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A novel type of cold mix pavement material made with calcium-alginate and aggregates

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Abstract

This paper has been prepared in the frame of a research focused on the development of Cold Mix pavement materials made with calcium-alginate Capsules (CMC) instead of with just bitumen emulsion, as it is normally made. The initial objective was to remove most of the water in cold mix asphalt by encapsulating bitumen droplets. The encapsulation method allowed the preparation of polynuclear capsules with bitumen emulsion encapsulated, which membrane was made of calcium-alginate. Capsules were mixed with aggregates at the ambient temperature. During mixing, the capsules containing bitumen emulsion would break, release their content and coat the aggregates. To study CMC, an extensive experimental programme has been carried out to evaluate the effect of compaction energy, cement content, curing time and binder type on the mechanical properties of CMC. It was found that CMC test samples increased their Marshall stability linearly with the increase of the compaction energy. Test samples could be demoulded immediately after compaction. Furthermore, the Marshall stability of CMC increased with the curing time, and the general strength improved with the increasing amount of capsules in the mixture. It was found that the bitumen in CMC did not have an important role on the strength of the pavement material, which came mainly from the alginate in the capsules. In short, cold mix pavement materials made with calcium-alginate (Ca-alginate) capsules is a novel material for pavements that has shown potential to be an alternative for conventional cold mix asphalt made with bitumen emulsion.

Keywords: Cold Mix pavement Materials; Compaction energy; Capsules; Bitumen emulsion; Portland cement.

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1 INTRODUCTION

Cold Mix Asphalt (CMA) is a complex road construction material that is manufactured at the ambient temperature by mixing aggregates with water and a bitumen emulsion that acts as the binder. In the United Kingdom, the use of CMA is largely limited to surface treatments, such as surface dressing and slurry surfacing, as well as bond/track coating (Brown and Needham, 2000). The strength of CMA tends to be easily affected by the exposure to environmental and mechanical factors, such as moisture and continuous traffic loads (Marienfeld and Guram, 1999; Liang and Zhou, 1997). This happens because moisture reduces the curing rate of CMA and increases its damage susceptibility (Choudhary et al., 2012) by effect of the loss of the interfacial adhesion properties of the mixture (Guo et al., 2014). Authors as Thanaya et al. (2009) and Khalid and Mooney (2009) have reported that CMA presents some disadvantages compared with conventional Hot Mix Asphalt (HMA), such as high air void content, weak life strength, and long curing times. Nevertheless, CMA also presents advantages in terms of costs, ecology, energy savings and health and safety performance compared with conventional hot mix asphalts (Saadoon et al., 2017). Likewise, the flexible performance of CMA makes them especially attractive for low-medium traffic roads (Gómez-Meijide and Pérez, 2014). Contrary, some weaknesses of CMA versus hot mixes are majorly as result of their raw material typology, design variables and manufacturing conditions.

In CMA manufacturing, the bitumen emulsion must be reverted into bitumen to act as a binder: a process known as de-emulsification or breaking (Das, 2008; Saadoon et al., 2017). Water inside the CMAs is the main factor that delays their strength gain (Oke, 2011). Water is the second element of bitumen emulsions and comprises between 25% and 60% of an emulsion (James, 2006). The curing of CMAs is a process where water evaporates from CMA and the bitumen can bond the aggregates together (Saadoon et al., 2017). CMAs thereby gain strength with the curing time (Fang et al. 2015). Previous studies have reported that full curing of the cold mixes by effect of the interstitial water evaporation may take place between 2 to 24 months under field conditions (Thanaya, 2007). Hence, it is very important to remove the water from emulsions of the CMA to improve the strength and accelerate the curing time (Fortuny et al., 2007; Jenkins, 2000; Saadoon et al., 2017).

Additionally, to accelerate cold mix asphalt curing and improve its mechanical properties, lime or Portland cement can be added to the mixture (Oruc et al., 2006; Fang et al., 2015). Cement provides improvements on their Marshall stability (Wang and Sha, 2010), lower moisture content, curing rates, enhanced strength and material stiffness, and improves the compatibility of the aggregates with the emulsion (Fang et al., 2015). For these reasons, between 1% and 3 % of Portland cement may be added to cold mixes by mass of aggregates (Head, 1974; Thanaya, 2007).

Furthermore, due to the relevance for this paper, it is important to comment on the existence of inorganic-organic composite building materials, composed of sticky rice and lime, which was used in ancient China as a binder in public constructions, such as roads, or walls (Yang et al., 2010). The inorganic component was calcium carbonate, and the organic component was amylopectin, which comes from the sticky rice soup added to the mortar and works by combining chemically with the lime and inhibiting the growth of calcium carbonate crystals, which produced a very compact microstructure. This material had lower water absorption properties, higher strength, and lower shrinkage than lime used on its own (Luo and Zhang, 2013).

This paper aims to prepare Cold Mix pavement Materials made with calcium-alginate Capsules (CMC) or Particles (CMP) as an alternative material to the conventional Cold Mix Asphalt (CMA). To do that, bitumen emulsion has been encapsulated in a calcium-alginate matrix and, calcium-alginate particles have been manufactured. After, the capsules and particles were mixed with aggregates and compacted and, it was found that they created a composite material that is stronger than standard CMA. In the paper, the influence of the amount of calcium-alginate capsules and particles has been evaluated. Furthermore, the effect of compaction energy, curing time and cement additions on the mechanical properties of CMC and CMP have been evaluated.

2 MATERIALS AND METHODS

2.1 Raw materials

Limestone aggregates, bitumen emulsion, Portland cement, and bitumen, were used in this study. Raw materials for calcium-alginate capsules and particles consisted of a cationic bitumen emulsion K1-60, 60% bitumen content, with density of 1.03 g/cm^3, sodium alginate ($C_6H_7O_6Na$) and, calcium chloride ($CaCl_2$) in granular pellets and 93% purity. The aggregates used were well-graded crushed limestone, with size between 14 and a few microns (see the aggregate gradation in Figure 1). Portland cement type CEM I 52.5 N was used as a filler replacement to improve the properties of CMC. Finally, virgin bitumen of 160/220 penetration grade was used to manufacture hot mix asphalt.

2.2 Encapsulation procedure of calcium-alginate capsules and particles

The calcium-alginate capsules were prepared by ionotropic gelation of alginate in the presence of calcium. Figure 2 shows a schematic diagram of the preparation of the capsules. The encapsulation procedure used in this research is as follows:

- First, 800 ml of bitumen emulsion, 100 g of sodium alginate and 1200 ml of deionised water were pre-heated at 95ºC, introduced into a 2500 ml Pyrex glass container that was on a hot plate to maintain the temperature at 95ºC and stirred at 6000 rpm for 15 min until a stable bitumen-alginate emulsion was produced.

- At the same time, a calcium chloride solution was prepared by mixing 250 ml of deionised water with 15 g of calcium chloride in a 500 ml Pyrex glass container that was on a hot plate prepared to maintain the solution at 95ºC and, stirred at 400 rpm for 15 min to produce a stable calcium chloride solution.

- Then, the calcium chloride solution at 95ºC was placed into a blender device and stirred at 13600 rpm for 1 min. Capsules were produced by letting the bitumen-alginate emulsion drop into the calcium chloride solution from a 1000 ml pressure equalising dropping funnel (at an approximate speed of 1.7 mm/min) with a 3 mm outlet size, the blades in the blender cut the drops before the calcium-alginate had hardened, producing capsules of approximately 0.5 mm diameter. The bitumen emulsion was encapsulated into a polymeric porous structure by the cross-linking of calcium-alginate via ionotropic gelation of sodium alginate in the presence of calcium ions. Al-Mansoori et al (2017) and Norambuena-Contreras et al (2018) have used this encapsulation technique with successful results to produce calcium-alginate (Ca-alginate) capsules with asphalt self-healing purposes.

- After this, the capsules were left in the calcium chloride solution for 24 h, to reduce their temperature to 20±1ºC. Then, the capsules were sieved and washed with deionised water. They were dried for 30 min under the constant movement of air at 20±1ºC, produced by a fan. Finally, the Ca-alginate capsules containing bitumen emulsion were stored in a freezer, at -20ºC to minimise any possible degradation.

Furthermore, the same proportions of calcium-chloride, sodium alginate, water and experimental procedure were selected to manufacture Ca-alginate particles, which did not contain bitumen emulsion. These particles were made to evaluate the binding effect of bitumen emulsion. Examples of an individual calcium-alginate capsule that contains bitumen emulsion and a calcium-alginate particle without bitumen emulsion are shown in Figure 3(a) and (b), respectively.

2.3 Test specimen's preparation

Marshall test specimens with 100 mm diameter and 50 mm height were prepared, see Figure 4. Table 1 describes the manufacturing process for the 15 different types of mixtures evaluated in the study. The raw materials used in the preparation of the mixtures such as bitumen, bitumen emulsion, calcium-alginate capsules and calcium-alginate particles with, and without, cement addition, were manufactured in batches with 3060 g of aggregates. The amount of raw materials in the mixture was added by total weight of aggregates, see percentages in Table 1.

2.4 Morphological characterisation of the calcium-alginate capsules and particles

The morphology of the Ca-alginate capsules and particles was evaluated by Optical microscopy, Fluorescence microscopy and Environmental Scanning Electron Microscopy (ESEM). To determine the size distributions of the capsules and particles, more than 120 capsules and particles were randomly selected and examined by using a stereo microscope at 5 and 20 magnification. The ESEM scanner of samples containing Ca-alginate capsules and particles was also carried out.

2.5 Water content of the calcium-alginate capsules and particles

To measure the accessible water content in the calcium-alginate capsules and particles, 3 samples of approximately 50 g of each type were dried in an environmental room with constant movement of air, at 20±1ºC for 24 h. After 24 h, the capsule and particle samples were dried using a silica desiccant for 8 h, and then weighed using a precision balance

2.6 Density of the calcium-alginate capsules and particles

To determine the density of the calcium-alginate capsules and particles, a Helium Pycnometer was used. It was chosen because it has the ability to measure the real density of a granular or porous solid by determining the volume of the solid portion isolated. The test was carried out at room temperature 20±1ºC, and 3 samples of approximately 0.2 g of each capsule and particle type were poured into a sealed sample chamber size 1 cm^3 within the pycnometer. Finally, the density of calcium-alginate capsules and particles was recorded at 20 min at a pressure value of 165 kPa.

2.7 Marshall Stability tests

Marshall Stability test was used in this study to measure the mechanical performance of the pavement materials studied. The tests were executed according to BS EN 12697-34, at 20±1ºC, and the loading speed rate applied in the specimens was 50 mm/min. In the case of the hot mix asphalt, the specimens were immersed in a water bath at 60ºC for 40 minutes before testing, and the elapsed time between the removals of the specimen from the water bath to the test did not exceed 30 seconds. The Marshall results shown are the average of 3 tests.

2.8 Curing process of the test specimens

All the Marshall test specimens of the CMA, CMC, and CMP materials studied (see Table 1) were demoulded after compaction, and cured at room temperature, 20±1ºC and relative humidity of 60% for six different curing times: 1, 3, 7, 14, 21 and 28 days (Garcia et al. 2013; Gómez-Meijide and Pérez, 2014).

2.9 Water content in the test specimens at different curing times

Water content in the Marshall test specimens was measured following the procedure described by Garcia et al. (2013). For that, the mass of each test specimen at the different curing times (from 1 to 28 days) was recorded using a balance with a precision of 0.5 g. Then, after 28 days, the same test specimens were dried at 90ºC for 12 h and weighed again to determine the remaining amount of water in the mixture and the water content of each sample was calculated by the following equation:

$$WC_m = \left(\frac{m_{ct_i} - m_{dry}}{m_{ct_i}}\right) \times 100 \qquad (1)$$

Where m_{cti} is the mass in (g) of the test specimen at a specific curing time i, and m_{dry} is the mass in (g) of the same test specimen after 28 days and dried at 90ºC for a period of 12 h.

2.10 X-ray computed tomography

X-ray computed tomography (CT-Scan) was used to evaluate and compare the air voids distribution in 50 mm length and 50 mm width test samples of CMC 4C2-50 that had been cured for 1 day, and HMA. For CT-Scan characterization, a micro CT system operated at 160 kV and 63 µA with a pixel size 55 µm was used. Additionally, a small sub-sample of approximately 5 mm long taken from the CMC 4C2-50 sample was also examined. The micro CT system operated at 60 kV and 83 µA with a pixel size of 5.7 µm was also used.

3 RESULTS AND DISCUSSION

3.1 Evaluation of the morphology and composition of the capsules and particles

Based on the optical microscopy measurements, it was found that the size of the Ca-alginate capsules and particles exhibits a normal distribution curve with the majority of agglomeration diameters ranging from 0.4 mm to 0.64 mm for capsules, Figure 5(a), and from 0.4 mm to 0.74 mm for particles, Figure 5(b).

By knowing that the average water content was approximately 67% in the particles and 73% in the particles, the density of the capsules was 1.12 g/cm^3, the density of the bitumen emulsion was assumed to be 1.03 g/cm^3, and the density of the calcium-alginate polymer was 1.74 g/cm^3, the composition of Ca-alginate particles can be readily calculated and the composition of Ca-alginate capsules can be assessed by using the following two equations system:

$$\begin{gathered} M_b + 67 + M_p = 100 \\ \rho_{b-cap} \times \left(\frac{M_b}{\rho_b} + 67 + \frac{M_p}{\rho_p} \right) = 100 \end{gathered} \quad (2)$$

where M_b and M_p are the mass proportions, expressed as percentages of bitumen emulsion and calcium-alginate, respectively; $\rho_{b\text{-}cap}$ is the density of the capsules; ρ_b is the density of the bitumen; and ρ_p is the density of the calcium-alginate polymer.

Table 2 presents the composition for the Ca-alginate capsules and particles. From these data, the authors find relevant to remark that the mass percentage of bitumen contained in the CMC specimens with 4% and 10% of capsules was 0.20% and 0.50%, respectively. This represents amounts of 15 and 6 times less bitumen, than in HMA. Likewise, the amount of calcium-alginate contained in CMA made with 4% and 10% of capsules was 0.98% and 2.46%, respectively.

3.2 Effect of compaction energy and cement addition on the Marshall strength of CMC

Figure 6 shows the average Marshall force resisted by CMC specimens made with capsules and 3 different cement contents, ager 24h curing, at 20ºC. In every case, the force resisted increased linearly with the number of blows applied; e.g., in the CMC 4C0 mixtures, from 2.21 kN at 20 blows to 9.22 kN at 100 blows. Moreover, the force resisted by the CMC increased proportionally to the amount of cement additions. For instance, in Figure 6 it can be seen that the slope of Marshall's force vs number of blows curve increased with the amount of cement. For instance, in the CMC with 0%, 1%, 2% and 3% of cement the slopes were 0.08 kN/blow, 0.12 kN/blow, 0.17 kN/blow and 0.21 kN/blow, respectively. It is unclear if the strength's increase by the effect of cement is mainly due to the hydration properties of the cement or to the interaction of the cement's hydration product and calcium-alginate and this will be a matter for future investigation.

Additionally, the average strength registered for HMA, compacted with 50 blows per flat face, is also shown in Figure 6. For the same number of compaction blows, the average force resisted by the HMA specimens was similar to that of CMC 4C2-50. This shows that unlike Cold Mix Asphalt (CMA) that may require lengthy curing periods of several days, CMC can be readily used onsite after 24 curing period, just by adding 2% of cement, which is in the same range of cementitious additions as CMA. Note that although the testing temperature of HMA was 60ºC, this strength is still higher to that of equivalent HMA that is reported in the literature, such as Garcia et al. (2013).

Moreover, Figure 7 shows the average air void distribution along the height of CMC 4C2-50 and HMA samples, measured from CT-Scan images. It can be observed that the air void contents across both test samples (line A-A') were approximately 7.2% and 7.6%, respectively. CMC shows very similar strength and air void content to HMA after 24h curing, which may be due to the interaction of the cement's hydration products with the Ca-alginate capsules' materials, although further research is still required to understand the reasons for this.

Figure 8(a) shows an example of a CT-Scan cross-section image of the internal microstructure of CMC 4C2-50, after 24 hours curing. In this Figure, it can be observed that, although the shape of the capsules adapted to the solid skeleton of the material, the bitumen in the capsules remained unmixed. Furthermore, most of the bitumen in the capsules, remained unmixed and unbounded to the aggregates. This, and the low amount of bitumen used in CMC are indications that bitumen is not the main bonding material in CMC. Moreover, a dense binder can be observed between the particles, which can be composed of cement and calcium-alginate. The authors hypothesize that unreacted alginate remained in the capsules and alginate may have reacted with the cementitious materials to produce a binder that is equivalent to that reported by Yang et al. (2010) and Luo and Zhang (2013) between sticky rice, which has a similar composition to that of alginate, see Sachan et al. (2010), and lime. This remains to be investigated.

Finally, by comparing Figure 8(a) to Figure 8(b), which corresponds to a CMA with 6% of cement, reported in Garcia et al. (2013), it can be observed that CMC shows a much denser microstructure, which corresponds to a lower amount of water in the material and explains its early strength acquisition.

3.3 Effect of binder type and amount on the mechanical strength of cold mixes at different curing times

Figure 9(a) shows the average results of Marshall force registered at different curing times for CMA, CMC and CMP test specimens. All specimens have been compacted with 50 blows on each flat face. From Figure 9(a) it can be concluded that: 1) the strength of CMA, CMC and CMP specimens increased with the curing time, and 2) the strength resisted by all the materials depended on the type of binder used, i.e., bitumen emulsion, Ca-alginate capsules or particles and, on the amount of binder added to the mixtures.

In Figure 9(a) it can be observed that the force resisted by CMA 7C0-50 and CMA 17C0-50 at 1 and 28 days curing increased from 1.15 kN to 9.29 kN, and from 0.51 kN to 5.15 kN, respectively. This increase of the strength with time is consistent with the conclusions published by Saadoon et al. (2017) that indicated that CMA gained strength with the curing time due to the evaporation of water from the road's surface. The addition of bitumen emulsion introduces an excess of water in the mix, which delays the adhesion of bitumen to the aggregates and increases the required curing time. For example, the mixture with 17% bitumen emulsion (CMA 17C0-50) showed lower strength than the mixture with 7% emulsion (CMA 7C0-50). This can be verified by comparing the results of average water content for both mixes, shown in Table 3 where it is observed that the water contents for CMA specimens with 17% of bitumen emulsion were always greater than that of specimens with 7% for all evaluated curing times. This effect also occurred in the cold mix specimens containing different amounts of Ca-alginate capsules (CMC) with bitumen emulsion and Ca-alginate particles (CMP), where higher contents of capsules, from 4% to 10%, did not increase the strength of the mixture, probably as a result of the increase in the water content of the test specimens, although this hypothesis must still be confirmed in further research.

Furthermore, Figure 9(a) shows that CMC 4C0-50 and CMC 10C0-50, made with Ca-alginate capsules had higher strength than all the CMA test specimens evaluated in this Figure; see in Figure 10(a) the density of the calcium-alginate binder when compared to that shown in Figure 8(b). Additionally, the strength of CMP 4C0-50 and CMP 10C0-50 was remarkable similar to the strength of equivalent CMC materials, at every curing time, although approximately 5% lower. This result can be due to the bitumen in the capsules, which helped the bonding of the aggregates and therefore increased the mechanical strength of the mixtures. As a proof of this, in Figure 10(b), it can be observed that small globules of bitumen are well integrated within the binder. In addition, it can be observed that in mixtures with 4% of capsules, bitumen played an important role on the binding of the aggregates, especially during the first 14 days curing. Moreover, the fact that the Marshall force resisted by the material was lower with higher additions of binder, points to an optimum amount that must be studied in further research. Based on the previous results, it can be concluded that calcium-alginate was the main contributor to the increase of strength of the material and cold mixes made with capsules and particles and likewise Ca-alginate particles can be used as an excellent alternative as binder to cold mixed pavements versus bitumen emulsion.

Moreover, Figure 9(b) shows the influence of the addition of 1% Portland cement on the Marshall force resisted, measured at different curing times in CMA and CMC materials. In it can be observed that cement addition improved the strength of all the materials studied, which is consistent with results found by Fang et al. (2016), where the cement to increase the strength of CMA specimens.

By comparing the forces resisted by CMA and CMC in Figure 9(b), it was found that CMC with 4% of capsules increased its strength during all curing period, while CMC with 10% of Ca-alginate capsules specimens nearly stopped gaining strength after 7 days curing, which may be due to the combination of an excess of water, which reduced the strength of the specimens, and adding a 1% of cement was not enough to fully overcome this problem, and an excessive pore size, which prevented capillary evaporation from the test specimens (Saadoon et al. 2017). Finally, by comparing all the water content results of Table 3 with the Marshall forces in Figure 9(a) and (b), one can conclude that the strength of all the materials studied is simply proportional to the amount of water present in the mixture, independently of the binder used.

4 CONCLUSIONS

This paper has evaluated the mechanical properties of Cold Mix pavement materials made with different types and amounts of binder, including bitumen emulsion, Ca-alginate capsules that contain bitumen emulsion, and Ca-alginate particles. Additionally, the effect of adding 1%, 2% and 3% w/w of Portland cement on the Marshall force resisted by test specimens has been evaluated. The main conclusions of this paper are summarised as follows:

- The encapsulation method used in this study allowed the preparation of Ca-alginate capsules that contained bitumen emulsion and Ca-alginate particles without bitumen, sized between 0.4 mm and 0.74 mm, which can be added inside cold mixes to bind the aggregates during the pavement material’s manufacturing process.

- Cold mix specimens made with 4% of Ca-alginate capsules with, and without cement additions increased their Marshall stability linearly with the increase of the number of Marshall compaction blows, which are equivalent to the energy of compaction.

- CT-Scan images of cement treated cold mix specimens containing 4% of Ca-alginate capsules revealed that the bitumen in the capsules did not mix properly in the material. The bitumen added only 5% of the total strength of the material and was effective only during the first 7 to 14 curing days. Ca-alginate was the main binder type that held the aggregates together.

- It was found that the Marshall stability of cold mixes increased with the curing time, and that this happened due to the evaporation of water from the pavement material. In order to accelerate the curing of Cold Mix pavement materials, the amount of water in the mixture must be minimised.

- Alginate formed an intimate composite with the hydration products of cement, which proved to be very dense and work well as a binder. In the future, by-product alternatives to alginate from the wood and food production industries, with equivalent composition and properties, will be investigated.

- Finally, this study has proved that Cold Mixed pavement materials made with 4% Ca-alginate particles and 2% cement, can be an alternative to conventional cold mixes made with bitumen emulsion, since they produced a material with equivalent Marshall Stability to Hot Mix Asphalt, after 24h curing. Future research should also explore the use of fast hydrating cements, such as calcium-aluminate to accelerate this reaction even further.

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6 REFERENCES

Al-Mansoori, T., Micaelo, R., Artamendi, I., Norambuena-Contreras, J., Garcia, A., 2017. Microcapsules for self-healing of asphalt mixture without compromising mechanical performance. Construct. Build. Mater. 155, 1091-1100.

Brown, S., Needham, D., 2000. A study of cement modified bitumen emulsion mixtures. J. Assoc. Asphalt. Pav. 69, 92-121.

Choudhary, R., Mondal, A., Kaulgud, S., 2012. Use of cold mixes for rural road construction. In. IJCA. Proc. Int. Conf. on Emerging Frontiers in Technology for Rural Area (EFITRA-2012) EFITRA, 4, 21-25.

Das, A., 2008. Principles of Bituminous Pavement Design and the Recent Trends, C. E. D, I. I. T. D, Kanpur.

EN 12697-34 Bituminous Mixtures, Test methods for hot mix asphalt, Part34: Marshall test, British Standards Institution.

Fang, X., Garcia, A, Winnefeld, F., Partl, M., Lura P., 2015. Impact of rapid-hardening cements on mechanical properties of cement bitumen emulsion asphalt. Mater. Struct. 49, 487-498.

Fang, X., García, A., Lura, P., 2016. Overview on cold cement bitumen emulsion asphalt. Rilem Technical Letters, 1, 116-121.

Fortuny, M., Oliveira, Z., Melo, V., Nele, M., Coutinho, C., Santos, F., 2007. Effect of salinity, temperature, water content, and pH on the microwave demulsification of crude oil emulsions. Energ Fuel. 21(3), 1358-1364.

Garcia, A., Lura, P., Partl, N., Jerjen, I., 2013. Influence of cement content and environmental humidity on asphalt emulsion and cement composites performance. Mater. Struct. 46, 1275-1289.

Gómez-Meijide, B., Pérez. I., 2014. A proposed methodology for the global study of the mechanical properties of cold asphalt mixtures. Mater. Des., 57, 520-527.

Guo, M, Yiqiu Tan, Y, Zhou, S., 2014. Multiscale test research on interfacial adhesion property of cold mix asphalt. Construct. Build. Mater. 68, 769-776.

Head, W., 1974. An informal report of cold mix research using emulsified asphalts as a binder. Proc. Assoc. Asph. Paving. Technol. 43, 110-131.

James, A., 2006. Overview of Asphalt Emulsions, Asphalt Emulsion Technology, T. R. B: E-C102, TRANS. RES. B, Washington, DC.

Jenkins, K., 2000. Mix Design Considerations for Cold and Half-warm Bituminous Mixes with Emphasis on Foamed Bitumen (Ph.D. Thesis) UoS, South Africa.

Khalid, H.A, Monney, O.K., 2009. Moisture damage potential of cold asphalt. Int J Pavement Eng, 10(5), 311-318.

Liang, R., Zhou, J., 1997. Prediction of fatigue life of asphalt concrete beams. Int. J. Fatigue. 19, 117-124.

Luo, YB., Zhang, YJ., 2013. Investigation of sticky-rice lime mortar of the horse stopped wall in jiange. Herit sci.1: 26.

Marienfeld, L., Guram, K., 1999. Overview of field installation procedures for paving fabrics in North America. Geotext. Geomembranes. 17, 105-120.

Norambuena-Contreras, J., Yalcin, E., Garcia, A., Al-Mansoori, T., Yilmaz, M., Hudson-Griffiths, R., 2018. Effect of mixing and ageing on the mechanical and self-healing properties of asphalt mixtures containing polymeric capsules. Construct. Build. Mater. 175, 254-266.

Oke, O., 2011. A study on the development of guidelines for the production of bitumen emulsion stabilised RAPs for roads in the tropics (Ph.D Thesis) UoN Eng, UK.

Oruc, S., Celik, F., Akpinar, V., 2006. Effect of cement on emulsified asphalt mixtures. J. Mater. Eng. Perform. 16(5), 578-583.

Saadoon, T., Alvaro Garcia, A., Gómez-Meijide B., 2017. Dynamics of water evaporation in cold asphalt mixtures. Mater. Des, 134,196-206.

Sachan, N.K., Ghosh, S. K., Bhattacharya, A., 2010, Evaluation of glutinous rice starch based matrix microbeads using scanning electron microscopy, J. Chem. Phar. Res. 2(3), 433-452.

Thanaya, A., 2007. Review and Recommendation of Cold Asphalt Emulsion Mixtures Design, C. E. D, Indonesia, 9(1), 49.

Thanaya, A., Zoorob, E., Forth, P., 2009. A laboratory study on cold-mix, cold-lay emulsion mixtures, P. I. C. ENG: Transport, 162, 47-55.

Wang, Z., Sha, A., 2010. Micro-hardness of interface between cement asphalt emulsion mastic and aggregates. Mater. Struct. 43, 453-461.

Yang, F., Zhang, B., Ma, Q., 2010. Study of sticky rice-lime mortar technology for the restoration of historical masonry construction. Acc. Chem. Res. 43(6), 936-944.

1. TABLES

Table 1. Composition and manufacturing process used for the mixtures studied.

Mixture type	Manufacturing process description	Abbreviation
Hot Mix Asphalt	Raw materials were pre-heated at 160ºC for 2h. Then, aggregates with 3% of bitumen were mixed in a planetary mixer for 2 min at 160°C and poured into the Marshall moulds. The mixtures were compacted at 140ºC applying 50 blows on each flat face.	HMA
Cold Mix pavement material made with calcium-alginate Capsules (see Figure 3(a)) that contain bitumen emulsion (CMC)	Aggregates, 4% or 10% w/w of calcium-alginate capsules (%Cap: 4, or 10, respectively) and 0%, 1%, 2% or 3% of cement (%Cem: C0, C1, C2 and C3, respectively) were mixed for 2 min at 20±1ºC, followed by 60s of mixing by hand. Then, the mixture was poured into Marshall moulds and compacted by applying 20, 40, 50, 70, 80 or 100 blows (N_{Blows}: 20, 40, 50, 70, 80, 100, respectively) on each flat face of the specimens.	CMC %Cap %Cem - N_{Blows} *e.g. CMC 4C1-50 means that 4% w/w of capsules were used, 1% w/w of cement was added and, 50 blows were applied to compact the mixture.*
Cold Mix pavement material made with calcium-alginate Particles (see Figure 3(b)) (CMP)	Aggregates with 4% or 10% of calcium-alginate particles (%Par: 4, or 10, respectively) were mixed for 2 min at 20±1ºC, followed by 60s of mixing by hand. After this, the mix was poured into the Marshall moulds and compacted always by applying 50 blows on each flat face.	CMP %Par %Cem - N_{Blows} *e.g. CMP 4C0-50 means that 4% w/w of calcium-alginate particles were used, 0% w/w of cement was added and, 50 blows were applied to compact the mixture.*
Cold Mix Asphalt (CMA)	150 ml of water and aggregates were mixed for 1 min at 20±1ºC. Then, 7% or 17% w/w of bitumen emulsion (%E: 7, 17) and 0% or 1% of cement (%Cem: C0 and C1, respectively) were mixed for 3 min followed by 60s of mixing by hand. After, the mixes were poured into Marshall moulds and compacted always by applying 50 blows (N_{Blows}: 50) on each flat face of the specimens.	CMA %E %Cem - N_{Blows} *e.g. CMA 7C1-50 means that 7% of bitumen emulsion and 1% w/w of cement were used and, 50 blows were applied to compact the mixture.*

Table 2. Components of the calcium-alginate capsules and particles.

Binder type	Percent composition by mass (%)		
	Bitumen emulsion	Water	Calcium-alginate
Capsules (see Figure 3(a))	8	67	25
Particles (see Figure 3(b))	-	73	27

Table 3. Average water content in % w/w of the cold mix specimens measured at different curing time.

Mixture type	Curing time (days)						
	0	1	3	7	14	21	28
CMA 7C1-50	7.00	3.51	2.63	1.58	0.90	0.68	0.45
CMA 17C1-50	9.50	4.88	3.80	2.71	1.47	1.22	0.96
CMP 4C0-50	2.50	0.95	0.69	0.36	0.26	0.19	0.13
CMP 10C0-50	6.00	3.09	1.89	0.98	0.74	0.64	0.44
CMC 4C0-50	2.50	0.86	0.65	0.28	0.18	0.14	0.11
CMC 10C0-50	6.00	2.84	1.79	0.84	0.63	0.52	0.42
CMA 7C1-50	7.00	3.32	2.49	1.48	0.76	0.53	0.34
CMA 17C1-50	9.50	4.68	3.59	2.54	1.29	1.05	0.78
CMC 4C1-50	2.50	0.81	0.60	0.24	0.13	0.10	0.06
CMC 10C1-50	6.00	2.61	1.63	0.78	0.55	0.42	0.31

2. FIGURES

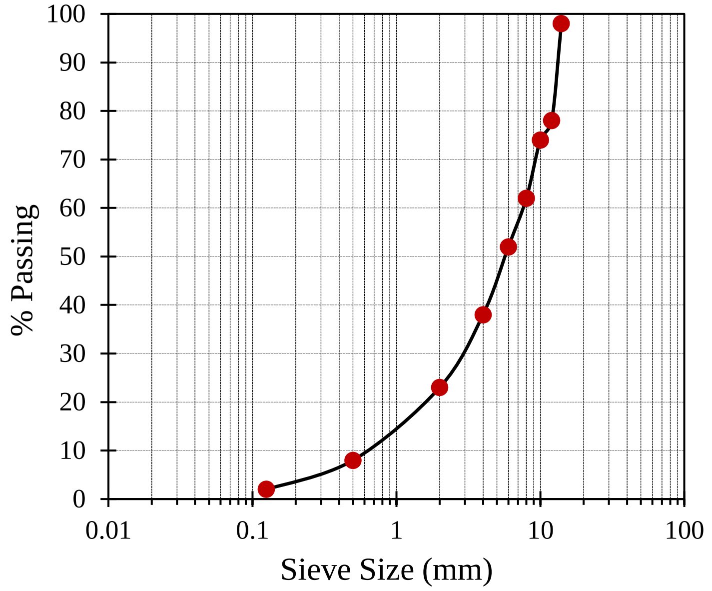

Figure 1. Aggregates gradation used in the mixtures studied.

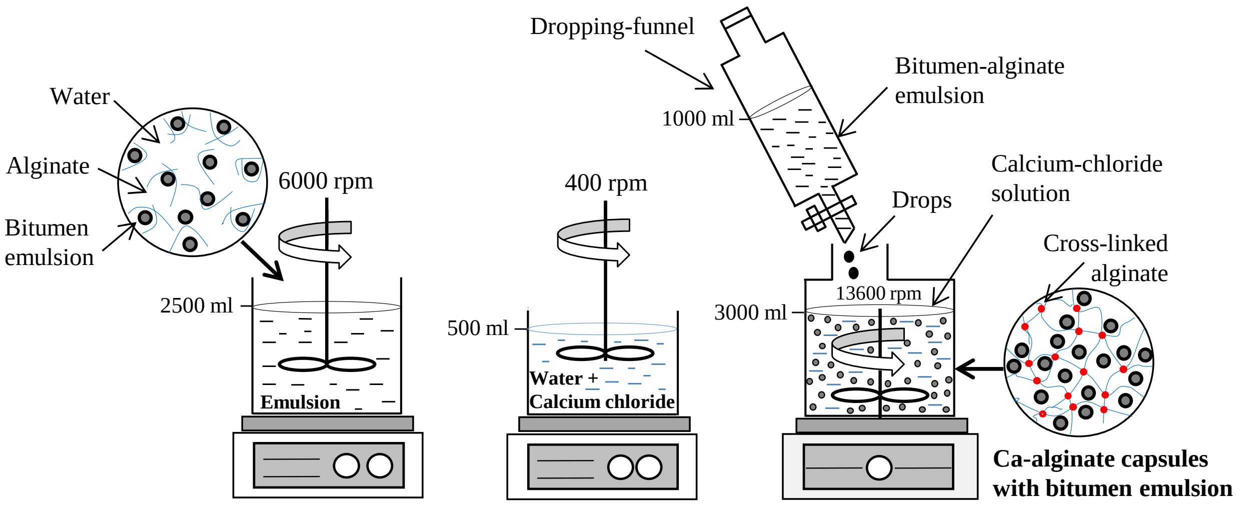

Figure 2. Schematic diagram of the preparation of Ca-alginate capsules containing bitumen emulsion. The procedure is also applicable to the manufacturing of the Ca-alginate particles without bitumen emulsion.

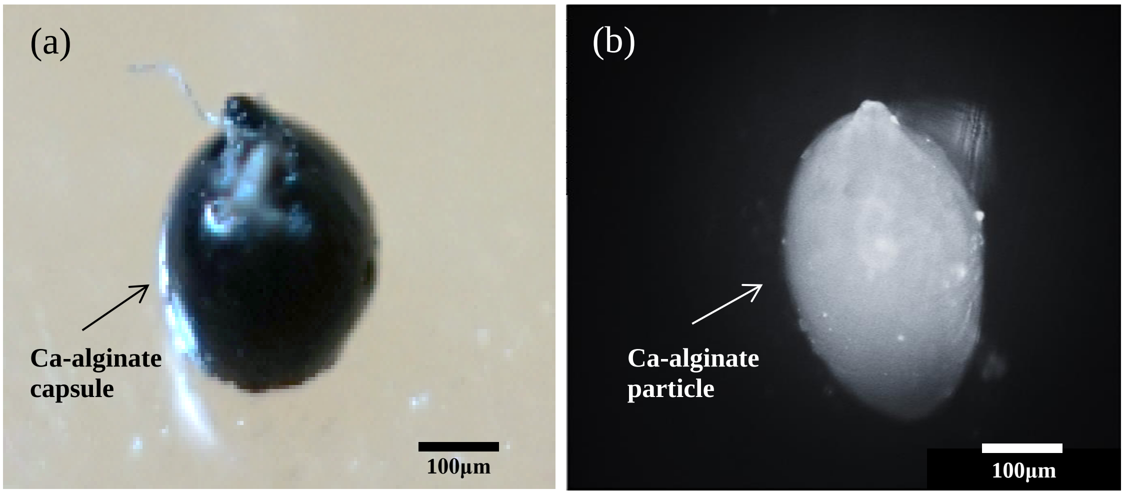

Figure 3. (a) Optical image of an individual Ca-alginate capsule containing bitumen emulsion. (b) Fluorescence image of an individual Ca-alginate particle without bitumen emulsion.

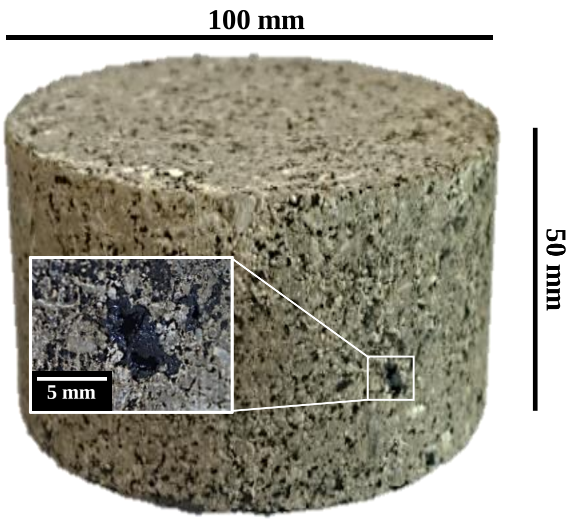

Figure 4. Test specimen of cold mix pavement made with Ca-alginate capsules with bitumen emulsion.

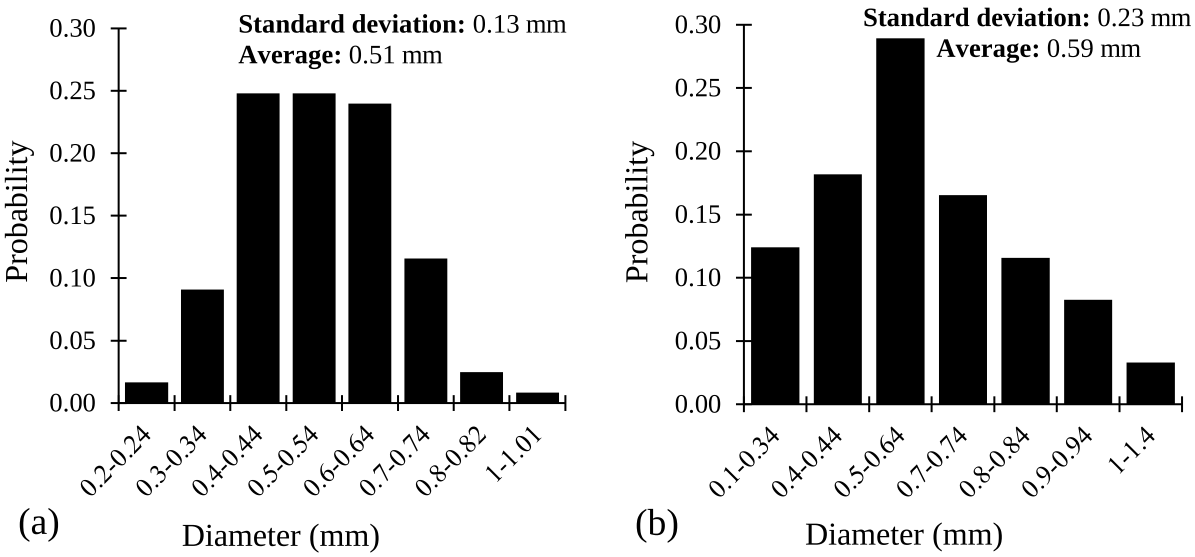

Figure 5. Sizes distribution of: (a) Ca-alginate capsules, see Figure 3(a), and (b) Ca-alginate particles, see Figure 3(b).

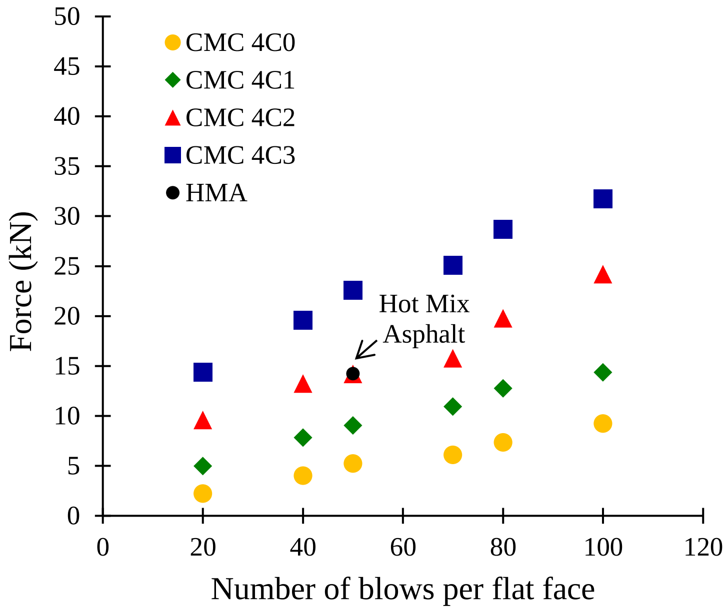

Figure 6. Variations in the Marshall force resisted by CMC test specimens, after 24h curing at 20ºC due to the effect of Marshall compaction configurations and Portland cement additions.

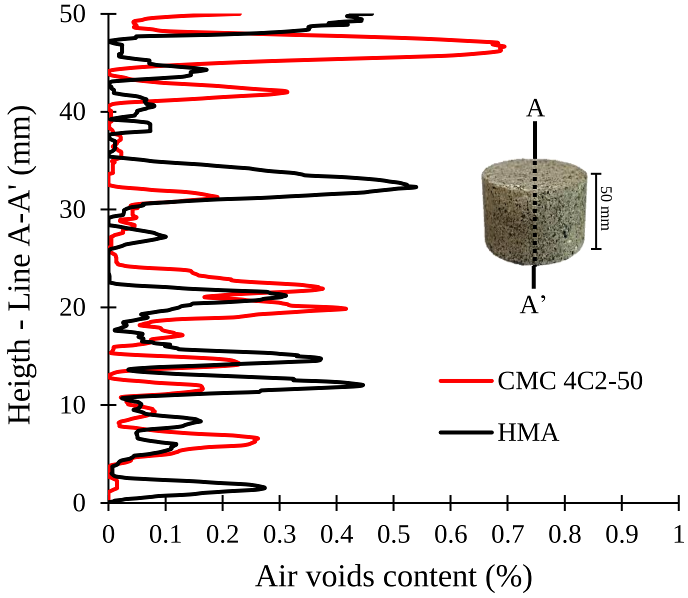

Figure 7. Average air voids distribution along the vertical axis of CMC 4C2-50 and HMA test samples.

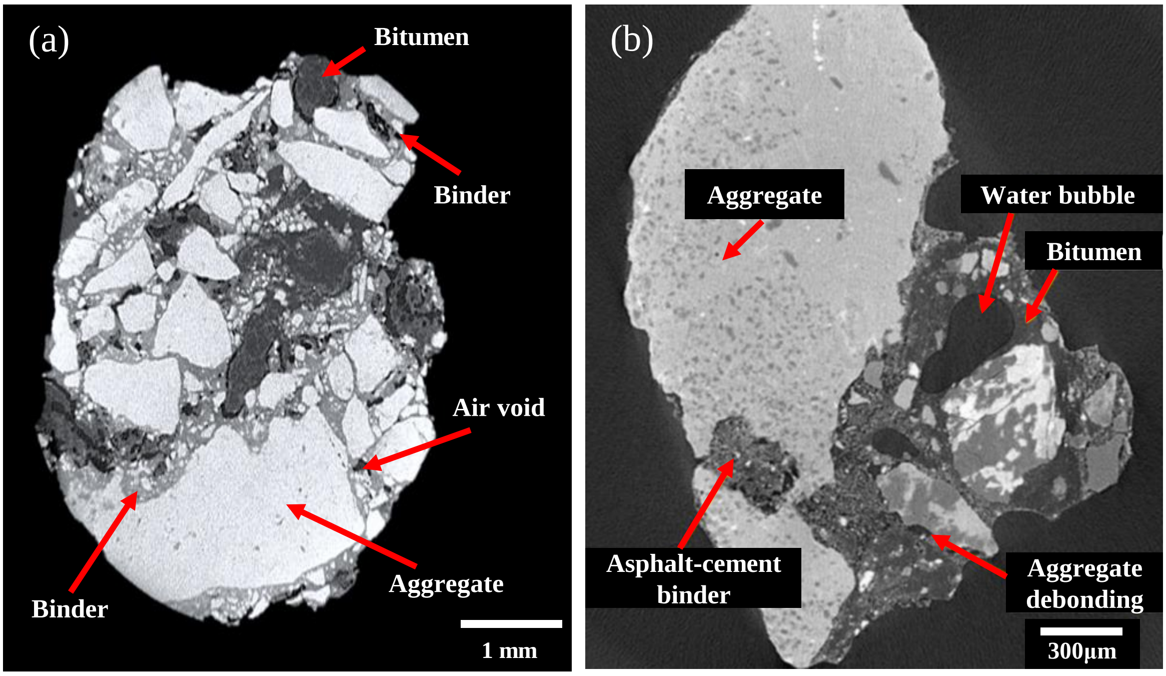

Figure 8. (a) CT-Scan detail of a cold mix pavement material sample CMC 4C2-50, cured during 28 days. (b) CT-Scan detail of a CMA, taken from a test sample, cured during 28 days, with 6% of cement (modified from Garcia et al. 2013).

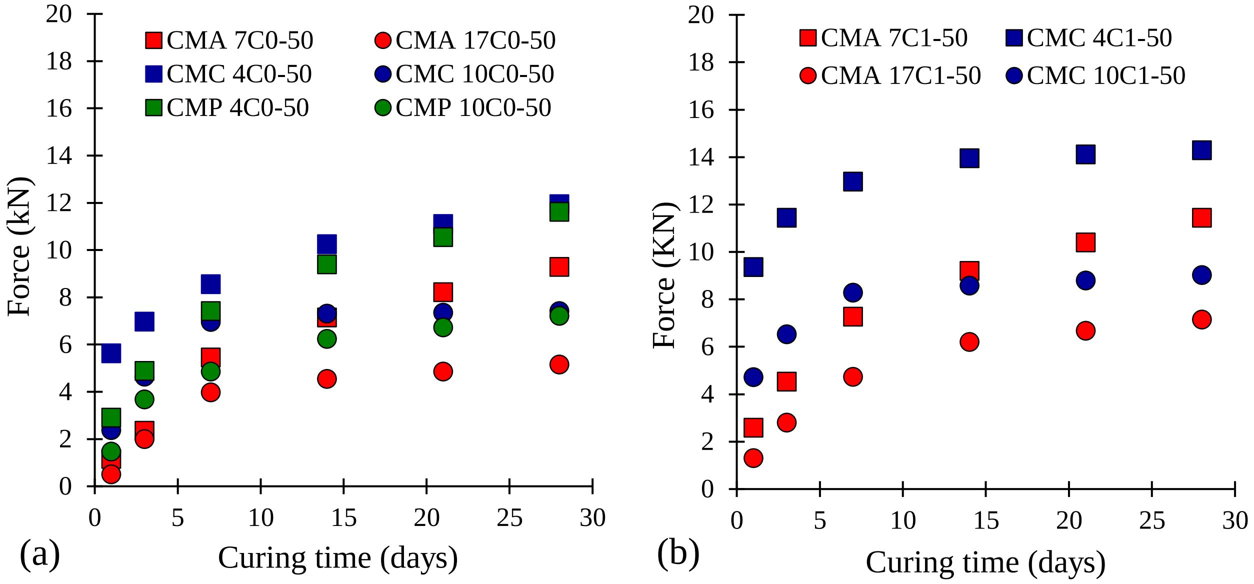

Figure 9. Average Marshall force registered at different curing times for (a) CMA, CMC and CMP without cement, and (b) CMA and CMC with 1% Portland cement.

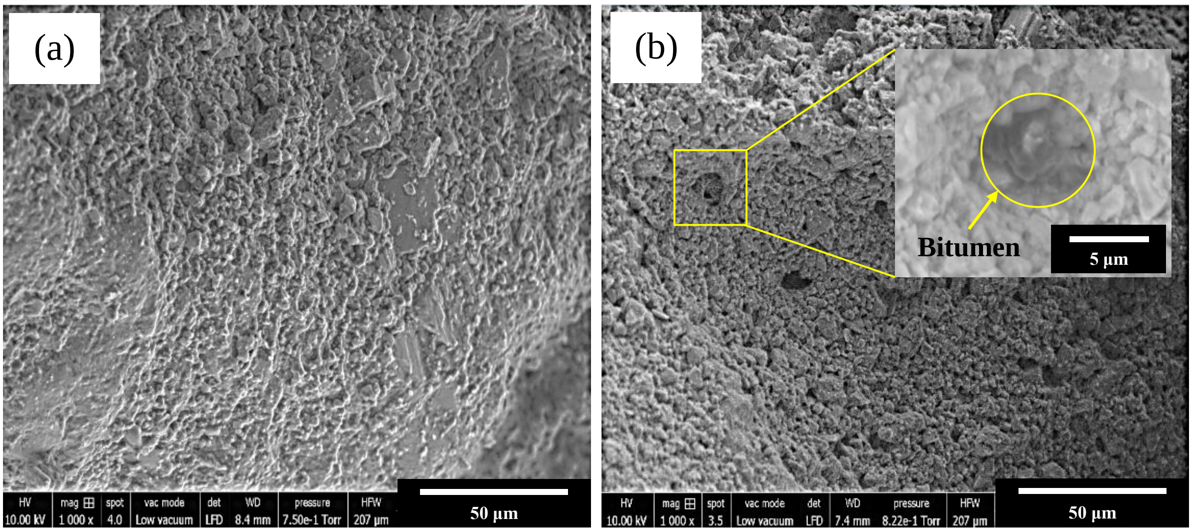

Figure 10. ESEM images of the binder's detail for mixes: (a) CMP 4C0-50 and, (b) CMC 4C1-50.