm/min)               | cm            | (ASTM D113)     | 120           | > 100                       |
| Flash point (cleave land open cup)        | °C            | (ASTM D92)      | 240           | > 232                       |
| Softening point                           | °C            | (ASTM D36)      | 54            | (52-60)                     |
| Solubility in trichloroethylene           | %             | (ASTM D2042)    | 99.9          | > 99                        |
| Kinematics viscosity at 135°C             | CST           | (ASTM D2170)    | 480           | > 400                       |
| Specific gravity at 25 °C                 | ........      | (ASTM D70)      | 1.02          | (1.01-1.05)                 |
| After thin-film oven test                 |               |                 |               |                             |
| Penetration of residue (25 °C - 100g - 5sec) | %             | (ASTM D1754)    | 56            | > 55                        |
| Ductility of residue (25 °C - 5 cm/min)   | cm            | (ASTM D1754)    | 32            | > 25                        |
| Loss in weight (163 °C - 50 gm - 5h)     | %             | (ASTM D1754)    | 0.70          | ....                        |

Table (2): Aggregate Physical Characteristics (ASTM D7064, 2013).

| Property              | Specification   | Coarse aggregate | Fine aggregate | Specification |
|-----------------------|-----------------|------------------|----------------|---------------|
|                       |                 |                  | Crushed sand   | Natural sand  |
| Bulk specific gravity | (ASTM C127-128) | 2.585            | 2.646          | 2.641         |
Table (3): Ordinary Portland Cement Physical Characteristics (SCRB, 2003).

| Physical properties |        |        |        |
|---------------------|--------|--------|--------|
| % Passing sieve No. 200 | 95     |        |        |
| Bulk specific gravity | 3      |        |        |
| Specific surface area (m²/kg) | 354    |        |        |

III. Design Method

1. Selection of Trial Grading

The three trial gradings generally fall along the coarse and fine limits of the grading suggested by the American Society for Testing and Materials (ASTM D7064, 2013). Physical characteristics of the aggregate such as surface texture, gradation, and shape, are affected by the amount of asphalt in the mix. These are thus utilised to select the optimum asphalt content for the design of porous asphalt surfaces, as presented in table (4).

Table (4): Aggregate sieve analysis distribution of porous asphalt binder.

| Sieve size (mm) | (ASTM D7064, 2013) | Minimum specification | Medium specification | Maximum specification |
|-----------------|---------------------|-----------------------|----------------------|----------------------|
| 19              | 100                 | 100                   | 100                  | 100                  |
| 12.5            | 85-100              | 85                    | 93                   | 100                  |
| 9.5             | 35-60               | 35                    | 48                   | 60                   |
| 4.75            | 10-25               | 10                    | 18                   | 25                   |
| 2.36            | 5-10                | 5                     | 8                    | 10                   |
| 0.075           | 2-4                 | 2                     | 3                    | 4                    |
According to the ASTM specification for each trial aggregate grading, an asphalt amount between 6.0 and 6.5% was initially chosen based on the aggregate specific bulk gravity. All gradation analysis distribution thus used 6% asphalt content.

2. Determination of Voids in the Coarse Aggregate Fraction (VCA)

For best performance, the OGFC mixture must have a coarse aggregate skeleton with stone-on-stone contact. The stone skeleton is that portion of the total aggregate blend retained on the 4.75 mm [No. 4] sieve (ASTM D7064, 2013). The condition of stone-on-stone contact within an OGFC mixture is defined as the point at which the percent voids of the compacted mixture is lower than the VCA of the coarse aggregate in the dry-roddeed test, in accordance with Test Method C29/C29M. The VCA of the coarse aggregate only fraction, \( VCA_{DRC} \) is determined by compacting the stone with the dry-roddeed technique. When the dry-roddeed density of the coarse fraction is determined, the \( VCA_{DRC} \) can be calculated using the following equation from Test Method C29/C29M:

\[
VCA_{DRC} = \frac{G_{CA} \gamma_w - \gamma_s}{G_{CA} \gamma_w} \times 100
\]

Whereas:

\( G_{CA} \) = coarse aggregate bulk specific gravity (test method C127)
\( \gamma_s \) = fraction’s coarse aggregate bulk density for the dry-rod ded case (kg/m³) (test method C29/C29M), and

\( \gamma_w \) = water density 998 kg/m³ [62.3 lb/ft³].

3. Selection of Desired Grading

After compacting and cooling specimens, they were removed from the moulds and tested to determine their specific bulk gravity using Test Method D6752. Un-compacted specimens were utilised to identify the theoretically optimum density. Using the specific bulk gravity and the theoretical maximum density, the percent air voids \((V_a)\), and VCA of the compacted mixtures \((VCA_{MIX})\) were calculated using the following equations:

\[
V_a = 100 \times \left( 1 - \frac{G_{mb}}{G_{mm}} \right)
\]

\[
VCA_{MIX} = 100 - \left( \frac{G_{mb}}{G_{CA}} \times P_{CA} \right)
\]

Whereas:

- \( P_{CA} \) = the coarse aggregate percentage magnitude in the whole mixture,
- \( G_{mb} \) = the value of compacted mixture bulk specific gravity (gm/cm³),
- \( G_{mm} \) = theoretical max. Density value of the mixture (gm/cm³), and
- \( G_{CA} \) = the coarse aggregate fraction bulk specific gravity (gm/cm³)

| Aggregate gradation | Gmb (gm/cm³) | Gmm (gm/cm³) | Air void (%) | VCA_DRC (%) | VCA_MIX (%) |
|---------------------|-------------|-------------|--------------|--------------|-------------|
| Maximum aggregate   | 2.022069    | 2.411576    | 16.15154     | 42.25319     | 41.33262    |
| Medium aggregate    | 1.971583    | 2.431118    | 18.90222     | 42.25319     | 37.45848    |
| Minimum Aggregate   | 1.970704    | 2.396166    | 18.54423     | 42.25319     | 31.38749    |

As presented in Table (5), of the three trial gradings evaluated, the one with the highest air voids (minimum acceptable is generally 18%) and a VCA_MIX equal to or less than that determined by the dry-rod ded technique (VCA_DRC) was the medium aggregate; its sieve analysis distribution is thus considered optimum and it was selected as the desired grading.
IV. Optimum Asphalt Cement

The optimum binder content was found using the asphalt contents which ranged from 5.5 to 6.5% (OAC ±0.5 %) [21]. Three asphalt contents were thus evaluated, 5.5, 6.0, and 6.5%. The samples were assessed depending on the test of abrasion Cantabro (un-aging and aging), properties of draindown, and analysis of air voids. Optimum binder amount was achieved by measuring the average binder amounts related to the maximum limit of the binder test draindown, the lower limit of the Cantabro test, and the required amount of air voids, which is about 21%. The optimum asphalt content was thus determined to be 6.3%.

1. Cantabro Abrasion Loss Test:

The Cantabro abrasion loss test is presented by ASTM C131. This test measures resistance of compacted specimens to abrasion and is carried out in an abrasion machine. The test specimens were thus first placed in the abrasion machine without steel balls, then tested in the Los Angeles (L.A) abrasion machine for 300 rotations at a speed of 30 to 33 rpm. Aged compacted OGFC was also subjected to the Cantabro abrasion test to evaluate the effect of accelerated laboratory aging on resistance to abrasion. Aging was accomplished by placing suitably compacted specimens in a forced draft oven set at 60°C [140°F] for 168 h (7 days). The specimens were then cooled to 25°C [77°F] and stored for 4 hr. prior to the Cantabro test. Any loose material broken off from surfaces of the test specimens was discarded, and the masses of the specimens before and after the test recorded. The loss in the specimen weight is expressed in the percentage of weight of disintegrated particles to the initial weight of the specimen:

\[
\text{% L.A abrasion} = \frac{(A - B)}{A} \times 100
\]

A: initial weight of specimen before placing in the Los Angles abrasion drum, (gm).

B: final weight of specimen after 300 revolutions in the Los Angles abrasion drum, (gm).

2. Draindown Test:

This test method determines the amount of draindown in an uncompacted asphalt mixture sample evaluated by using basket drainage test (ASTM D6390-90). The sample was placed in a wire basket positioned on a plate of known mass. The sample, basket, and plate were placed in a force draft oven for one hour at a pre-selected temperature. At the end of one hour, the basket containing the sample was removed from the oven along with the plate containing the drained material. The amount of draindown is considered to be that portion of material (aggregate and asphalt cement) that has separated itself from the sample as a whole and been deposited on the plate. The wire basket used for this test was made of wire-mesh of 0.25 in (6.3 mm) openings; the depth of the wire basket was 165 ± 16.5 mm and the width was 108 ± 10.8 mm with a basket bottom of 25 ± 2.5 mm. The drainage loss was calculated as
\[ \% \text{Drainage loss} = \frac{D - C}{B - A} \times 100 \]

where

- A: mass of the empty wire basket, (gm).
- B: mass of the wire basket and sample, (gm).
- C: mass of the empty paper or steel container, (gm).
- D: mass of the paper or steel container plus drained material (aggregate and asphalt cement), (gm).

v. Result and discussion

As presented in Fig. 2, the Cantabro test result indicated that all asphalt binder contents were in accordance with standard specifications, where the test must not exceed 30\% on average while the loss for any individual specimen should not exceed 50\%.
Fig. 3. Cantabro loss unaged results

As presented in Fig. 3, the Cantabro test result illustrated that all binder amounts were within specification limits, which state that the average loss from the test must not exceed 20%.

Fig. 4. Draindown test results

As presented in Fig. 4, the draindown test results indicated that all binder content was within specification limits, which state that the highest draindown permissible must not exceed 0.3 %.
VI. Conclusion

This research aimed to find the preferable gradients and optimum asphalt content for permeable asphalt mixtures. Three aggregate gradings were used, maximum, medium, and minimum grading according to ASTM D7064 (2013).

Abrasion loss test results for aged and unaged mixtures using three percentages of asphalt cement (5.5, 6, and 6.5%) showed that the percentage decrease of abrasion loss indicated high strength in the selected mixtures. The draindown increased with increased asphalt content. Optimum asphalt content was thus identified by the means of taking the higher limit from the test of binder draindown, and the minor limit from the Cantabro testing. The required air void is about 21%, and the optimal binder content is thus 6.3% for permeable asphalt mixtures.

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