

Research Article

# Mechanical Performances of Pretreated Porous Convenient Asphalt Concrete

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## Abstract

Convenient Asphalt Concrete (CAC) is a kind of Asphalt Concrete with new technology, in which a pre-treated emulsified Asphalt is prepared firstly to avoid demulsification during mixing and then mixed directly and steadily with cement and aggregate. In this technology, cement and pre-treated emulsified Asphalt are evenly mixed into a binder, namely Convenient Asphalt Mastic (CAM). CAM is a new type of binder for modified asphalt concrete, with low energy consumption, less pollution, and normal atmospheric temperature construction. The mixture, named Porous Convenient Asphalt Concrete (PCAC), is formed by mixing CAM as a binder and aggregate with gradation adjustment according to the 'Permeable Pavement Guide' of the Japan Road Contractors Association. In this study, the mechanical properties of PCAC and Hot Mix Porous Asphalt Concrete (PA) are compared and analyzed under the control of wrap film thickness and porosity. The experimental results show that at the same porosity and under the most appropriate film thickness of PCAC and PA, the Marshall Stability Value and the Tensile Strength of PCAC is 3 to 4 times stronger than PA all. There is positive correlation with first, the strength of the binder wrapped around aggregate granule, and second, the aggregate particles being bonded well with each other. It is because that CAM has higher consistency, it can form thicker wrap film around the aggregate without adding any staple fiber, and CAM has higher strength after hardening. Therefore, the overall mechanical performances of PCAC are much better than PA. Consequently, PCAC can bear a larger axle load than PA. That reduces the damage of axle pressure on porous asphalt pavement and prolongs the service life of porous asphalt pavement.

## Keywords

Emulsified Asphalt, Pre-treated, Convenient Asphalt Mastic, Porous Convenient Asphalt Concrete

## 1. Introduction

Porous asphalt concrete can be used for the Open-Graded Asphalt Friction Course (OGAC), drainage pavement, and permeable pavement. The main structural feature of the porous pavement's asphalt concrete is that they have 15~20% voids. These porosity results mainly from the removal part of fine aggregates of PA [1] (shown as Figure 1). However, after removing these fine aggregates, the stability of aggregate

particle stacked structure decreases, and the statically indeterminate order formed by aggregate stacked also decreases, resulting in structural instability under external force. The adhesion behavior between aggregate particles is given in Equation (1) under the Mohr-Coulomb theory [2, 3]. Due to the reduction of fine aggregate, frictional angle  $\theta$  is reduced, and hence, reduce the friction between aggregate particles. In

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order to maintain the shear strength of asphalt concrete, the bonding force should be strengthened. As a result, the adhesion between aggregate particles should be improved. PA needs to improve the adhesion between aggregate particles, and there are two main methods. The first is to upsurge the strength of the binder and the second is to thicken the thickness of the wrap adhesive of aggregate particles [4-6].

$$\tau = C + \sigma \tan \theta \quad (1)$$

These two methods will be detailed in the following two sub-sections.

### 1.1. Upsurge the Strength of the Binder

The first method requires modification of the adhesive. Here, the adhesive is the asphalt binder. The modification of asphalt binder is usually carried out by pure oxygen blowing, evenly adding sulfur or polymer to the mix. In this study, asphalt was modified by adding cement. [7, 8]

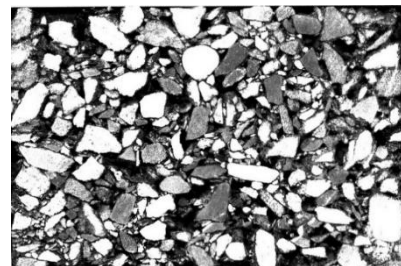
As mentioned, asphalt was modified here by adding cement to improve the emulsified asphalt concrete mechanical properties. Unfortunately, the stability of emulsified asphalt will be damaged by the presence of cement. It is because when cement is added, it will cause emulsified asphalt immediate demulsification and loss of workability. Basically, cement will absorb water from the emulsified asphalt that causes an increase of emulsion concentration. Micelles in emulsified asphalt are getting closer to each other, collision and mergers follow. Finally, emulsified asphalt demulsified, reduced, and reunited into asphalt cement. Asphalt cement is a high viscosity plastic semi-solid material, and it is difficult to mix. This reduces the workability of the cement asphalt mastic mixture (shown as Figure 2). Currently, two approaches have been used to overcome this problem. First is to mix water and aggregate first, then add slow-setting emulsified asphalt, and finally add cement until uniform. The second is mixing the aggregate and cement evenly first, then adding water to continue to mix, and finally adding slow-setting emulsified asphalt to mix evenly. [9-12] Anyway, the above two mixing procedures add a lot of water in order to increase the stability of emulsified asphalt during the mixing process. Unavoidably, the mixture of cement asphalt concrete will have high water content. Such excess water needs to be removed so that cement asphalt concrete can achieve relatively tight compaction.

This unique innovation is different from previous research on cement asphalt concrete. To overcome the strength reduction and interference of the construction continuity process caused by additional water content in cement asphalt concrete, a novel technique is suggested that allows pre-treated emulsified asphalt and cement directly mixed into uniform cement asphalt mastic (named Convenient asphalt mastic, CAM). It is then mixed with the aggregate to form cement asphalt concrete (named, Convenient Asphalt Concrete,

CAC). Pretreatment is to add water reducer to cationic rapid-setting emulsified asphalt (CRS-1) and mix it following the program. When the water reducer molecules are fully absorbed on emulsified asphalt micelles, that protects the integrity of emulsified asphalt micelles and maintains the stability of asphalt emulsion (as shown in Figure 3). The pretreatment makes it possible for the emulsified asphalt to be mixed directly with cement and dry aggregate without demulsification. It is because the water reducer can block the contact of asphalt micelles with cement and promote each other to disperse. Therefore, the emulsified asphalt micelles and the cement will not adhere to each other and agglomerate, and the CAC mixture achieves good workability.

### 1.2. Increase of the Warp Film Thickness

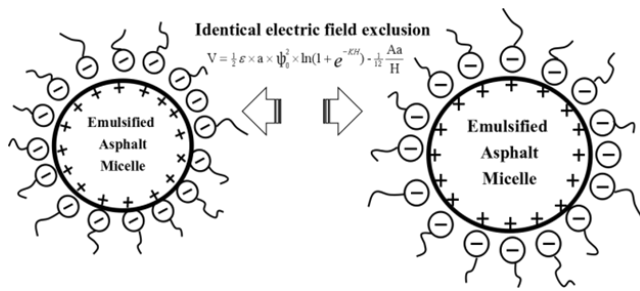
Recalled that to improve the adhesion between aggregate particles, the second method wants to increase the warp film thickness of asphalt outside the porous asphalt concrete aggregate. It is achieved by improving the viscosity of asphalt (or adding short-staple fibers) [13, 14]. As the result of this study, the thickness of CAM wrap film on aggregate particles of PCAC is about 7 times that of porous modified asphalt concrete. Therefore, CAM has a much thicker coating thickness than modified asphalt. The wrapping thickness of CAM on aggregate particles can be increased by either reducing the amount of Naphthalene Superplasticizer (NSP) or increasing Portland cement in CAM. Adjusting the dosage of these two materials can improve the viscosity of CAM and increase the thickness of the CAM wrapping on PCAC aggregate outside.



**Figure 1.** Porous Asphalt Concrete (Removal Much of the Fine Aggregate).



**Figure 2.** Emulsified Asphalt Demulsified after Mixing with Cement and Lost Workability.



**Figure 3.** FSP Ions Enhance the Mutual Exclusion of Electric Property between Emulsified Asphalt Micelles and Reduce the Tendency of Micelle Coalescence.

## 2. Experimental Program

To understand the enhancement effect of increasing film thickness on the mechanical properties of porous asphalt concrete, this study designed experiments to compare the mechanical properties under the change of porosity and film thickness of PCAC and PA as follows.

### 2.1. Materials

The materials used in this study mainly include petroleum asphalt, emulsified asphalt, Portland cement, water reducer, and aggregate.

#### 2.1.1. Petroleum Asphalt

Using AC 60/70 asphalt to mix porous asphalt concrete (PA). It was used as the control group of porous cement asphalt concrete (PCAC). The penetration grading of the petroleum asphalt is 67, the density (15 °C) is 1.033g/cm<sup>3</sup>, other basic performance indicators meet ASTM D946/D946M

requirements.

#### 2.1.2. Emulsified Asphalt

Using Cationic Rapid Setting Emulsified Asphalt (CRS-1), the general technical indexes are following ASTM D977-20. The technical indexes' importance to this study is shown in Table 1. Usually, when emulsified asphalt is mixed with cement or aggregate, it is used slow-setting emulsified asphalt and over-wet materials. However, to reduce the interference of other agents on the pretreatment, CRS-1 with fewer additives was used in this study.

#### 2.1.3. Portland Cement

Type I Portland cement is used, and the general technical indexes meet ASTM C150/C150M requirements. The main technical indexes are shown in Table 2.

#### 2.1.4. Water Reducer

Naphthalene Superplasticizer (NSP) which the main component of Naphthalene sulfonate formaldehyde condensation sodium salt, is brown-yellow powder and easily soluble in water, the solution is brown sticky, alkaline. The NSP used is a 30% concentration solution prepared by reverse osmosis treatment of purified water, using a dose of 2.4% of emulsified asphalt weight.

#### 2.1.5. Aggregate

The coarse aggregate used is an artificial broken granite aggregate. Fine aggregate is machine-made sand, and the main technical indexes are shown in Table 3.

**Table 1.** Specification Indicators of Cationic Asphalt Emulsion (CRS-1).

Specifications Indicators	Results	Requirements	Specifications
Demulsification Rate	Rapid Setting	—	ASTM D6936-17
Particle Charge	Cation (+)	—	ASTM D244-09
Residue by Distillation (weight ratio) / %	50.3	≥50	ASTM D244-09
Residue penetration Grading (25°C) / 0.1mm	91	50~200	ASTM D5/D5M-13

**Table 2.** Specifications Indicators of Cement.

Specifications Indicators		Results	Requirements	Specifications
Setting Time/min	Initial Setting	56	>45	ASTM C191-13
	Final Setting	354	<6.5	ASTM C191-13
Compressive / MPa	28days	43.5	≥42.5	ASTM C39/C39M

**Table 3.** Specifications Indicators of Aggregate.

Coarse Aggregate			Fine Aggregate	
Apparent Density (g/cm <sup>3</sup> ) ASTM C127-01	Los Angels Abrasion Test (%) ASTM C131/C131M-20	Water Absorption (%) AASHTO T85	Apparent Density (g/cm <sup>3</sup> ) ASTM C128-15	Sand Equivalent (%) ASTM D2419-14
2.74	32.3	1.1	2.76	72.8

## 2.2. Proportioning

### 2.2.1. Porous Asphalt Concrete (PA)

The design of the mix ratio of porous asphalt concrete (PA) mainly refers to the Permeable Pavement Guide issued by Japan Road Contractors Association [1], and the maximum aggregate particle size is 13.2mm. The aggregate gradation composition is shown in Table 4. The optimum binder dosage in this study is the asphalt over stone ratio of 5.5%.

### 2.2.2. Porous Cement Asphalt Concrete (PCAC)

CAM and petroleum asphalt are two different binders. In this study, the composition of CAM was Cement/CRS-1=1, NSP/CRS-1=2.4%, and the density of CAM was 1.51g/cm<sup>3</sup>. At present, there is no reference composition suitable for the mixture design of the PCAC. This study is based on the trial-and-error method of a large number of previous tests. The selection of PCAC's aggregate gradation is based on the gradation composition of PA. Since the addition of fine aggregate will improve the viscosity of CAM and thus reduce its workability, fine aggregate with sizes below 2.36mm is removed. The PCAC aggregate gradation composition is shown in Table 5. The best ratio of CAM for PCAC is 18%.

## 2.3. Experimental Design

The asphalt over stone ratio of porous asphalt concrete is 4.5%, 5.0%, 5.5%, and 6.0%. The CAM content of PCAC is 15%, 16%, 17%, 18%, and 19% respectively. According to the porosity and film thickness of the two kinds of porous asphalt concrete (PA, PCAC), the regression trend and difference degree of Marshall stability value (M.S.V.) and indirect tension strength (I.T.S.) were analyzed to define the strength improvement efficiency.

**Table 4.** Gradation Composition of Porous Asphalt Concrete (PA).

Sieve Mesh (mm)	19.0	13.2	4.75	2.36	0.075
Passing / %	100	95	23	15	5

**Table 5.** Gradation Composition of Porous Convenient Asphalt Concrete (PCAC).

Sieve Mesh / mm	19.0	13.2	4.75	2.36
Passing / %	100	94.4	13.3	0

## 3. Research Results

The porosity of PA and PCAC varies from 15% to 20% in the specification, and comparative analysis of mechanical properties is performed under the same independent variable (porosity). Since the difference in viscosity when the asphalt binder and CAM are suitable for mixing, this difference results in a CAM film thickness that is more than 7 times that of asphalt. Therefore, the effect of film thickness on mechanical properties was analyzed and the mechanical properties were compared to the optimal adhesion content.

### 3.1. Relationship Between Porosity and Mechanical Properties

A discussion of the relationship between air voids and strength in PA. According to P. Kumar Mehta's book, the porosity of solid materials has an inverse relationship with strength, as shown in Equation (2) [15]. When the size and axial force of a test block remained unchanged, the smaller the fracture area of the vertical plane under axial force (the increase of the air voids in the section), the greater the stress under the vertical plane under axial force. The test block with a small stress area is easier to achieve yield strength in the process of increasing stress. Therefore, the greater the porosity of the test block, the lower the Marshall stability value and tensile strength. The Marshall stability test and the tensile test are used to evaluate the mechanical properties in this study. In the Marshall stability test, the pressure mode of external force is similar to the biaxial pressure test. The tensile test, also known as the split tension test, is an operation similar to the pressure test in which the lateral pressure difference is caused by uniaxial pressure. Hence, the tension trend is similar to that of the pressure test. Therefore, Equation (2) applies to both me-

chanical tests.

$$S = S_0 e^{-kp} \quad (2)$$

S: compressive strength when porosity is p;  $S_0$ : compressive strength when porosity is zero; p: porosity; k: constants corresponding to various materials.

As shown in Figure 4 and Figure 5, the Marshall stability

value regression formula for PCAC and PA are  $y=33.356e^{-0.063x}$  and  $y=6.6807e^{-0.049x}$ , respectively. Similarly, the tensile strength regression formula for PCAC and PA are, respectively  $y=3645.3e^{-0.132x}$  and  $y=94.307e^{-0.025x}$ . Both results approach Equation (2) mathematical pattern. Therefore, they are suitable to explain the trend of the PCAC and PA about porosity against both Marshall stability value and the tensile strength study.

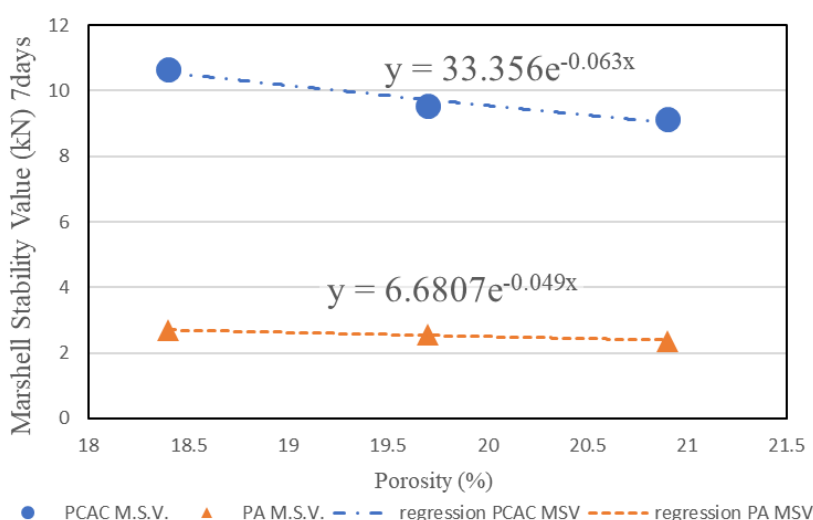


Figure 4. Trends in Porosity and Marshall Stability Value.

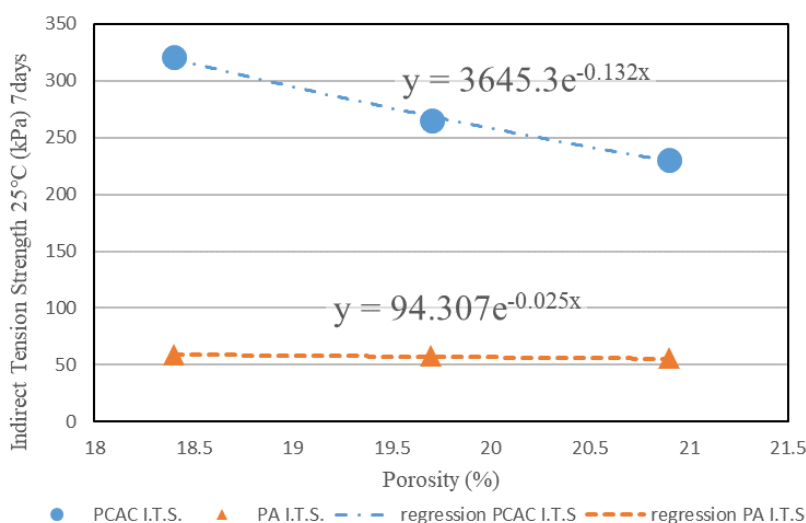


Figure 5. Trends in Porosity and Tension Strength.

Variations of M.S.V. and I.T.S. for PA are not obvious with the change of porosity. For PCAC, M.S.V. and I.T.S. are declining as porosity increases. Under the condition of the same porosity, the binder strength of PCAC is much higher than that of PA and shows several times different in M.S.V. and I.T.S.. Specifically, PCAC is 3 to 4 times higher than PA in M.S.V. In the case of I.T.S., PCAC is

about 4 to 5 times higher than PA, as shown in Figure 6. Compared with PA, the mechanical strength of PCAC is significantly enhanced at the same porosity. The difference in mechanical strength between PCAC and PA is mainly due to the difference in a binder. The strength of the binder positively affects the strength of the test block under various porosity which is indicated in the difference of  $S_0$  in



Equation (2).

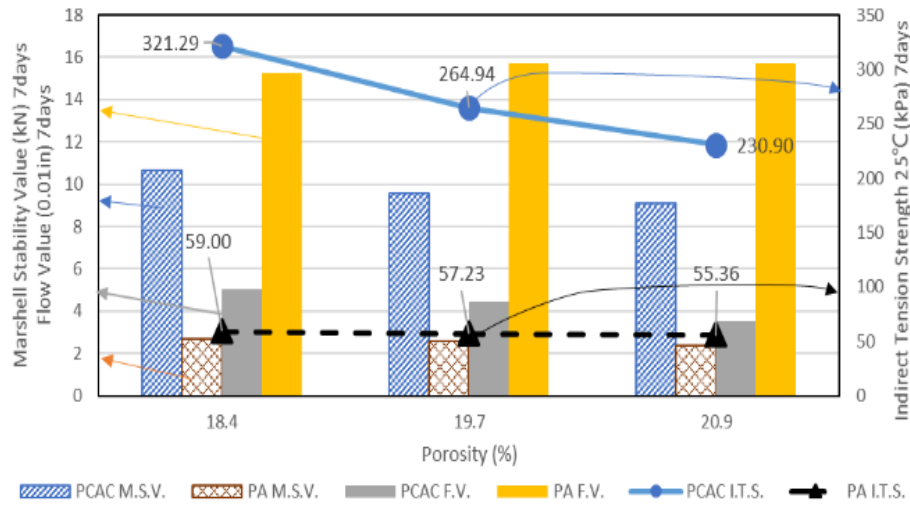


Figure 6. Diagram of Porosity and Mechanical Properties.

### 3.2. Relationship Between Film Thickness and Mechanical Properties

In this study, due to the high viscosity of CAM that can wrap a thick mastic on the aggregate surface of PCAC, PCAC and PA can have a great difference in warp film thickness. PCAC's aggregate gradation and the amount of adhesive material are adjusted and estimated according to PA's dosage of the Japan Road Contractors Association so that the porosity of PCAC can be between 15% and 20%.

For the calculation of warp film thickness, the method suggested by Asphalt Institutes (AI) MS-2 Manual was used in this study and is shown in Equations (3) to (5) [16, 17]. The amount of binder was obtained from the proportioned design data first, then the aggregate surface area was calculated, and finally, the film thickness of the asphalt binder and CAM were obtained.

$$SA = \sum(P_i \times FA_i) \quad (3)$$

$$SA = 0.41 + 0.41a + 0.82b + 1.64c + 2.87d + 6.14e + 12.29f + 32.77g \quad (4)$$

$$Pbc = (DA \times Gb \times SA) / 10 \quad (5)$$

In Equations (3) to (5), SA is the specific surface area of aggregate.  $P_i$  is the sieve mesh passing percentage (%) of specified aggregate particle sizes.  $FA_i$  is the surface area coefficient relative to various particle sizes of aggregate. Pbc is the asphalt content. DA is the asphalt (or CAM) film thickness ( $\mu m$ ). Gb is the asphalt (or CAM) density. Variables a, b, c, d, e, f, and g are the corresponding  $P_i$  of aggregate particle sizes 4.75mm, 2.36mm, 1.18mm, 0.6mm, 0.3mm, 0.15mm, and 0.075mm, respectively. According to

Equation (4), Table 6, and Table 7, the specific surface area (SA) of PA and PCAC is 22.14  $m^2/kg$  and 5.90  $m^2/kg$ , respectively. The film thickness of different PA and PCAC, their proportions can be attained by employing Equation (5) with known binder weight (Pbc), density (Gb), and the specific surface area (SA) obtained above, as shown in Table 8.

In order to create porous asphalt concrete that can permeate enough flow, several fine particle sieve sizes of aggregate are removed in the continuous gradation of aggregate. Then cause the accumulation of aggregate particles have an unstable state with high potential energy. In this unstable state, strong bonding forces are required to cohere aggregate particles, to lead to the accumulation structure of aggregate particles stable. Therefore, it is necessary to have a strong and thick binder outside the aggregate particles for consolidation. As shown in Figure 7 and Figure 8, the M.S.V. and I.T.S. of PCAC and PA are positively correlated with the binder film thickness, which in turn is correlated with the viscosity of the binder [18]. Figure 9 and Equation (6) show the relationship between film thickness and viscosity.

$$\int_0^{360} F_a d\theta + \int F_c dV + \int F_w dV = 0 \quad (6)$$

$\theta$  is the Contact Angle that forms from the edge of that the liquid droplets in contact with a solid surface around circumference 360°. V is the volume of the droplet.  $F_a$  is the liquid and solid phase contact interfacial specific adhesion force.  $F_c$  stands for specific liquid cohesion.  $F_w$  represents the specific weight of the liquid.

For similar material and size of the droplet, the density and volume V of the droplet are alike. Therefore, the weight of a droplet approaches a constant. The interfacial specific adhesion force  $F_a$  is related to the type of substance. The materials used in this study are aggregates of the same rock

material and asphalt binder with different viscosity. The contact specific interface adhesion force between liquid and solid phase is similar. Cohesion is positively related to molecular weight and the explicit properties of molecular weight are manifested by viscosity. Obviously, when the viscosity is greater, the film thickness  $h$  will be thicker. That is, the film thickness  $h$  is positively correlated with the specific cohesion force  $F_c$  in Equation (6).

Due to the thick warp film outside the aggregate of the porous asphalt concrete, the bonding failure mode between asphalt and aggregate should include the failure mode of the bonding interface and the failure mode of the binder.

The mechanical properties of thick warp film failure of porous asphalt concrete depend on the amount of work done by an external force, which is called fracture energy and is equal to the area bounded by the stress-displacement curve and displacement axis [19-22]. The fracture energy is described as follows:

$$G = \int \tau(x) dy \quad (7)$$

$$W = \int \sigma(x) dy \quad (8)$$

In Equations (7) and (8),  $G$  and  $W$  are fracture energy corresponds to shear and tensile forces in which  $\tau(x)$  and  $\sigma(x)$  represent the shear stress-displacement curve and tensile stress-displacement curve, respectively. The bonding failure between asphalt and aggregate is mainly composed of adhesion failure and cohesion failure. The total failure energy of asphalt thick film is the sum of shear fracture and tensile fracture energy, which is expressed according to the failure mode of the bonding surface and the failure mode of the bonding material in Equation (9) as follows.

$$W+G = \int \tau_1(x) dx + \int \tau_2(x) dx + \int \sigma_1(x) dx + \int \sigma_2(x) dx \quad (9)$$

$\tau_1(x)$ : shear stress-strain relation function of adhesion between asphalt and aggregate interface.

$\tau_2(x)$ : shear stress-strain relation function of binder (asphalt) mixture under shear force.

$\sigma_1(x)$ : tensile stress-strain relation function of tension between asphalt and aggregate interface.

$\sigma_2(x)$ : tensile stress-strain relation function of binder (asphalt) mixture under tension.

The fracture energy of the bonding is positively correlated with the bond strength. The bond strength is related to different states involved in the bond theory. There are three main states of the bond theory. The first one is the permeability of the binder to the surface of the bonded material, which is positively correlated with the bonding force. The second is the strength of the binder base material. The strength of the binder after hardening is also positively correlated with the bond strength. The third is the new chemical bonds formed by the bonding material and the bonded surface. Clearly, the stronger the new chemical bond (or the more the number of newly formed bonds), the stronger the

bond strength. [23, 24]

The bond strengths due to  $\tau_1(x)$  and  $\sigma_1(x)$  are related to the first and third states of the bond theory. As the viscosity of CAM is much higher than that of molten asphalt during hot mixing, the permeability of molten asphalt binder to aggregate is better than CAM. In addition, the good permeability of molten asphalt binder suggests that the distance between asphalt and aggregate surface molecules is relatively close. It is easier to generate new intermolecular forces. That is, asphalt binder and the aggregate surface formed more H bonds than CAM. Obviously, in the first and third states of bond theory, molten asphalt binder is superior to CAM in terms of bonding effect. However, the bonding forces increased by these two states of bonding effect do not contribute too much to the bond strength than the strength of bonding base material. Although the viscosity of hot molten asphalt binder is low, CAM is a solid elastic material when hardening. In terms of the effect of the strength of the material itself, the resistance of CAM to external force is obviously superior to asphalt, that is a liquid viscoelastic material in normal temperature.

After bonding, the shear strength of CAM (CEMENT /CRS-1=1.1, NSP/CRS-1=4%) is about 150N/cm<sup>2</sup> and the shear strength of asphalt binder (SBS modified asphalt, pin penetration 55) is 60N/cm<sup>2</sup>. The former is 2.5 times the latter. Obviously, the bond strength corresponding to  $\tau_1(x)$ ,  $\sigma_1(x)$ , and  $\tau_2(x)$  are the three main factors that affect the fracture energy of the surface bonding of aggregate and the adhesive material. Accordingly, the mechanical strength of PCAC is significantly higher than that of PA because the shear strength of CAM material is much higher than the PA's binder in the bonding surface.

In summary, as mentioned in section 1, there are two methods to enhance the mechanical strength of porous asphalt concrete associated with Mohr-Coulomb theory (see Equation (1)). The asphalt concrete binder made from pretreated CAM not only greatly increases the mechanical strength of the binder but also increases the warp film thickness of aggregate due to an increase in the viscosity of the binder by adjusting the material composition. As the film thickness increases, the agglutination between aggregate particles in concrete will increase and the shear strength will increase accordingly, thus with the increase of the Marshall stability value. It can be seen from Figure 7 and Figure 8 that the Marshall stability value of PA and PCAC will increase with the increase of the film thickness. Furthermore, increasing bond strength will increase the C value of cohesion in Equation (1) and the effective stress  $\sigma$  of friction, under the same porosity. The Marshall stability value and tensile strength of PA and PCAC are given in Figure 6. Due to the difference in mechanical strength of asphalt and CAM binder, the Marshall stability value of PCAC reaches about 4 times PA. The tensile strength of PCAC also reaches about 4 to 5 times PA. In summary, this study suggests that pretreated CAM can strengthen the mechanical properties of the binder and increase the film thickness of the aggregate wrapping mastic that finally improves the mechanical properties of porous concrete.

**Table 6.** Calculation of specific surface areas of aggregate for PA.

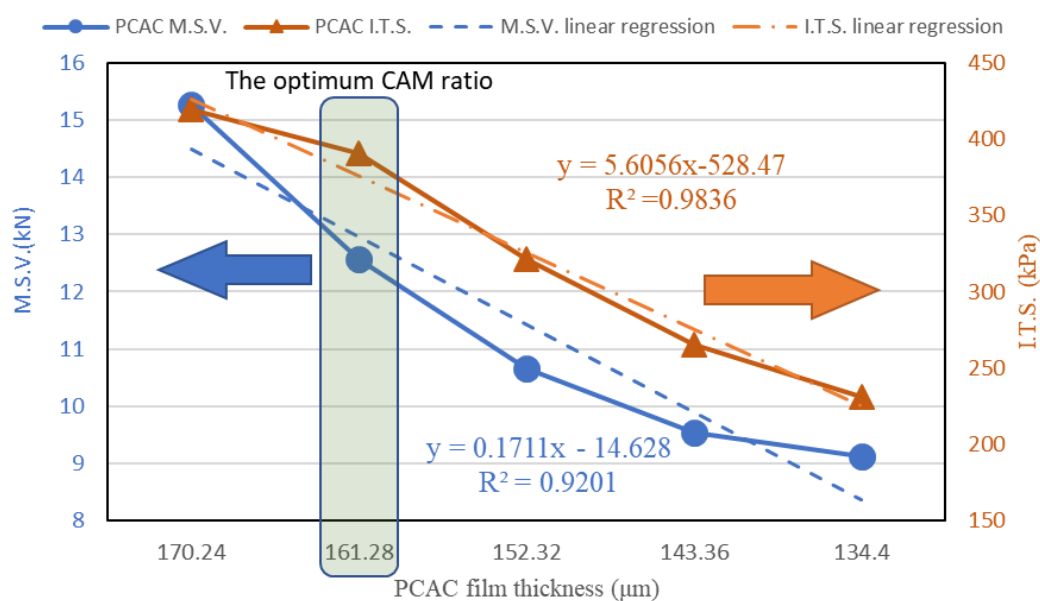
Sieve Mesh /mm	FA <sub>i</sub>	P <sub>i</sub> (%)	P <sub>i</sub> × FA <sub>i</sub>	SA (m <sup>2</sup> /kg)
>4.75	0.41	-	0.41	22.14
4.75	0.41	23	9.43	
2.36	0.82	15	12.3	
1.18	1.64	0	0	
0.6	2.87	0	0	
0.3	6.14	0	0	
0.15	12.29	0	0	
0.075	32.77	0	0	

**Table 7.** Calculation of specific surface areas of aggregate for PCAC.

Sieve Mesh /mm	FA <sub>i</sub>	P <sub>i</sub> (%)	P <sub>i</sub> × FA	SA (m <sup>2</sup> /kg)
>4.75	0.41	-	0.41	5.9
4.75	0.41	13.4	5.49	
2.36	0.82	0	0	
1.18	1.64	0	0	
0.6	2.87	0	0	
0.3	6.14	0	0	
0.15	12.29	0	0	
0.075	32.77	0	0	

**Table 8.** Aggregate film thickness.

PA	Asphalt Content Ratio (%)	4.5	5.0	5.5	6.0	-
	Asphalt Content (g)(Pbc)	42.4	47.4	52.4	57.4	-
	Asphalt Film Thickness (μm)(DA)	18.54	20.73	22.91	25.10	-
	Connected Air Voids (%)	21.99	20.88	19.85	18.63	
PCAC	Mastic Content Ratio (%)	15.0	16.0	17.0	18.0	19.0
	Mastic Content (g) (Pbc)	120.0	128.0	136.0	144.0	152.0
	Mastic Film Thickness (μm) (DA)	134.70	143.67	152.65	161.63	170.614
	Connected Air Voids (%)	20.96	19.53	18.22	17.09	14.78

**Figure 7.** Relationship between Film Thickness and Mechanical Properties of PCAC.



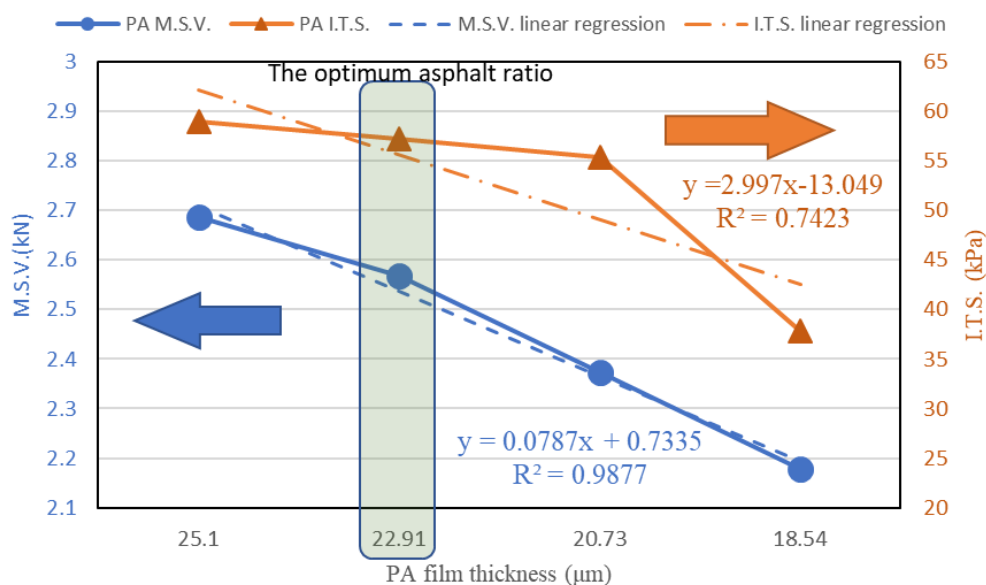


Figure 8. Relationship between Film Thickness and Mechanical Properties of PA.

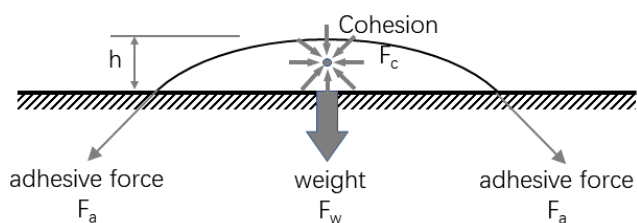


Figure 9. Force Balance Diagram of the Binder Film Thickness Formed.

## 4. Discussions

1. When the water permeability of PCAC is high, it exhibits a larger porosity, which subsequently leads to a reduction in its strength. If the aggregate gradation of PCAC is to remain constant while enhancing its strength, the cement content in the binder (CAM) of PCAC needs to be increased to improve the strength of CAM. However, as the cement content in CAM increases, the viscosity of CAM also rises. This increase in viscosity causes a thicker layer of CAM binder to adhere to the outer surface of the aggregate, thereby reducing the porosity and water permeability of PCAC. Consequently, in the material composition of PCAC, an increase in permeability is negatively correlated with the enhancement of strength.
2. In the pretreatment of CRS, NSP plays a critical role as both a demulsifier and a stabilizer. As a demulsifier, NSP facilitates a mild demulsification reaction in emulsion asphalt, causing slight aggregation of the asphalt micelles and enabling the recovery of asphalt's properties from the asphalt emulsion. Additionally, NSP func-

tions as a stabilizer. After the emulsified asphalt is demulsified, the granular asphalt restored from the asphalt emulsion forms an electrostatic adsorption layer on its surface with NSP. This results in granular asphalt particles with the same charge being evenly distributed within the pretreated CRS.

NSP is also the key substance that determines the workability of CAM and absolutely governs CAM's viscosity. To achieve good water permeability porosity in PCAC, it is necessary to maintain low CAM viscosity, which ensures a thin CAM film thickness on the aggregate surface. This requires the addition of NSP. Furthermore, to enhance the strength of PCAC, when increasing the cement content to improve CAM strength while maintaining low CAM viscosity, the addition of NSP remains essential.

Therefore, pretreating CRS with NSP is necessary to ensure both good water permeability and adequate mechanical strength in PCAC.

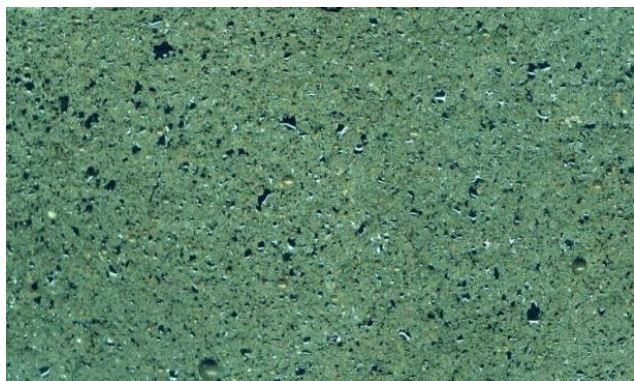
3. Comprehensive above two points, to increase the strength of the PCAC, the strength of CAM must be increased. To improve the CAM strength, the cement content of CAM must be increased. The increase of CAM's cement content increases the viscosity of CAM, which causes the thickness of the pcac grain to be thickened by CAM. The thickening of CAM will cause the porosity of PCAC to decrease and the water permeability to decline.

The method to maintain both the strength and water permeability of PCAC is to reserve some NSP dosage during the CRS pretreatment for reducing the viscosity of CAM. However, the increased dosage of NSP should not be too much. If the dosage of NSP is increased too much, it will cause stratification and segregation of CRS and cement in the CAM. Therefore, the pretreatment of CRS is critical for enhancing the performance of CAM. Proper pretreatment ensures ho-

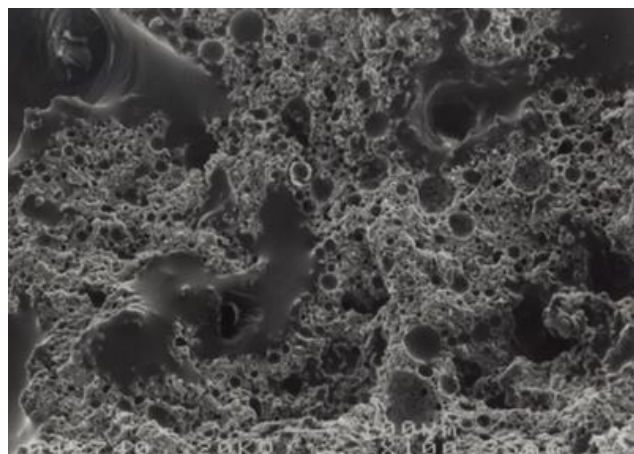
homogeneous mixing of CRS and cement, stabilizes the properties of CAM, and adjusts workability according to the mix design requirements.

## 5. Conclusions

1. Due to the high viscosity of the PCAC binder (CAM), which has a thick mastic film outside the aggregate, PCAC achieves effective porosity in a range of 15% to 20% and meets water permeability specifications. A part of fine aggregate is removed in the preparation of PCAC. It can be seen from Table 4 and Table 5 that the aggregate of PCAC at particle size 4.75mm is 10% less than PA, and at 2.36mm is 15% less. This adjustment results in larger Voids in Mineral Aggregate (VMA) in PCAC, and PCAC aggregate accumulation stability is less than PA. However, the higher strength of the PCAC binder is enough to compensate for the instability of aggregate accumulation caused by the larger VMA. In terms of the overall effect, the strength strengthening effect of CAM on PCAC is significantly higher than that of the asphalt binder on PA.
2. In CAM, the asphalt material is not in a continuous state. As shown in Figures 10 and 11, the asphalt material exists in the state of independent small blocks in CAM. Therefore, the main strength of CAM should come from cement hydration products. Asphalt is a buffer material that can increase the flexibility and toughness of the binder. As CAM is mainly composed of cement hydration products, it has low sensitivity to high temperatures. Accordingly, the low thermal sensitivity and good mechanical strength of PCAC contribute to better resistance to permanent deformation when applied in high temperature areas Pavements.
3. Compared to PA, PCAC has higher mechanical strength under the same permeability of porous concrete pavement, allowing vehicles with higher axle load, extending the road service time, and reducing road maintenance.
4. High-strength materials usually mean brittleness. In subsequent studies, long-staple fibers could be employed to increase the toughness of PCAC.



**Figure 10.** In the Cross-Section of CAM, Asphalt Adhesives are Distributed Dispersively.



**Figure 11.** SEM Images of CAM Show That the Asphalt Binder is not in a Continuous State.

## Abbreviations

CAC	Convenient Asphalt Concrete
CAM	Convenient Asphalt Mastic
PCAC	Porous Convenient Asphalt Concrete
PA	Hot Mix Porous Asphalt Concrete
OGAC	Open-Graded Asphalt Friction Course
CRS	Cationic Rapid Setting Emulsified Asphalt
NSP	Naphthalene Superplasticizer
AC	Asphalt Concrete
ASTM	American Society of Testing Materials
M.S.V.	Marshall Stability Value
I.T.S.	Indirect Tension Strength
AI	Asphalt Institutes
VMA	Voids in Mineral Aggregate

## Author Contributions

**Cheng Tsung Lu:** Conceptualization, Data curation, Methodology, Writing – original draft, Writing – review & editing

**Ming Yan Chung:** Resources, Supervision, Funding acquisition, Project administration

## Data Availability Statement

The data is available from the corresponding author upon reasonable request.

The data supporting the outcome of this research work has been reported in this manuscript.

## Conflicts of Interest

The authors declare no conflicts of interest.

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