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# CHARACTERIZATION OF STABILISED SEWAGE SLUDGE FOR REUSE IN ROAD PAVEMENT

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Abstract

In recent years, the disposal of sewage sludge has been a major concern worldwide because of their potential treat in relation with the contamination of ground water and food chain. Furthermore, their poor mechanical properties don't allow a possible direct use in civil engineering applications. For these reasons, it was important to explore more opportunity to reuse this by-product of sewage treatment. In this frame, the solidification-stabilisation technique (S-S) which is based on hydraulic binders can improve the properties of sewage sludge so that it can be used in civil engineering application, especially in road pavements. In this context, this paper investigates the possibility of using the solidified sludge in road construction. To achieve this goal, an experimental protocol was conducted using a several combined binders: combination of Cement/Limestone filler and Cement/Lime, with different amounts in the target to fix the optimal mixtures amount. Several tests were conducted to characterise the mechanical and geotechnical properties of the solidified sludge. The results indicate that the solidified sludge using a combined mixture of cement and lime allows a possible use as base and sub-base layer.

Keywords: sewage sludge, hydraulic binders, road pavements, geotechnical properties

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## 1. INTRODUCTION

Wastewater treatment plants generate by-products called sludge, these residues contain in their composition organic pollutants, pathogenic microorganisms, heavy metals, and organic xenobiotics [1,2]. The toxicity of sludge is considered high for the human life and the environment, it can affect the survival development and reproduction of plants [3]. If the sludge is dumped without appropriate treatment, it can contaminate soil, water and can present a danger threat to human health and environment [4]. The Global world production of sewage sludge has been estimated at 1.3 billion tons per year, and by the year 2050, this quantity is expected to reach 2.2 billion tons [5]. To eliminate these wastes, environmentally friendly treatment methods have been used to absorb the increasing quantities of sludge produced by wastewater treatment plants [6]. In this context, among the most used treatment methods there are landfilling, agriculture and Solidification/Stabilisation (S-S), which was the subject of this study.

The S-S technique attracted a lot of attention in recent years, and it was considered as an effective solution to be apply [7, 8]. Moreover, this technique allows reducing the toxicity and the use of these residues instead of their disposal [8-10]. The S-S technique uses binders and additives such as cement, fly ash, lime to transform sewage sludge into construction materials that can be used in road construction [11]. Numerous studies have been focused this method in the field of civil engineering. Lim et al. [7] studied the stabilization of sludge using combinations of lime, fly ash and sludge loess. They observed that the unconfined compressive strength meets the standards for construction materials. Kim et al [12] used the solidified sludge treated with slag and quicklime as a landfill cover used the solidified sludge treated with slag and quicklime as a landfill cover. Chen et al [11] studied the stabilisation of sewage sludge and municipal solid waste with various binders including Portland cement, Lime, Gypsum and a combination of some of these binders. They concluded that S-S technique increased the strength of the sewage sludge and reduced the leachability of toxicity. Lucena et al. [1] focused on the application of the S-S technique using lime, cement, and bitumen as additives. They obtained acceptable results for their reuse in road construction; this method represents an interesting alternative to reduce the environmental impact resulting from these wastes. Fan et al. [13] studied the geotechnical properties of sewage sludge solidified with Sulfo-Aluminated cement, the results show that the strength and hydraulic conductivity of the stabilised sludge was close to that of the high organic soil. They deduced that the stabilised sludge does not meet the requirements for landfilling but can be used as a building material.

In addition, several studies have shown that cement is the most used binder in stabilisation or in sealing works, and often leads to insufficient results due to the high-water content, the presence of organic matter and heavy metals. For this reason, cement is usually supplemented with additives to improve the treatment results [14, 15].

To our knowledge, few research studies on the stabilisation of raw sludge by combined binders. Therefore, the aim of this paper is to evaluate the effect of combined binders (Cement/Lime and Cement/Limestone Filler) with different amounts on the intrinsic characteristics of the sewage sludge. The target is to find an optimal binder association in order to assess their use as a road construction material.

## 2. MATERIALS

The used sewage sludge was obtained from a wastewater treatment plant of Constantine district (Algeria). The method of water treatment includes: 1) pre-treatment; 2) a biological treatment by activated sludge; and 3) a physical treatment or a secondary decantation. The collected sludge has a black colour and disagreeable smell due to the presence of organic matter. The samples were obtained manually in plastic bags to avoid water loss during transport, in order to measure the natural water content of the sludge. The samples were collected directly from the drying beds. The sludge sampling and conservation were carried out according to ISO 5667-13 and ISO 5667- 15, respectively [16 ,17].

The cement used is CEM I /A42.5N type, with a density of 3.2 g/cm3 and Blaine specific surface area of 3500 g/cm2, it meets with the European standard EN 197-1 [18]. The chemical composition of cement is presented in Table 2.

The lime (CaO) used in this study, has a density of 2 g/cm3 and Blaine specific surface area of 5000 g/cm2, it conforms to the (NF EN 459) standard [19].

The limestone filler has a density of 2.6 g/cm3 and Blaine specific surface area of 3460 cm2/g, the $CaCO_3$ content is 98%, and it conforms to the NFP 18-508 specifications for construction uses [20].

The physical and chemical properties of all materials are presented in Tables 1, and 2.

Table 1. Physical characteristics of Sewage Sludge

| **Chemical properties** | Values |
|---|---|
| Manganese | 0.013 mg/l |
| Copper | 0.039 mg/l |
| Iron | 0.021 mg/l |
| Zinc | 0.089 mg/l |
| Nickel | 0.012 mg/l |
| Cadmium | 0.048 mg/l |
| Chrome | 0.158 mg/l |
| Plomb | 0.122 mg/l |
| Gypsum | 41.50 % |
| **Physical properties** | |
| Moisture content | 66.76% |
| Liquidity limit | 66.44% |
| Plasticity limit | 50.37% |
| Plasticity index | 16.07% |
| Density | 1.71($t/m^2$) |
| Value of Blue | 1.01 |

Table 2. Chemical composition of the cement, sludge, and lime

| | $SiO_2$ | $Al_2O_3$ | $Fe_2O_3$ | CaO | MgO | $SO_3$ | $K_2O$ | $Na_2O$ | Mno | $P_2O_5$ | $TiO_2$ | Cl | $CaCO_3$ |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Cement | 21.64 | 3.98 | 4.66 | 62.59 | 1.62 | 2.36 | 0.56 | 0.18 | | | | 0.016 | |
| Sludge | 31.1 | 9.42 | 7.48 | 39.6 | 2.27 | 2.66 | 1.44 | 0.3 | 0.16 | 4.37 | 0.76 | | |
| Lime | < 2.5 | <1.5 | < 2 | >83.3 | <0.5 | <2.5 | | <4,7 | | | | | <10 |

## 3. EXPERIMENTAL PROGRAM

An experimental program was carried out on the sewage sludge treated with the combined Cement/Lime and Cement/Limestone filler binders, in order to identify the effect of the binders on the geotechnical and mechanical characteristics of the sludge, and the optimal mixtures of the solidified sludge. For each combination, three specimens were made for each test period (14, 28 days). The combination of binders and their designations are presented in the Table 3.

A series of tests were carried out on the different mixtures: 1) Atterberg limit in accordance with the NF P 94-051 standard [21] to determine the liquidity limit, plasticity limit and plasticity index; 2) the Proctor study to determine the dried density and the optimal water content according to the NF P 94-093 standard [22], the sludge has been dried, then it is mixed with the different combinations; 3) Compression and indirect tensile tests, they were carried out on cylindrical specimens 10x20 cm in accordance with NF P 98-232-1 [23] and NF P 98-232-3

[24], they were prepared at the optimal water content and tested at 14 and 28 days of cure. The immediate bearing is carried out in accordance with the standard NF P 94-078 [25]. This test is recommended to determine the capacity of an elaborated material, to support the circulation of the machines in the building site.

Table 3. Mixing Design

| Combination 1 | Designation | Combination 2 | Designation |
|---|---|---|---|
| 2%C +2%L | 2C2L | 2%C +2%LS | 2C2LS |
| 4%C +2%L | 4C2L | 4%C +2%LS | 4C2LS |
| 6%C +2%L | 6C2L | 6%C +2%LS | 6C2LS |
| 2%C +4%L | 2C4L | 2%C +2%LS | 2C4LS |
| 2%C +6%L | 2C6L | 2%C +2%LS | 2C6LS |

C: Cement, L: Lime, LS: Limestone filler the numbers in the designation represent the percentage of the total.

# 4. RESULTS AND DISCUSSION

## 4. 1. Atterberg Limits

The Atterberg limit values of sewage sludge stabilised by combined binders (cement/lime and cement/limestone filler) were presented in Figure 1.

The results show that, increasing the amount of combination binders leads to an increase in the plasticity limit (PL) in both cases. On the other hand, the limit of liquidity (LL) increases in the case of cement/limestone filler and decreases significantly in the case of cement/lime. As a result, the decrease in the plasticity index (PI) is evident. The decrease in the plasticity index can be explained by the hydration of the added binders, which causes the flocculation of the slurry particles and leads to an improvement in their compactness, which results in an increase in the plasticity limit accompanied by a slight increase in the liquidity limit. Several research works attribute changes in the technical properties of soil or sediment mixed with cement, lime and limestone filler to cation exchange, particle flocculation, agglomeration and pozzolanic reactions [32]. Therefore, it can be deduced that the effect of the binders in stabilising the sludge is greater. A rapid formation of physical bonding between the particles causes an increase in Atterberg limits and a decrease in their plasticity.

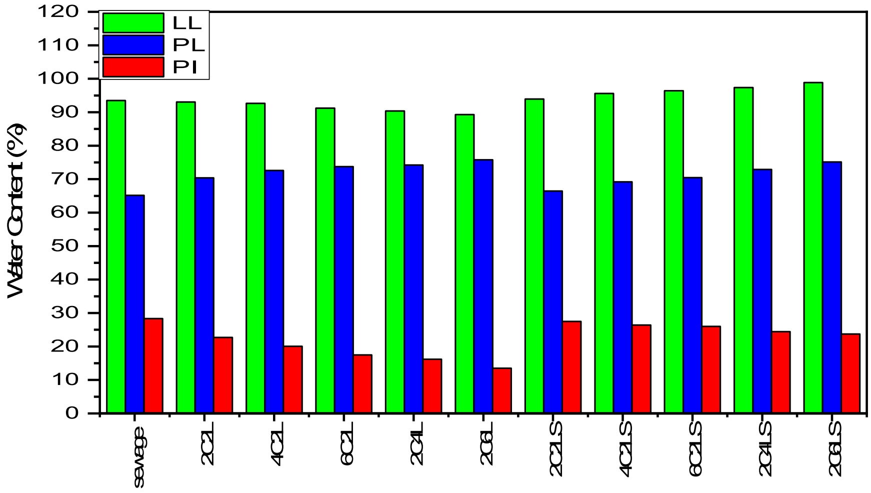

Fig. 1. The Atterberg limit results for all mixtures

## 4.2 Proctor Compaction test

The compaction curves for different mixtures of the sewage sludge stabilised by the binders are shown in Figures 2 (cement/lime) and Figure 3 (cement/limestone filler), and the variation of the maximum dry density and optimum water content of the different mixtures are presented in Figure 4.

The results show that the optimal dry density decreases with the addition of the binders but is not significant in the case of high cement content. For the optimal water content, it is increased especially in the case of lime and limestone filler. For example, the dry density decreases from 1.47 t/m3 to 1.36 t/m3 in the case of cement/lime and the water content increases from 13.95% to 21.78%. The same observations in the case of cement/limestone filler. The increase in the optimum water content is caused by the increase in the specific surface area of the particles in the mixture compared to the reference sludge due to the addition of fine materials. Moreover, the higher density in mixtures with high cement amount compared to lime and limestone filler may be due to the optimal water content required for the hydration of these binders which is less important in cement [26, 28, 29]. Previous research has attributed the change in maximum dry soil density to both the grain size distribution and the specific densities of grains and stabilisers [30].

In terms of increasing the optimum water content, the binders help to increase the specific surface area of the particles in the mixture compared to the reference sludge by adding fine materials. Indeed, these binders contribute to the enlargement of flocculated particles and their coefficient of friction thus penalising the rearrangement of the grains during compaction, resulting in a decrease in the optimal dry density, these observations confirm the results of Al Amoudi et al. [31] on soil stabilization by cement and lime and the research of Wang et al. [32] on sediment stabilization by cement and lime.

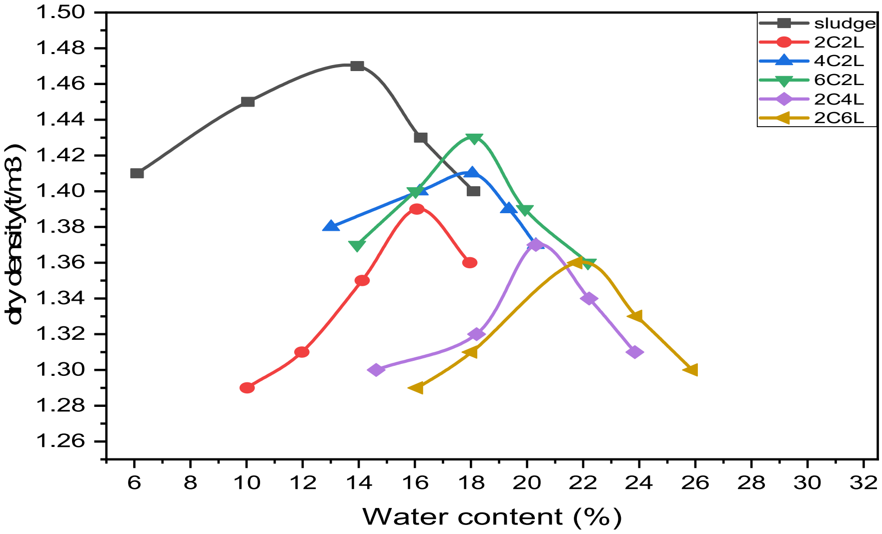

Fig. 2. Variation of dry density with moisture content, the case of cement/lime

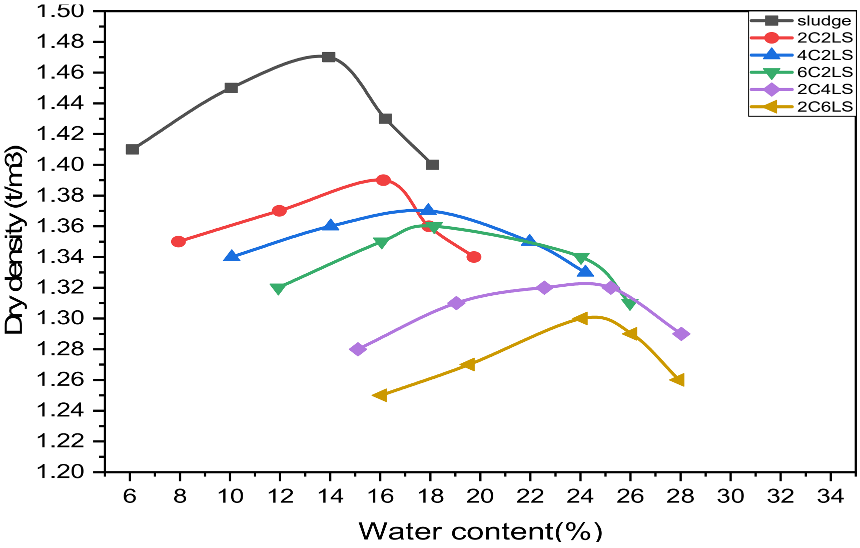

Fig. 3. Variation of dry density with moisture, the case of cement/limestone filler

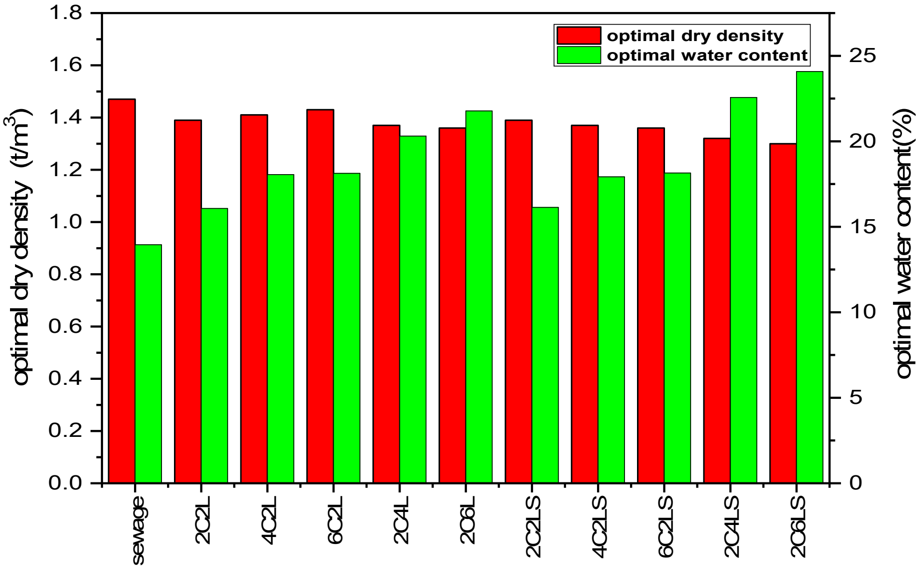

Fig. 4. Variation of the maximum dry density and optimum water content

## 4.3 Mechanical properties

Figure 5 outlines the variation of the unconfined compressive strength of the studied mixes as a function of the hardening time. The results indicate that the compressive strength increases continuously over time due to the continuation of the pozzolanic reaction [13]. The results show the effect of the combination of cement and lime which gives the best outcomes. In addition, the results show that the compressive strength increases with the cement amount; they represent 30 % for 4C2L and 55 % for 6C2L. In the case of rising the amount of Lime the results show that the optimal amount is 4 %, rising this amount to 6% leads to a decrease of 11 % of the strength at 28 days. In addition, these results show the effect of varying the rate of the combined cement/limestone filler binders. The results indicate that the compressive strength is not linked to the content of the two binders, but the highest strengths were always recorded in the case of high cement dosages compared to those of the limestone filler. Additionally, the results shown that the compressive strength at 28 days increased by 32.51% for 4C2LS, 46.45% for 6C2LS, and 21.02% for 2C4LS except for the 2C6LS mix which decreased by 21.75% compared to the 2C2LS mix.

The development of compressive strength is mainly attributed to the formation of an amount of C-S-H gel. The C-S-H gel with cementations properties could not only fill the void space, but also effectively bind the sludge particles, which is consistent with previous research on sludge stabilisation with hydraulic binders [1, 11, and 26]. On the other hand, the addition of lime and 6% limestone filler with cement slightly decreases the compressive strength, which explains the disadvantageous role of these high-dosage binders in inhibiting the hydration reaction and the formation of hydrated calcium silicates, which is confirmed by other research studies such as Farooq et al. [27], these authors observed that the compressive strength was increased by adding lime until the content reached 4% and then decreased for higher proportions. The difference in compressive strength between the sludge stabilising binders, which is lower in the case of cement/limestone filler than in the other case of cement/limestone, may be due to the different chemical reaction mechanisms between the sludge and these stabilising binders.

Figure 6 displays the evolution of tensile strength for the two studied mixtures cement/lime and cement/limestone filler at 14 and 28 days of curing. According to the results, the tensile strength increases with time and their scaling with binder dosage are similar to the results of compressive strength. In the case of cement/lime, the tensile strength increases by 12.95% for 4C2L, 25.32% for 6C2L, 5.73% for 2C4L and decreases to 13.5% for 2C6L and in the case of cement/limestone filler, the tensile strength increases to 8.19% for 4C2LS, 22.36% for 6C2LS, 4.36% for 2C4LS and decreases to 19.02% for 2C6LS compared to 2C2LS.

The increasing trend of compressive and tensile strength with the amount of binder is observed, although the gain in tensile strength is not significant when compared with the gains in compressive strength. The comparison between the results recorded shows that the strengths of the second mix (cement/limestone filler) are lower than those of the first mix (cement/lime), revealing that cement and lime were potential stabilisers for improving the strength of the solidified sludge.

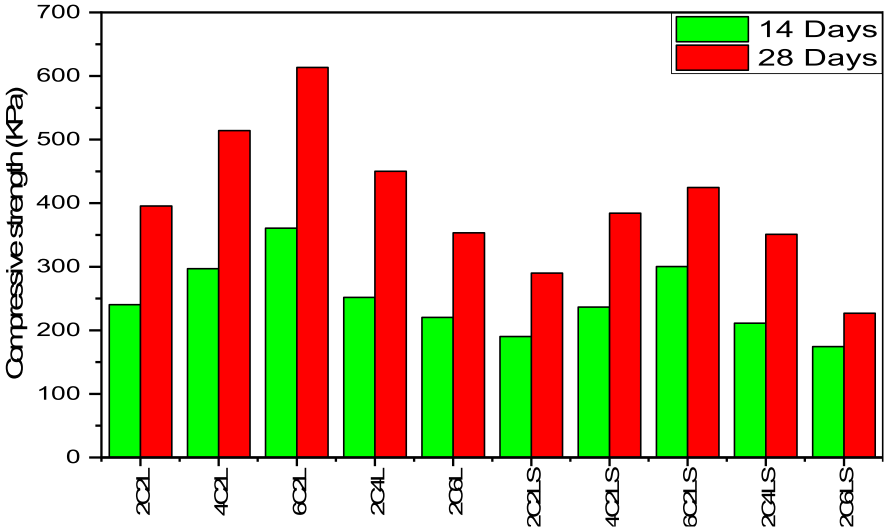

Fig. 5. Compressive strength of the studied mixtures

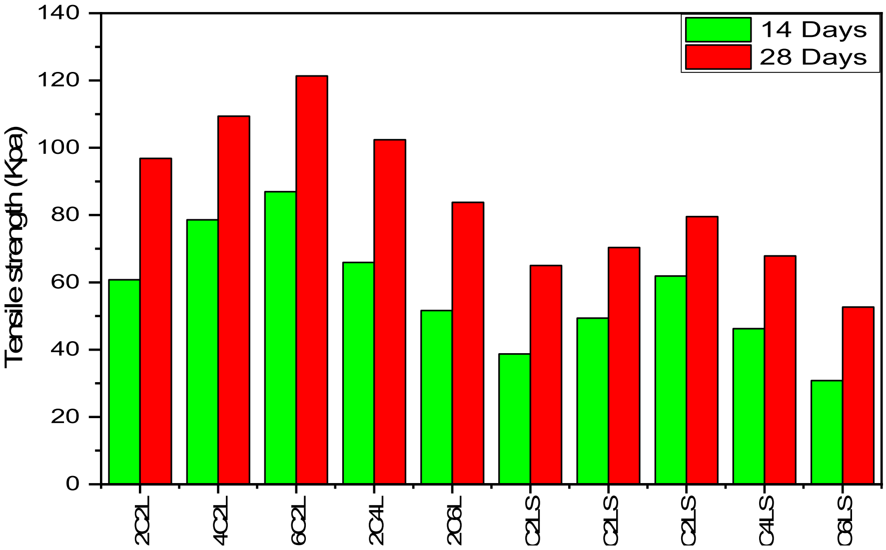

Fig. 6. Tensile strength of the studied mixtures

## 4.4 Immediate bearing index (IBI)

The immediate bearing index (IBI) measured on all the mixtures studied is shown in Figures 7 and 8. The comparison of the variation the IBI index and the optimum water content of different mixtures is presented in Figure 9.

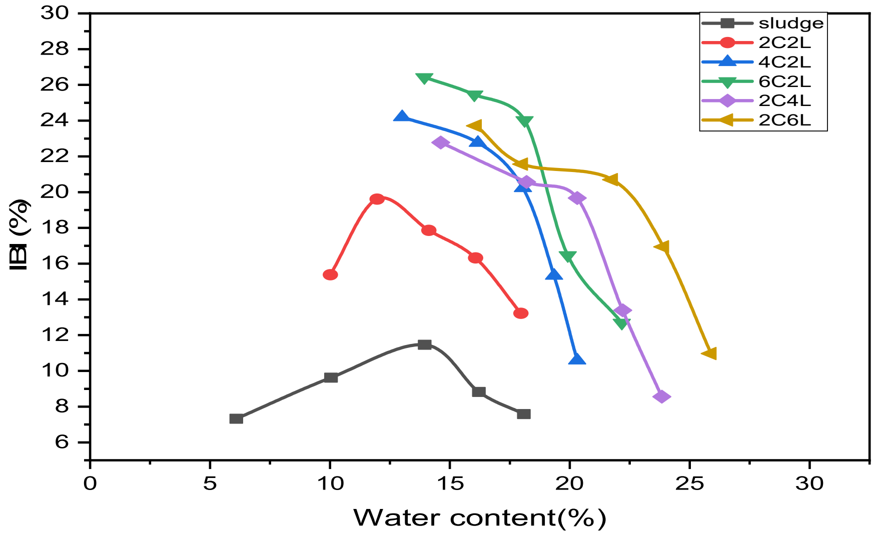

Fig. 7. Immediate bearing index (case of cement/lime)

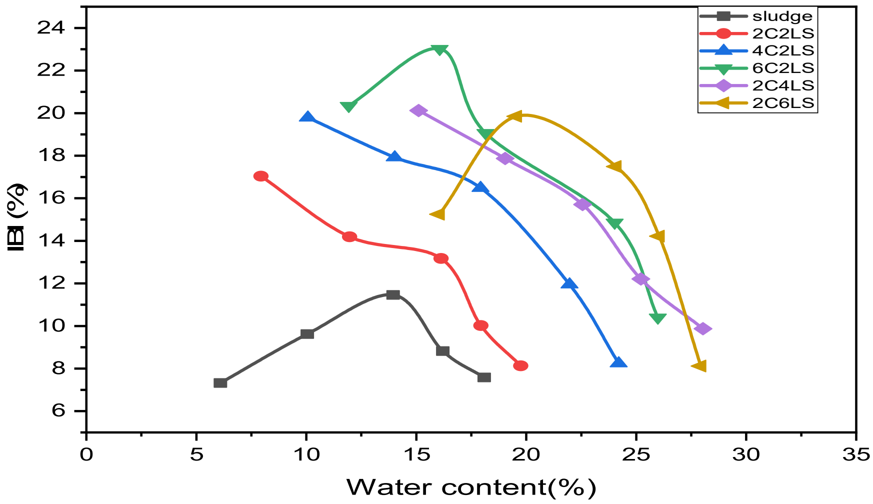

Fig. 8. Immediate bearing index (case of cement/limestone filler)

The results show that all the values vary between 16.32% and 24.02% in the case of cement/limestone. For cement/limestone filler samples, the values vary between 13.17% and 19.07%. In the case of mixtures 4C2L, 6C2L and 2C6L the values reach the minimum value set by the GTS [36] for reuse in the pavement shape layer, which is equal to 20. In addition, the results show that the improvement in the bearing capacity of the treated sludge (increase in IBI) is related to the reduction in the volume of voids in the particles of the constituted mixture which could be due to their right distribution.

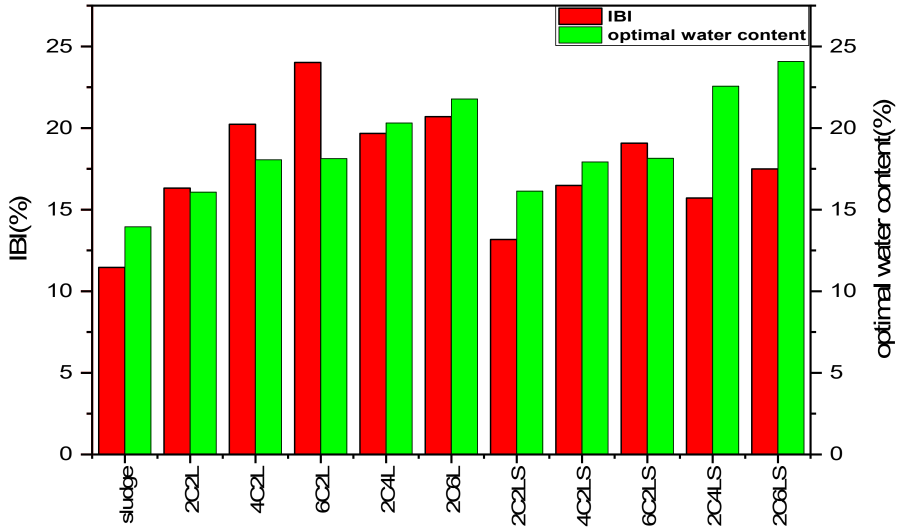

Fig. 9. Variation of IBI index and the optimum water content of different mixtures.

## 4.5 Macroscopic monitoring

The evaluation of crack conditions due to the presence of expansive minerals in soils is considered as a key parameter in road construction, for this reason the assessment of this factor through macroscopic monitoring is essential [34,35,37]. For this reason, figures 10 and 11 show the typical crack evolution of different mixes studied at 7 and 28 days of hardening for cement/lime and cement/limestone filler. It is noticed that in the first days of hardening the solidified sewage sludge separated from the cutting ring due to drying shrinkage and small cracks also appeared at the edge of the samples. The sludge sample shrunk further after 7 days of drying, and cracks extended from the edge to the centre, although this was not very evident in the case of cement/limestone filler mixtures. Contrary to cement/limestone filler mixtures, which were more significant, and many cracks appeared with greater widths and depths.

This macroscopic observation confirms the low mechanical properties in the high amounts of lime and filler and the less important role of limestone filler in this study (Figure 12).

Fig. 10. Macroscopic monitoring of samples stabilised by cement/lime

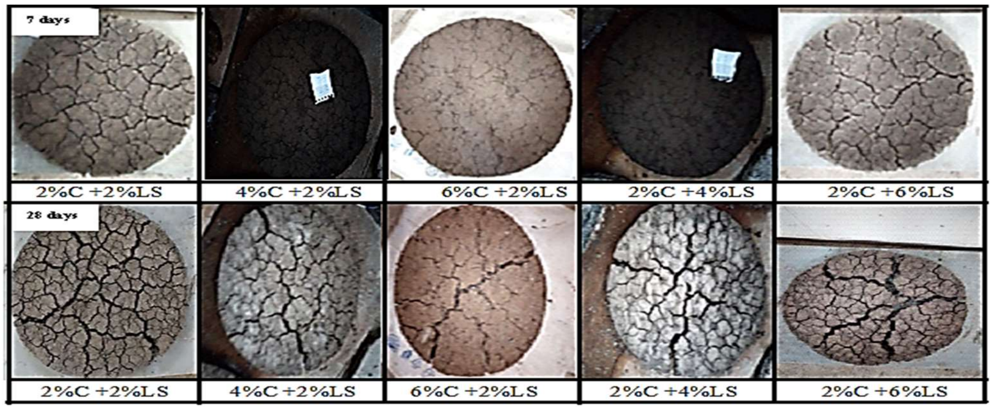

Fig. 11. Macroscopic monitoring of samples stabilised by cement/limestone filler

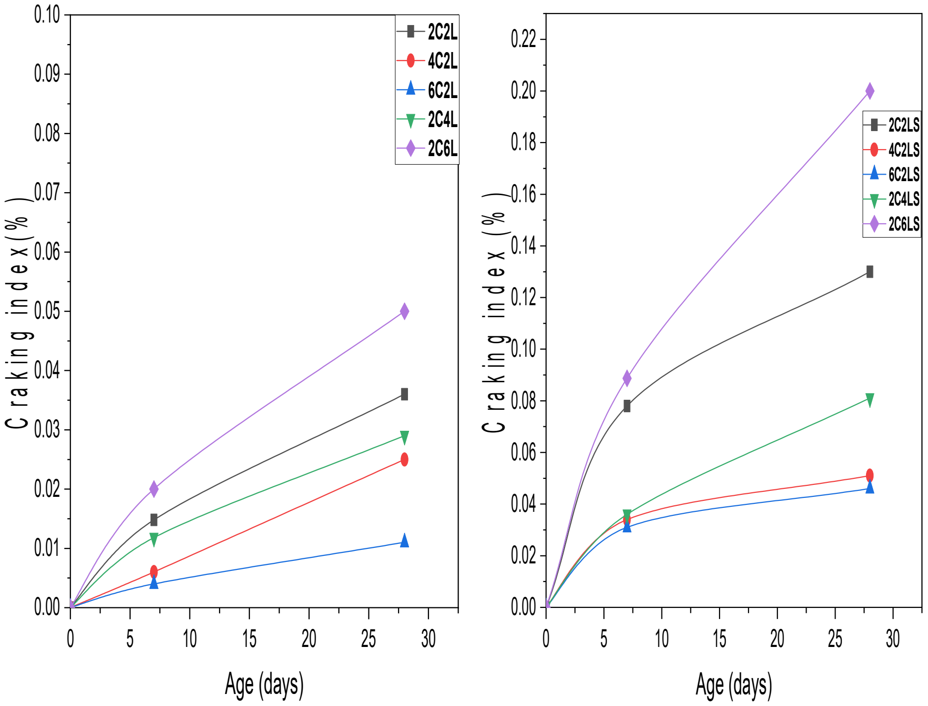

Fig. 12. Evolution of cracking of the studied mixtures

## 5. CONCLUSION

Based on the above experimental results, the following conclusions can be pointed out:

- The incorporation of combined cement/lime and cement/limestone filler binders into the raw sludge results in a decrease in the dried density and an increase in the water content. This change is considered an indication of the improved mechanical characteristics of the sludge stabilized with these binders.
- The results of the Atterberg limit test of Sewage Sludge treated with cement/lime and cement/limestone filler show a decrease in the plasticity index which gives a better workability to the stabilized sludge allowing a longer from the period of on-site work to the wet seasons.
- The value of the immediate bearing index shows us that the mixtures 4C2L, 6C2L and 2C6L reach the minimum value set by the GTS for reuse in the pavement shape layer
- The mechanical properties of the sludge stabilized by the combined binders (cement/lime and cement/limestone filler) increase with the hardening time

and the cement dosage. The opposite is true for high dosage of lime and limestone filler, which could not be improved considerably. The mechanical performance of the sludge solidified by the cement/lime combination is much higher than that of the cement/limestone filler.

- Cracks have been observed with the naked eye in the samples have high amounts of limestone filler and lime combined with cement which confirms the mechanical behaviour of these binders to stabilize the sewage sludge.
- Macroscopic observation also shows cracks of great depth for the sludge stabilized by the cement/limestone filler combination. This shows the negative effect of limestone filler during hydration process.

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