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Sustainable Modeling of Water Retention Curve for Cement Cold Asphalt Mixtures

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Abstract. Cold Asphalt Mixture (CA) is one of asphalt types which used in pavement. It is manufactured with water, bitumen emulsion, aggregate and sometime cementitious materials. This type of asphalt involves economic, safety, health, and environmental benefits compared to other paving materials. However, it is restricted to using as a structural layer due to weak performance especially at first ages. Trapped water inside *CA* at early curing stages is the reason behind this weak performance. This research aims to investigate the effect of the bitumen emulsion and cementitious materials on the capillarity and water retention curve (WRC) of *CA* (with and without cementitious materials). With this objective, the effect the bitumen emulsion and cementitious materials was assessed from the point of view of water evaporation and specifically the head capillarity of WRC. With this purpose, WRC was calculated for unbound materials (aggregate) and *CA*. Depending on the results of experimental tests (hydraulic conductivity tests), the WRC was theoretically predicted by using results of the pore size distribution index (sizes and structure of voids) which was calculated depending on the hydraulic conductivity tests. The results showed that the pore size distribution index (n) have a significant link with the hydraulic conductivity. Compared to unbound materials, the bitumen emulsion increased the hydraulic conductivity of *CA*, as a result, n. The cementitious materials have not significant effect on the n of the *CA*. There is a significant positive relationship between n and the capillarity, as a result, WRC too. Therefore, the bitumen emulsion reduce the curing capacity of *CA* by decreasing its capillarity. As a result, the time of drying increase. Finally, cementitious materials do not significantly contribute to increase the capillarity of *CM*.

Keywords. Cold asphalt mixture, evaporation, pore size distribution, matric suction, water retention curve.

1. INTRODUCTION

Asphalt concrete pavement is one of the most famous construction materials that is used in the roads building over the world. Cold Asphalt Mixture (CA) is type of asphalt, manufactured at ambient temperature from mix of water, bitumen emulsion, aggregate, with/without cementitious materials [1]. In comparison to other types of asphalt, *CA* involves many advantages: more economical [2], energy-efficient [3], health, safety, and environment. In spite of all this advantages, there is not encourage to using it as a structural layer because the weak performance of *CA*, especially at the first ages. This weakness of performance comes from trapped water inside pores, which is evaporated after long time [4].

The dynamics of water evaporation of the porous materials involves three stages (first, transition and second) [5]. The rate of water evaporation is reduces gradually from first to last stage [6]. Therefore, continuation of the first stage as much as possible is very helpful to accelerate the drying of material. Water contacting between the surface and bottom of material is necessary to keep continuation the first stage. With the first cuts in water contacts between the surface and bottom of the material, the first stage finishes and starts the transition [7-8]. The capillarity or suction is the property that describes the potential with which a material adsorbs and retains water in the interior of the pores. Therefore, this property is an important item in the first stage.

It is possible to investigate the capillarity by the water retention curve (WRC) which describes the relationship between the matric suction and the degree of saturation of a specific porous material [7]. The hydraulic and mechanical behaviour of porous material is linked with its WRC [9]. Delay development performance of *CA* is related to trapped water inside *CA* [10], therefore, WRC of *CA* has very importance influence on performance of CA, because its linking with capillarity and first stage of evaporation, as a result, drying and performance of *CA*.

This research aims to investigate the effect of bitumen emulsion and cementitious materials on the water retention capacity (WRC) of coarse aggregates (CA), with a focus on sustainable practices. To achieve this, both experimental work and theoretical analysis are incorporated. The first step of the work plan involves examining the WRC of unbound materials (aggregate), while the second step evaluates the WRC of *CA*, both with and without various cementitious materials. By exploring these materials, the study seeks to enhance the sustainability of construction practices and promote environmentally friendly solutions in the industry.

2. Theoretical Considerations

2.1 Concept the capillarity and the WRC of the porous medium

At unsaturated situation, the water will flow through the porous materials by capillarity. This property is one of physical properties of the porous materials like CA. The ability of materials to adsorbs and keep water in the interior of the pores is measured by the suction property. The WRC includes the linking between the water content (the saturation degree) and the matric suction of the porous material [11]. This suction can be found from the difference between the pore-air pressure and the pore-water pressure.

2.2 Calculation the capillary (capillary head) of material

Usually, in lab, the axis translation technique is used to measure the matric suction. Moreover, different models has been suggested to calculate WRC in porous materials [12-13]. Among these models, the four-parameter van Genuchten model is the most used because of its simplicity and flexibility [12]. However, all these different techniques, equipment and models, need a lot of time and efforts in lab.

According to previous researches [7,14], there are reliable relationship between the hydraulic conductivity and the suction of porous material. An comes fuenty between the hydraulic conductivity and pore size distribution index (n). n is used as an indicator of sizes of pores and differential in sizes of the pores. Figure 1 shows the methodology which is used to calculate the suction of porous materials.

Values of fitting parameters (K_1, K_2, α_1) of equations in Figure 1 are different depending on the porous material. In the current work, same materials, manufacturing and tests conditions which were used by previous researches were used [14-15]. Therefore, same values were adopted in the current work: *0.003*, *6.493*, and *0.134* respectively.

3. Materials and Methods

3.1 Description of materials

In the current work, CA mixture was prepared by mixing of water, bitumen emulsion, and aggregates, with/without cement. The water was tap water. Crushed limestone with maximum size (10) mm was used. The gradation of aggregate is included in Table 1, which is in accordance with BS EN 13108-1 (2006) [16]. The bitumen emulsion, which was used, is described as slow-setting cationic bitumen emulsion, which is classified as a C60B3 according to BS EN 13808 (2013) [17]. In this type of emulsion, the bitumen content is 60%. The quantity of bitumen emulsion, which was used, was chosen in order to leave 5% residual bitumen content in the CA after drying (curing). To prevent the excessive bitumen absorption when the emulsion is mixed with the aggregates, 1.5% water (by mass of dry aggregate) was mixed with dry aggregate according to previous studies which recommended this quantity of water [18]. Extra quantity of water was used in order to saturate *CA* samples during its manufacturing.

In addition to that, cement was used in CA as replacement of filler either 0, 2, 4, 6 or 8% by mass of dry aggregate. Three type were used OPC CEM I, 42.5 N, and two types of rapid hardening cement, calcium aluminate (CAC) and calcium sulfoaluminate cement (CSA). More information about behavior (hydration and hardening behavior) of the cement stated in reference [18] for OPC, [19-21] for CAC and CSA. The same aggregate of *CA* was used to manufacture samples of unbound materials (aggregate samples with bitumen binder).

Table 1. Gradation of unbound materials samples used in this research

Sieve size (mm)	31.5	20	16	14	10	8	6.3	4
Passing (%)	100	95	88.7	85.9	75.5	68.3	61.4	45.4
Sieve size (mm)	2.8	2	1	0.5	0.25	0.125	0.063	--
Passing (%)	35.6	28.3	19.9	14.9	11.9	9.7	7.8	--

In the current investigation, cold asphalt mixture samples without cement are represented as CA-C. Cold asphalt mixture with OPC, CAC and CSA were represented as CA-OPC, CA-CAC and CA-CSA respectively. The quantity of cement used in each mixture was denoted as percentage (0, 2, 4, 6, or 8) depending on the replacement quantity of filler. An example is 6OPC, which refers to the mixture made with OPC replacing approximately *6%* of the mass of dry aggregate. The mixture compositions of *CA* used in this study are summarized in Table 2.

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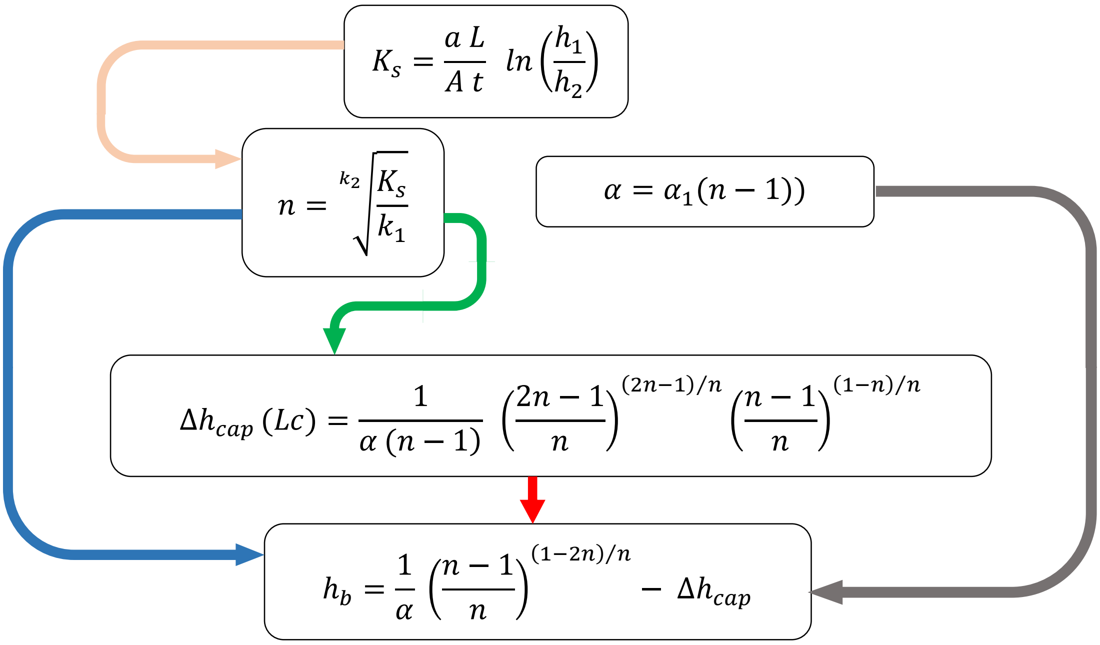

Figure 1. Relationship between the hydraulic conductivity and the suction of porous materials [7, 14]

Table 2. Amount of materials for 100 g of CA

Emulsion (g)	Pre-wet water (g)	Aggregate (g)		Cement		
		≥ 0.063 (mm)	< 0.063 (mm)	(g)	(%)*	W/C**
7.60	1.36	82.40	8.64	0	0	0
			6.82	1.82	2	2.418
			5.00	3.64	4	1.209
			3.18	5.46	6	0.806
			1.36	7.28	8	0.604

* *Percentage of cement by mass of aggregate*
*** Total water is 19 gm/ 100 gm of CA*

3.2 The preparation of test sample

CA was manufactured by following the procedure recommended by (Oke, 2011) [18] to produce homogeneous mixes, which stated that, this procedure of mixing produce homogeneous mixture of *CA*. This is done at ambient temperature and for *4* minutes. During the mixing and compaction of the *CA*, water content was *3.35%* of water provided by the emulsion and *1.5%* of water addition. In order compare *CA* and unbound materials, the same water content (3.35% + 1.5%) was used for all.

Casting and saturation was carried out according to (Han & Zhou, 2013) [22] to reach uniform density. The method involved pouring the material into the cylindrical mould (100 x100 mm^3) as layers. The thickness of every layer is *2* cm. the casting and compaction was manually (by hand). When all layers are casted and compacted. Every layer is saturated and covered by water (thickness of covering water is *3* mm) and leaved for *10* minutes before casting the next layer. After finishing all the layers, the walls of mould was tapped by plastic hammer in order to achieve more uniform density. Then, in order to sure that all pores of materials is filled by water, layer of water with thickness of 1 mm was put on the surface of materials and leaved for *2 h*. During this *2 h*, the surface of materials was covered by a plastic wrap in order to prevent evaporation of water. At end of this time, the level of water is checked, if decrease of water level is found, more water (1mm) is added until the level of water is become constant. When level of water is constant, the samples is be full saturated and ready to test. To *CA* samples, excluding emulsion water and water added during mixing, as an average, *7.64%* by mass of dry aggregates is quantity of water was needed in order to achieve full saturation of samples, while this quantity was *5.55%* of the unbound materials samples.

3.3 Hydraulic conductivity
At room temperature (*20 ± 2°C*), following the Florida Method (falling head method) [23], the hydraulic conductivity was measured. At different ages of evaporation, this test is done in order to follow and evaluate the structure of materials with evaporation. The samples was cured at *40 ± 2°C*, but before *4 h* from time of test, samples was conditioned at *20 ± 1°C*. Darcy's law which presented in Equation 1("The Florida Method (falling head method)," [23] was used to calculation the hydraulic conductivity of materials in this work

$$K_s = \frac{a\,L}{A\,t}\ ln\left(\frac{h_1}{h_2}\right) \qquad (1)$$

Where: a is the inner cross-sectional area of the graduated tube (cm^2), L is the test sample thickness (cm), A is the test sample cross-sectional area (cm^2), t is the time elapsed between the initial head and the final head (s), h_1 is the initial head across the test specimen (cm), h_2 the is the final head across the test specimen (cm).

4. Results
4.1 Pore size distribution index (n)
Figure 1 shows that n has relation with the hydraulic conductivity of the material. Therefore, all factors that affect the flow of water through the porous material affect this index too. Results of n are presented in Figure 2. The value of n for CA-C (3.852) is close to CA-OPC, CA-CAC and CA-CSA (in the range of 3.826 to 3.611). Therefore, cement does not significantly reduce n. As a result, if does not significantly increase the capillarity of *CA* according to the negative relationship between them (n and capillarity).

However, there is a negative relationship between n and quantity of cement, the reason stand behind that is products of cement hydration which lead to close some pores and reduce sizes of other pores of the *CA*.

Although big quantity of cement (up to *8%* of dry aggregate) is used in the manufacturing of *CA*, all samples had an n value much higher than aggregate samples. For example, (C10) has n = *2.55*, while average n of *CA* is *3.719*. According to previous publications bitumen emulsion increases the porosity of the material, possibly due to the presence of the emulsion and a consequent reduction in mix viscosity and compaction, compared to mixes with only aggregates and water [14]. In addition, as it has been reported by García, Lura, Partl and Jerjen (2012) [24], the presence of bitumen emulsion leads to poor compaction by Marshall method and increased air voids in *CA*. Increasing the porosity means increasing the sizes and numbers of pores, and as a result increasing n of the material too [7, 14]. The parameter of n is important item in calculation of WRC, therefore, all parameters and items that effect on values of n are effect on WRC and vice versa.

4.2 Water retention curve (WRC)
Generally, the results of WRC are inversely correlated to the capillary head (suction) and the saturation degree of the material (see Figure 3). At full saturation, the capillary head is zero, which means that the surface of water is at the same level than the solid materials. During drying, the

capillary head increases and saturation decreases gradually until the capillary head becomes maximum when saturation of materials is zero. At this time, saturation of materials is zero, the first stage of evaporation is finished and the transition stage is started. Therefore, if capillary head increase, the first stage will continuous for longer time. The final (or maximum) capillary head have important influence on time of full drying on period of first stage of evaporation, therefore, all our discussion will be focused on this parameter which will be referred have after as capillary.

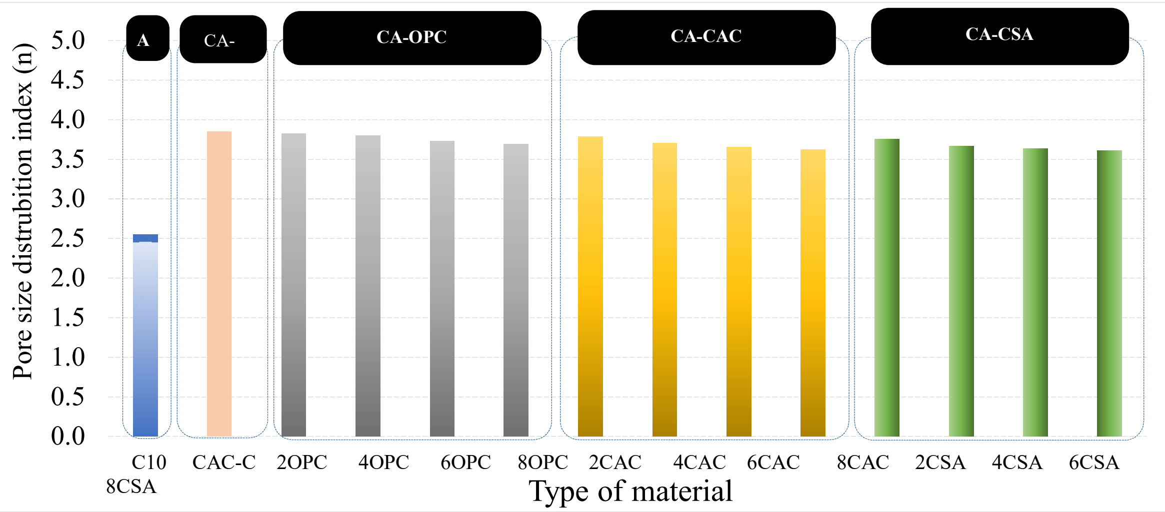

Figure 2. n of the CA and unbound materials

Normally, cement is used as an accelerator of drying in *CA* because its capillary ability to consume water during the hydration reactions. However, there is not significant difference between the capillarity of *CA* mixed with cement and not mixed. The biggest difference was *0.581 mm*, between CA-C and 8CSA. Therefore, cement does not help much in developing the capillarity of *CA*. This is in agreement with previous publication that stated that cementitious materials have not effect on dynamics of water evaporation of CA [15].

Moreover, as a quantity of cement is increased, value of capillary head is increased too. The reason behind that is because the hydration products lead to closing and reducing the sizes of pore, as a result, reducing value of *n* (see Figure 2) and increase the capillary head according to negative effect between them [14].

In spite of the big quantities of cement used in the current work (up to *8%* of dry aggregate), the capillarity of all *CA* samples are less than the capillarity of aggregate (sample maximum size *10 mm*) used for the manufacturing of *CA*. The differences between the capillarity of aggregate (C10) and *CA* samples are between *5.72* and *6.3 mm*. This phenomenon is produced by the same reasons which make that aggregate samples has lower *n* than *CA* samples according to the negative relationship between them (*n* and capillarity).

According to results of WRC, cement does not contribute to accelerate the dynamics of water evaporation in *CA*. The bitumen emulsion, delays the drying of *CA* by closing capillarity contact with surface of *CA* [14], reducing the capillarity of material and increasing porosity (*n*).

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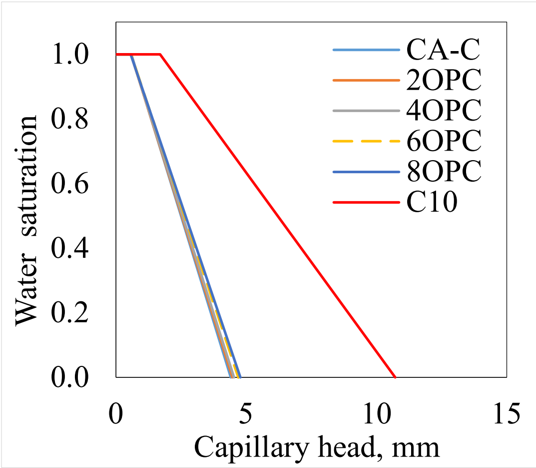
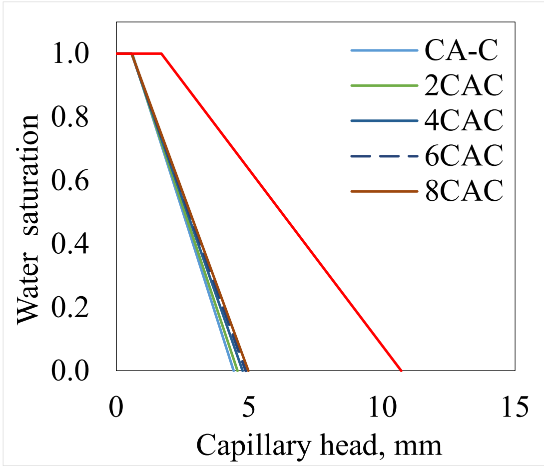


a



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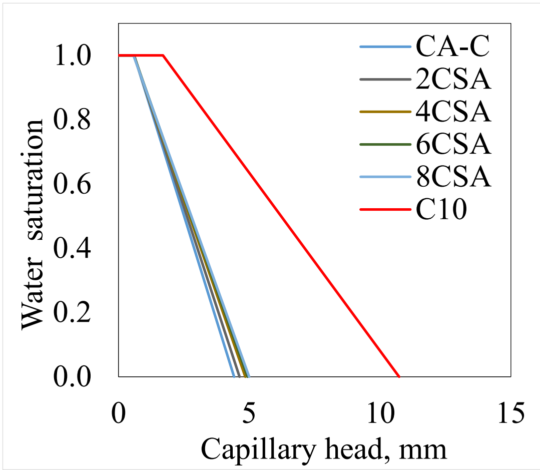

c

Figure 3. WRC of unbound material, CA-C, and CA-OPC (a), -CAC (b), -CSA (c)

5. Conclusion

In the current paper, the effect of bitumen emulsion and cement on the curing of *CA* was assessed from the point of view of water evaporation and specifically the capillarity head of WRC. With this purpose, WRC was calculated for unbound materials (aggregates) and *CA* (with and without cement). According to the results of this study, the following conclusions could be extracted:

- Compared to unbound materials, the bitumen emulsion increases the hydraulic conductivity of *CA*. As a result, *n* increases too. On the other hand, the cement has not significant effect on *n*.
- There is a significant direct relationship between *n*, capillarity, and WRC. According to this, the capillarity of *CA* is less than unbound material because the bitumen emulsion increases *n*. Therefore, the bitumen emulsion plays as negative role in the curing of *CA* by decreasing its capillarity. As a result, the period for full drying increases.
- Cement does not significantly contribute to increase the capillarity of *CA*. Therefore, from the view point of capillarity, this material does not help much to accelerate the curing of *CA*.

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