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CHARACTERIZATION OF MECHANICAL PROPERTIES AND SHRINKAGE BEHAVIOR OF COLD RECYCLED MATERIAL (CRM) STABILIZED WITH DIFFERENT ACTIVE FILLERS

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Abstract

Cold recycled material (CRM) is considered one of the most innovative and green road materials. CRM offers many advantages over the traditional Hot Asphalt Mix (HMA). However, due to the presence of water in its composition, cement is usually incorporated as a co-binder, but it could have a detrimental impact as it can contribute to increasing the drying shrinkage, which in turn can lead to brittle behavior when it is subjected to high strain load cycles. This research paper presents a study on the mechanical properties and shrinkage behavior of CRM stabilized with different active fillers. To address this issue, cylindrical and prism specimens of CRM mixtures and their mortar were prepared respectively. Indirect tensile strength (dry and wet) and water loss over time were conducted on mixture specimens while drying shrinkage measurements tests were performed on a mortar scale. Results show that CRM mix/mortar with ET filler exhibited superior drying shrinkage characteristics along with comparable mechanical properties compared with the cement stabilized mixture.

Keywords: cold recycled materials, drying shrinkage characteristics, active fillers

1 Introduction

The increased awareness of sustainability and environmental challenges in pavement construction has resulted in the development of green asphalt pavement technologies. CRM is one potential eco-friendly solution [1]. However, because of the hydraulic binder inclusion, CRM exhibits behavior that combines asphalt-like and concrete-like behaviors. The viscoelastic response of the CRM mixture is provided by the bituminous binder [2]. The hydraulic binder, such as cement, enhances mechanical properties, but it may also cause brittle behavior and inherited shrinkage properties [3]. In this context, finding a sustainable low CO_2 emission hydraulic binder, which can boost the strength development of CRM mixtures in the initial stages by the fact of binding more water than making rigid structures within materials matrix with fewer shrinkage strains is of great importance. This paper presents and analyses the effects of different hydraulic binders on the strength, water sensitivity, and drying shrinkage characteristics of CRM materials.

2 Materials and methods

2.1 Materials

The gradation of CRM mixtures and mortars consisting of RA aggregate, basalt sand, and limestone filler are shown in Figure 1. The aggregate gradation was established by 85 % RA 0/16, 10 % fine aggregate, and 5 % filler (by dry mass). The mortar aggregate was prepared by eliminating the coarse aggregate (retained on the 2 mm sieve).

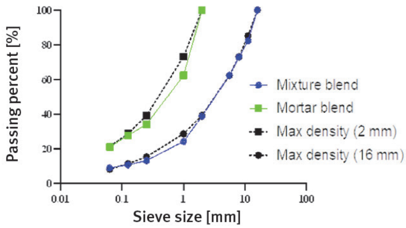

Figure 1 Gradation curves

A cationic slow-setting bitumen emulsion with a residual bitumen concentration of 60 % was used. Five active fillers were employed to ensure a better assessment of filler influences on the mechanical behavior and shrinkage of CRM mixes including Ordinary Portland Cement (CE), ladle slag (LD), silica fume (SF), Ettringite binder (ET: 70 % LD+30 % gypsum), and geopolymer (GE: 55 % LD+ 35 %Fly ash+ 10 % SF). The bitumen emulsion and filler content (by dry aggregate mass) was fixed to 5 % emulsion content and filler content of 3 % respectively. The five mixtures were named with the filler type (CE, ET, GE, LD, and SF) and the residual bitumen to filler mass ratio (B/C) was 1. To find the optimum water content, preliminary mixes were produced at different water contents including 2 %, 3 %, 4 %, and 5 %. Specimens were compacted with a vibratory hammer for 30 seconds each and then cured for 3 days at 50 °C and 90 %RH and then 3 days at 50 °C drying, then 1 day cooling in laboratory condition. This accelerating curing condition was followed to have a fully hydrated hydraulic binder and at the same time a dry specimen that can be evaluated. To find the optimum water content for each mix, first, a common air voids value for all mixtures was selected, and then the optimal water content for each mixture was chosen. The common air void values for all mixes are 18 % which gave water contents of 3.57 %, 4.13 %, 4.35 %, 2.45 %, and 4.18 % for CE, ET, LD, SF, and GE mixtures, respectively.

2.2 Specimen preparation

Twin-Shaft Pugmill mixer for mixture and planetary mixer for mortar was used. The mixing procedure followed in this study is as follows: mixing the dry aggregate for 1 min, then adding the external water and mixing for 1 min followed by adding filler and mixing for 1 min then finally adding bitumen emulsion and mixing for 2 min. After mixing, moulds with diameters of 150 mm with 50 mm were filled with mixture mix and compacted with a vibratory compactor, following the procedure detailed in [4]. The mortar specimens for shrinkage tests were statically compacted using 30x40x160 mm moulds. The compaction was done by applying a vertical force of up to 18 kN at a deformation rate of 20 mm/min. After reaching 18 kN, the force was kept constant for 3 min.

2.3 Testing methods

2.3.1 Tests on CRM mixture specimens

Since CRM is evolutive material, the indirect tensile test (ITS) was used to quantify the strength of the mixture specimens at different curing times (3, 7, 14, 28, and 90 days). ITS results over curing time can be reflected in the shrinkage behavior. The ITS was obtained following the EN 12697–23:

$$ITS = \frac{2F}{\pi DH} \tag{1}$$

where F, D, and H, are respectively, the maximum load, the specimen diameter, and specimen depth. ITS tests were conducted at 5 °C. The specimens were cured at 20 °C and 65 %RH at curing time 3, 7, 14, 28, and 90 days, specimens were conditioned for 4 h at the testing temperature before testing. The indirect tensile strength ratio (ITSR) was used to measure the strength reduction due to the water soaking of mixtures. Two sets of specimens were prepared for ITS testing dry and wet. The dry set specimens were tested after being cured at 20 °C and 65 %RH after 14 days of curing. While the wet set was tested after 3 days of immersion in water at 40 °C after a curing time of 14 days.

Besides, the water loss rate (ωt) of each specimen was measured by weighing the specimens at each curing time as it can be used as a useful approach to identify the mechanical performance of CRM materials, especially at an early age (within days). Water loss can be calculated as follow:

$$\omega_t = \frac{m_0 - m_t}{m_p} \cdot 100 \tag{2}$$

Where $\omega_{t,}$ $m_{0,}$ m_t and m_p are water loss rate at time t, %, measured mass of the specimen at time zero, g, the mass of specimen at time t, g, and dry mass of the specimen, g respectively.

2.3.2 Tests on CRM mortar specimens

The drying shrinkage test is non-destructive and intended to measure the drying shrinkage behavior of CRM mortar. Tests were carried out on 2 prism specimens with dimensions of 30 x 40 x 160 mm^3 cured at the same curing conditions of the ITS test and length measurement was taken using a horizontal length comparator with the aid of two steel studs connected to both sides of the specimen. Before taking any measurements, a metal reference bar was utilized to calibrate the micrometer. Changes in length and weight of all specimens were examined and recorded at 1, 3, 7, 14, 28, and 90 days following casting. Moisture loss rate, drying shrinkage strain, and coefficient were calculated by using Eqs. (1), (2) and (3) respectively:

$$\varepsilon_t = \frac{L_0 - L_t}{Lt} \tag{3}$$

$$\alpha_d = \frac{\varepsilon_t}{\omega_t} \tag{4}$$

Where $\varepsilon_{t,}$ $L_{0,}$ L_t, and α_d are drying shrinkage strain at time t, (mm/m), the mean value of initial readings on all faces, mm, the mean value of readings on all faces at time t, mm and the drying shrinkage coefficient at time t, 10^{-6} respectively.

3 Results

3.1 Indirect Tensile Strength - ITS

Figure 2a summarizes the development of ITS for all mixtures over time. It can be observed that the ITS values are markedly increased over time with a sharp increase at the initial curing stage. The ITS of all mixtures reached 50 % of long-term strength during the initial curing days and proceeded to gradually rise after 28 days, indicating the long-term impact of filler hydration and maybe also the hardening of bitumen. In general ET and CE, both have comparable strength over time and are higher than those with GE, LD, and SF. However, CE has a higher ITS value than that of ET at the 28 and onward (1.4 MPa at 90 days) while ET has the highest short-term curing strength; ITS was 0.75 MPa and 0.85 MPa, 3 and 7 days respectively. Compared to the mixture with CE, the ITS of SF, GE and LD mixtures were comparable and have lower ITS than CE.

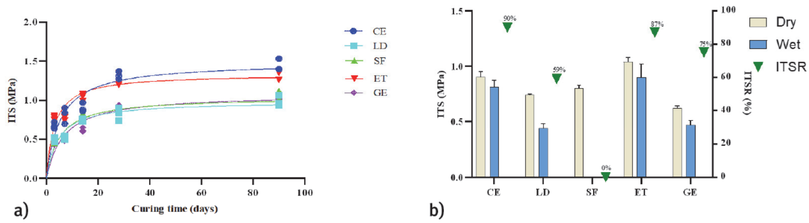

Figure 2 Development of ITS over curing time of CRM mixtures

3.2 Water damage

The water damage results for CRM mixtures with various fillers are illustrated in Figure 2b. It can be observed that the ITSR of CRM treated with CE, ET, GE, and LD are in the range from 60 % to 90 %. In contrast, the SF mix exhibited poor water resistance (zero ITSR). This could be due to the low reactivity of SF with of mix components as found in previous work [5] which results in a lack of cohesion. Besides, the ITSR values of CRM with CE and ET are comparable and higher than those for the rest. However, the CE mixture has a slightly higher ITSR which might be attributed to delayed hydration during water soaking. The LD and GE mixtures showed relatively low ITSR compared to the CE mixture. It can be concluded that incorporating ET had an acceptable improvement in the moisture damage resistance of CRM.

3.3 Drying shrinkage

The shrinkage cracking is a critical problem in the forming of cracks in the CRM as it limits its application in pavement construction. Accordingly, enhanced resistance to drying shrinkage is often related to the greater life expectancy of asphalt pavement when CRM is employed. Drying shrinkage is induced primarily by a reduction in the moisture content of the mixture as a result of multiple processes such as capillary tension, adsorption of water, and intermolecular interactions. Typically, CRM materials have higher moisture loss through hydration and externally through drying. To analyze the drying shrinkage properties of the CRM mixture, three indicators were utilized in this study: moisture loss rate, drying shrinkage strain, and drying shrinkage coefficient.

3.3.1 Water loss rate

The water loss in CRM is mainly derived from water evaporation and heat generation in the hydration process of filler. On the other hand, the hydration process also compensates for the water loss when the high reactive filler is added due to the formation of hydration products. Figures 3a and b show the water loss rate of both mixture and mortar specimens, respectively. The water loss rate decreased as a function of curing time regardless of the filler type. The water in the specimens evaporates quickly throughout the first 7 days of the test, notably during the first three days. After 7 days, the pace of decrease in water loss was reduced. This implies that the majority of the water loss happened within the first seven days. The loss of water in specimens clearly slowed from 7 to 28 days. After 28 days, the moisture loss rate is almost steady. During curing, moisture evaporation in mortar specimens was quicker than in the mixture. This is governed by different factors including the length of the moisture migration paths, curing conditions, surface area, and the pore water in voids next to the surface. It can be seen that the SF mortar, despite having the lowest water content, has the highest moisture loss. The reason behind that is the SF filler has poor reactivity (low pH) therefore most of the water went out during the drying process. Furthermore, the LD and GE fillers showed comparable water loss trends and higher water loss compared to CE and ET mortars. CE and ET have the lowest total water loss about 25 % and 28 % at 90 days respectively.

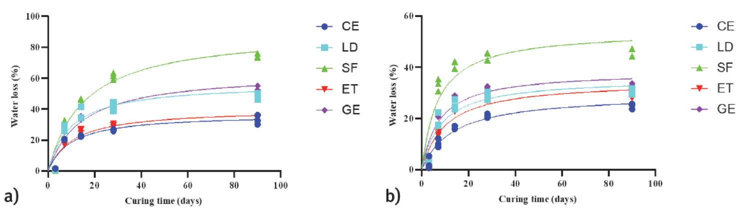

Figure 3 Evolution of water loss for: a) Mixtures; b) Mortars

3.3.2 Dry shrinkage strain

Figure 4a depicts the evolution of drying shrinkage strain for five different mortars over a 90-day period. Except for the ET, which showed no perceptible volume change, the drying shrinkage values all increased over time. It can be noticed from Figure 4a that the drying shrinkage of rest started substantial at the early ages (3 days after casting) and then flattened at 14 days, then being stable for the onward which is similar to the water loss rate. This is due to the fact that the dry shrinkage strain is proportional to the rate of water loss. The rate of water loss shortens the space between interior particles, increasing the dry shrinkage strain. In this scenario, the SF mortar has the highest total shrinkage, and it is far from the other four mortars.

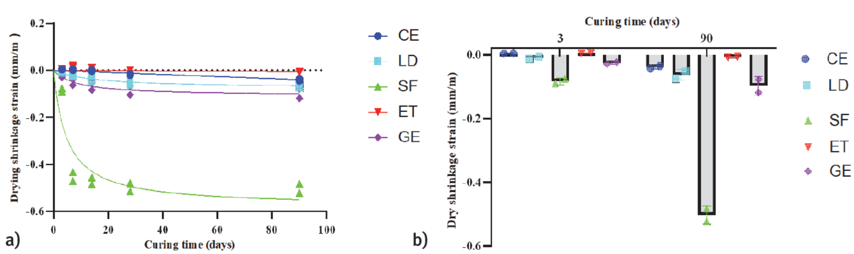

Figure 4 Dry shrinkage strain: a) over curing time; b) at 3 and 90 days

This is due to the shrinkage stress being higher than the provided internal stress which can be clearly detected from Figure 2b as it has extremely poor water resistance. Similar findings were reported in the literature [6]. LD and GE both have increased drying shrinkage strain when they are compared with the CE mortar as a reference but there is no dramatic difference among them as their main hydration products are to some extent similar. Besides, the CE specimen, when compared with ET mortar, has significant shrinkage strain which is almost 4 times higher than ET at 90 days with the lowest water loss as was discussed previously and stated in [7]. On the contrary, ET showed the smallest shrinkage which is -0.007 mm/m after 90 days but a mass change that is comparable to that of CE. The total shrinkage strains after 3 and 90 days are illustrated in Figure 4b.

3.3.3 Dry shrinkage coefficient

The drying shrinkage coefficient is attributed to the difference in the strain as a function of water loss, revealing the mixture's sensitivity to moisture change. The lesser the drying shrinkage coefficient (absolute value) of CRM, the less sensitive it is to water change, implying that the CRM is more resistant to cracks caused by drying shrinkage. The reason for this is that the coefficient is influenced by changes in dry shrinkage strain and water loss rate. When the water loss rate values are stable, the shrinkage coefficient values stabilize as well. In Figure 5a, there are two distinct different trends. The first starts low and then increases with time while the second trend is mirrored around the X-axis. Both trends have a sharp change at the initial curing days and then with time flatten to a stable rate. The CE and ET mortars have initially low shrinkage coefficients and then increased with time following the first trend while SF, LD, and GE have high shrinkage coefficients and then decrease with time following the second pattern. The drying shrinkage coefficient of all mortars is shown in Figure 5b at 3 and 90 days. When incorporating ET filler, the mortar's sensitivity to moisture changes is reduced, in that way enhancing the anti-dry shrinkage ability.

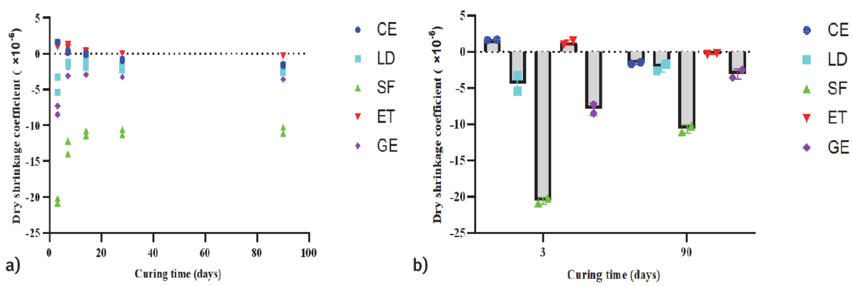

Figure 5 Dry shrinkage coefficient: a) over curing time; b) at 3 and 90 days

3.4 Relation between shrinkage characteristics and mechanical properties

In general, losing water by evaporation causes a drying shrinkage by internal stress driven by shrinkage which has a consequence on the ITS behavior of CRM. Taking SF as an example, SF showed a higher water loss led to higher drying shrinkage which is reflected in the ITS value as well as poor ITSR. In this case, the unreacted water (which was necessary for compaction) is subjected to the drying process during the curing process and was evaporated while trying to find an easy path to be out leading to reduced bonding in the mixture skeleton resulting in low adhesion response. On the other hand, ET filler provides the CRM with shrinkage compensation as a result of ettringite formation at the initial curing time and gaining the strength, and eventually, there were not many changes in its structure later on which reduces self-desiccation shrinkage by minimizing the tensile strains that arise in the capillary space. This performance of the ET might be related to its adequate nucleation and the growth rate of ettringite resulting from the interaction between gypsum and ladle slag, both of which include the primary components for making ettringite binder, namely SO_3, CaO, and Al_2O_3. This result is in agreement with the indirect tensile strength at an early age (see Figure 2a) [8]. Thus, adding ET will not increase the strength in the long term as much as cement does but will efficiently enhance the shrinkage resistance of the road base [9].

4 Conclusions

This study adopts indirect tensile strength (ITS) over time, water damage resistance (ITSR), and shrinkage characteristics to study the influence of five active fillers on the behavior of CRM. Based on the test results the following conclusions can be drawn:

- The results of the ITS test showed that CE allows increasing the indirect tensile of CRM in the long-term with a higher drying shrinkage that makes it sensitive to cracking.
- The ET mortar exhibited superior shrinkage characteristics and resulted in a mixture with a fast early mechanical property within the first curing days, allowing for timely next layer construction.
- The addition of SF to CRM leads to the highest mass loss, larger ultimate drying shrinkage magnitude, low ITS, and very poor water sensitivity.
- LD and GE allow for general low strength and higher shrinkage compared with CE.
- The result of the ITS test is correlated with water loss rate and shrinkage strain.

As a final conclusion, adding ET can mitigate drying shrinkage cracking as it can compensate for the shrinkage action. Thus, ET can be employed to limit the road base cracking resulting from dry shrinkage to some extent. Besides, since the intended aims of utilizing the CRM are to provide an environmentally friendly material as well as a cost-effective product, by-product fillers such as ET are a better option to economically improve the CRM mix performance. Therefore. It is suggested to regulate by-product fillers to reduce the dry shrinkage of CRM.

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