Study of the impact of sediments on the mechanical behavior of concrete and towards the penetration of carbon dioxide

Estudo do impacto dos sedimentos no comportamento mecânico do concreto e na penetração do dióxido de carbono

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ABSTRACT  
Dam reservoirs are exposed to a loss of water storage capacity due to the phenomenon of siltation. This particularity can be expressed by the siltation of reservoirs and the entrainment of particles transported by watercourses. Siltation of reservoirs is a critical state which causes a reduction in the storage capacity of dams. Algeria is characterized by a semi-arid climate, which annually loses a considerable volume of water storage. The carbonation of concrete is influenced by a number of parameters which accelerate its kinetics. These parameters are the porosity of the concrete, the quantity of lime contained in the cement, the concentration of CO₂ in the atmosphere and the humidity of the environment. It should be noted that, water being the vector for moving aggressive agents, carbon dioxide can only diffuse through the concrete if the latter is not completely saturated and not perfectly dry at the same time. Another factor increasing the permeability of concrete is the amount of limestone added to the cement during its manufacture at the factory. This
permeability allows the diffusion of CO₂ or other aggressive agents in the concrete. The addition of limestone to cement must therefore be used with caution. The objective is to propose economically competitive and easy-to-implement formulations which allow the valorization of these materials in the making of ordinary concrete by partial substitution of cement (10, 20 and 30%) and its influence on the progress of long-term carbonation after six years of curing in the open air. The sediment is treated by calcination at 750°C to make it active. Natural carbonation tests were carried out on the study concretes in order to evaluate their durability. The results obtained confirmed the possibility of producing concretes incorporating calcined sludge at dosages of up to 30% without compromising the quality of these concretes from the point of view of behavior in the face of attacks by the dissolution of carbon dioxide from the air in the interstitial solution of concrete, meeting economic, ecological and technological objectives.

**Keywords:** calcined sediment, calcination, eco-concrete, sustainability, natural carbonation.

**RESUMO**

Os reservatórios das barragens estão expostos à perda de capacidade de armazenamento de água devido ao fenômeno de assoreamento. Essa particularidade pode ser expressa pelo assoreamento dos reservatórios e pelo arrastamento de partículas transportadas pelos cursos d’água. O assoreamento dos reservatórios é um estado crítico que provoca redução na capacidade de armazenamento das barragens. A Argélia é caracterizada por um clima semiárido, que perde anualmente um volume considerável de armazenamento de água. A carbonatação do concreto é influenciada por uma série de parâmetros que aceleram sua cinética. Esses parâmetros são a porosidade do concreto, a quantidade de calcário contida no cimento, a concentração de CO₂ na atmosfera e a umidade do ambiente. Deve-se notar que, sendo a água o vetor de movimentação dos agentes agressivos, o dióxido de carbono só pode difundir-se através do concreto se este não estiver completamente saturado e ao mesmo tempo perfeitamente seco. Outro fator que aumenta a permeabilidade do concreto é a quantidade de calcário adicionado ao cimento durante sua fabricação na fábrica. Esta permeabilidade permite a difusão de CO₂ ou outros agentes agressivos no concreto. A adição de calcário ao cimento deve, portanto, ser utilizada com cautela. O objetivo é propor formulações economicamente competitivas e de fácil implementação que permitam a valorização destes materiais na confecção de concretos comuns por substituição parcial do cimento (10, 20 e 30%) e sua influência no progresso do concreto a longo prazo. carbonatação após seis anos de cura ao ar livre. O sedimento é tratado por calcinação a 750°C para torná-lo ativo. Foram realizados testes de carbonatação natural nos concretos estudados para avaliar sua durabilidade. Os resultados obtidos confirmaram a possibilidade de produzir concretos incorporando lama calcinada em dosagens de até 30% sem comprometer a qualidade desses concretos do ponto de vista do comportamento diante de ataques pela dissolução do dióxido de carbono do ar no intersticial. solução de concreto, atendendo objetivos econômicos, ecológicos e tecnológicos.

**Palavras-chave:** sedimento calcinado, calcinação, ecoconcreto, sustentabilidade, carbonatação natural.
1 INTRODUCTION

Dam reservoirs are exposed to a loss of water storage capacity due to the phenomenon of siltation. This particularity can be expressed by the siltation of reservoirs and the entrainment of particles transported by watercourses. Siltation of reservoirs is a critical state which causes a reduction in the storage capacity of dams. [1] It is the natural consequence of the degradation of watersheds. Algeria is characterized by a semi-arid climate, which annually loses a volume of water storage. [3] However, the quantities of sediment removed by dredging operations and placed downstream of the structure can lead to pollution of rural areas in the long term. [6]

For the sake of environmental protection and in the spirit of sustainable development, it is imperative to find a solution to the problem of massive sediment storage. [27,28]

Our work is based on a study of the valorization of these sediments which are found in considerable quantities (that of the Chorfa dam located in western Algeria, commonly called sediment. These materials (after calcination to make them active) find their use in several fields including that of civil engineering as full-fledged components (partly substitutable addition to cement) of cementitious materials. [14] The development of construction materials is a current problem where researchers are trying to find materials suitable for each region and which are less expensive in the country. [56] The treatment of sediment is the set of processes used to improve their physical and mechanical properties. [53] This treatment can be done in two different ways: either by stabilizing the silt by adding other products which improve certain properties, or by decontamination. [22] In all cases the objective of the treatment is the recovery of the silt. [51]

The partial substitution of portland cement with one or more mineral additions, when available at competitive prices, can be advantageous not only from an economic, ecological and rheological point of view but also from a mechanical point of view. [41]

The use of calcined sediment in concrete as a substitute for cement has various advantages, the main ones of which relate to the fact that cement is the most expensive component of concrete, that its production requires a large
consumption of energy and that the Producing one ton of cement releases approximately one ton of carbon dioxide into the atmosphere. [20] [38]

Calcined sediment like metakaolin is considered a reactive pozzolan. [47, 48] The lime released during the hydration of the clinker compounds reacts with the pozzolanic material in the mixture to form products which contribute to the mechanical strength of the concrete. [17] [43] The use of calcined sediment as a partial replacement for cement in concrete has been widely studied in recent years. The literature clearly shows that sediment is an active pozzolan and contributes to improving the early and long-term mechanical properties of cement/concrete paste. [52] [59] During this study, natural carbonation was measured respectively on concrete samples. [7] [9]

The concretes were produced with percentages of calcined sediment of 10, 20 and 30% substituted for cement. [61] [36]. The objective of this article is to explore and evaluate the potential of using calcined sediment from the Chorfa dam in western Algeria as a partial substitute for Portland cement in concrete. By investigating the mechanical properties and environmental benefits of incorporating varying percentages (10%, 20%, and 30%) of calcined sediment into cementitious materials, this study aims to contribute to sustainable construction practices. The research seeks to address the challenges of sediment management in dam reservoirs while proposing an innovative solution that reduces cement production’s ecological footprint and enhances the economic and mechanical properties of concrete.

2 MATERIALS USED

2.1 CEMENT

The cement used is CEMI 42.5 R Portland cement with a Blaine specific surface area equal to 3220 cm²/g from the Zahana cement plant (west Algeria), according to the Algerian Standard NA442. [46]

The chemical compositions of cement and mineralogical compositions of clinker are given in Tables 1 and 2.

<table>
<thead>
<tr>
<th>Elements</th>
<th>SiO₂</th>
<th>Al₂O₃</th>
<th>Fe₂O₃</th>
<th>CaO</th>
<th>MgO</th>
<th>SO₃</th>
<th>K₂O</th>
<th>Na₂O</th>
<th>PF</th>
<th>RI</th>
</tr>
</thead>
<tbody>
<tr>
<td>Content (%)</td>
<td>22.30</td>
<td>5.10</td>
<td>3.99</td>
<td>63.60</td>
<td>1.43</td>
<td>1.24</td>
<td>0.70</td>
<td>0.34</td>
<td>1.18</td>
<td>0.36</td>
</tr>
</tbody>
</table>

Source: Authors.
### Table 2: Mineralogical composition of clinker [%].

<table>
<thead>
<tr>
<th>Elements</th>
<th>C₃S</th>
<th>C₂S</th>
<th>C₃A</th>
<th>C₄AF</th>
<th>CaO Free</th>
</tr>
</thead>
<tbody>
<tr>
<td>Content (%)</td>
<td>53.13</td>
<td>23.55</td>
<td>6.76</td>
<td>12.13</td>
<td>&lt; 0.1</td>
</tr>
</tbody>
</table>

Source: Authors.

#### 2.1.1 Granulometry

The particle size analysis makes it possible to determine the size and the respective weight percentages of the different families of grains constituting the sample.

The test consists of classifying the different grains that constitute the sample using a Mastersizer 2000 laser particle size analyzer.

The Mastersizer 2000 (Figure 1) is a laser particle size analyzer measuring particle size over a range of 0.02µm to 2 mm.

This technique, adapted to very fine powders, uses the principle of diffraction and diffusion of a laser beam. [45]

![Figure 1: Mastersizer 2000 particle size analysis device (LAFARGE).](image)

Source: Authors.

The result of the particle size analysis of a sample of the cement used is shown in Figure 2. [45]
2.1.2 Densities

2.1.2.1 Apparent Density

The apparent density of the cement was determined according to standard NF 18-555, by weighing a one-liter container, filled with cement without any settlement.

Absolute density: The absolute density of the cement was determined according to standard NF P 18-555, by the Le Chatelier pycnometer and benzene.

2.1.2.2 Specific Surface

The specific surface area (surface area of solid in contact with the external environment per unit mass) and expressed in cm²/g, was determined using the Blaine BSA1 apparatus (Figure 3), according to standard NF EN 196 -6.
The different physical characteristics of cement are presented in Table 3.

Table 3: Summary table of the physical characteristics of the cement used.

<table>
<thead>
<tr>
<th>Characteristics</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Apparent density of cement (g/cm³)</td>
<td>1.1</td>
</tr>
<tr>
<td>Absolute density of cement (g/cm³)</td>
<td>3.03</td>
</tr>
<tr>
<td>Fineness according to Blaine's method (cm²/g)</td>
<td>3220</td>
</tr>
</tbody>
</table>

Source: Authors.

2.2 CALCINED SEDIMENT

The entire quantity of silt used is taken from the discharge zone downstream of the Chorfa dam, with Blaine specific surface areas equal to 6446 cm²/g. [11]

We proceeded with the treatment of the silt according to the following steps: (Safer et al., 2021). [5]

- after drying in an oven at 105°C, the vases were crushed and sieved dry. The sieves which pass through 80μm and which represent more than 95% of the sample are recovered for cooking. [18];
- the calcination operations required certain precautions: to avoid thermal shock the cooking speed was set at 5° per minute, the calcination temperature 750° C was kept constant for 5 hours. [57] [29];
- the product thus obtained (calcined sediment) was kept away from air and humidity. [42] [64] Figure 4 represents the appearance of the mud before and after calcination.

Figure 4: Appearance of the calcined sediment before and after calcination.
The chemical characteristics of the silt are grouped in Tables 4a and 4b.

Table 4a: Chemical composition of the sediment before calcination.

<table>
<thead>
<tr>
<th>Elements</th>
<th>Contents (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Silica SiO₂</td>
<td>36.95</td>
</tr>
<tr>
<td>Alumina Al₂O₃</td>
<td>10.94</td>
</tr>
<tr>
<td>Iron oxide Fe₂O₃</td>
<td>4.6</td>
</tr>
<tr>
<td>Lime CaO</td>
<td>16.37</td>
</tr>
<tr>
<td>Magnesia MgO</td>
<td>2.13</td>
</tr>
<tr>
<td>Sulfates SO₃</td>
<td>0.17</td>
</tr>
<tr>
<td>Potassium oxide K₂O</td>
<td>1.69</td>
</tr>
<tr>
<td>Sodium oxide Na₂O</td>
<td>0.21</td>
</tr>
</tbody>
</table>

Source: Authors.

Table 4b: Chemical composition of the sediment after calcination.

<table>
<thead>
<tr>
<th>Elements</th>
<th>Contents (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Silica SiO₂</td>
<td>45.72</td>
</tr>
<tr>
<td>Alumina Al₂O₃</td>
<td>13.54</td>
</tr>
<tr>
<td>Iron oxide Fe₂O₃</td>
<td>5.69</td>
</tr>
<tr>
<td>Lime CaO</td>
<td>20.25</td>
</tr>
<tr>
<td>Magnesia MgO</td>
<td>2.64</td>
</tr>
<tr>
<td>Sulfates SO₃</td>
<td>0.22</td>
</tr>
<tr>
<td>Potassium oxide K₂O</td>
<td>2.09</td>
</tr>
<tr>
<td>Sodium oxide Na₂O</td>
<td>0.26</td>
</tr>
</tbody>
</table>

Source: Authors.

2.2.1 Granulometry

The particle size analysis of a sample of the mud used is given in Figure 5.
2.2.2 Densities and Specific Surface Area

They are represented in Table 5.

Table 5: Summary table of the physical characteristics of the calcined sediment.

<table>
<thead>
<tr>
<th>Characteristics</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Apparent density of calcined sediment (g/cm³)</td>
<td>0.49</td>
</tr>
<tr>
<td>Absolute density of calcined sediment (g/cm³)</td>
<td>2.65</td>
</tr>
<tr>
<td>Fineness according to Blaine’s method (cm²/g)</td>
<td>6446</td>
</tr>
</tbody>
</table>

Source: Authors.

Figures 6a and 6b represent the XRD and EDS analysis carried out on calcined sediment.

Figure 6 a: XRD analysis of the calcined sediment.

![XRD analysis of the calcined sediment.](image)

(b) EDS analysis of the calcined sediment.

![EDS analysis of the calcined sediment.](image)

Source: Authors.

Chemical and mineralogical analyzes of the calcined sediment studied revealed the presence of essential minerals making up common hydraulic binders such as silica and alumina. [32] [53]
It would be enough to thermally activate the clay minerals so that they react with water if the limestone content is sufficient, to form compounds which set and harden at ordinary temperature. [37] [15]

2.3 AGGREGATES

The gravels used in the making of class 3/8 and 8/15 concrete are limestone and come from the Oran quarry. While the 0/3 sands are of limestone and siliceous origin for the 0/1 sea sand from the Mostaganem region. [16] [44]

The use of two sands with percentages of 60% quarry sand and 40% sea sand is necessary for the mixture so that it can fit into the standardized spindle. [35]

Figure 7 represents the aggregates used to make our concrete. [19] [60]

<table>
<thead>
<tr>
<th>Designation</th>
<th>Sea sand</th>
<th>Quarry sand</th>
<th>Gravel (3/8)</th>
<th>Gravel (8/15)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Appearance</td>
<td><img src="" alt="Image" /></td>
<td><img src="" alt="Image" /></td>
<td><img src="" alt="Image" /></td>
<td><img src="" alt="Image" /></td>
</tr>
</tbody>
</table>

Source: Authors.

The chemical and physical analyzes of the sea sand from Mostaganem and the aggregates from Oran are given in Tables 6 and 7.

<table>
<thead>
<tr>
<th>Constituents</th>
<th>Sea sand (%)</th>
<th>QS, G3/8, G8/15 (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Silica SiO₂</td>
<td>88.78</td>
<td>2.06</td>
</tr>
<tr>
<td>Lime CaO</td>
<td>9.80</td>
<td>54.58</td>
</tr>
<tr>
<td>Magnesia MgO</td>
<td>0.42</td>
<td>0.14</td>
</tr>
<tr>
<td>Alumina Al₂O₃</td>
<td>1.37</td>
<td>-</td>
</tr>
<tr>
<td>Iron oxide Fe₂O₃</td>
<td>0.94</td>
<td>0.13</td>
</tr>
<tr>
<td>Sulfates SO₃</td>
<td>0.03</td>
<td>-</td>
</tr>
<tr>
<td>Nature</td>
<td>Siliceous</td>
<td>Limestone</td>
</tr>
</tbody>
</table>

Source: Authors.
Table 7: Summary table of the physical characteristics of the aggregates used.

<table>
<thead>
<tr>
<th>Characteristics</th>
<th>Sea sand (SS)</th>
<th>Quarry sand (QS)</th>
<th>Gravel (3/8)</th>
<th>Gravel (8/15)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Apparent volumetric mass (g/cm³)</td>
<td>1.50</td>
<td>1.52</td>
<td>1.42</td>
<td>1.41</td>
</tr>
<tr>
<td>Absolute density (g/cm³)</td>
<td>2.64</td>
<td>2.65</td>
<td>2.59</td>
<td>2.63</td>
</tr>
<tr>
<td>Sand equivalent (%)</td>
<td>Visual</td>
<td>95.89</td>
<td>93.55</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>Piston</td>
<td>94.03</td>
<td>89.26</td>
<td>-</td>
</tr>
<tr>
<td>Fineness module</td>
<td>1.39</td>
<td>3.2</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Percentage of fines (%)</td>
<td>0.30</td>
<td>1.06</td>
<td>0.41</td>
<td>0.33</td>
</tr>
<tr>
<td>Absorption (%)</td>
<td>1.12</td>
<td>0.81</td>
<td>0.58</td>
<td>0.61</td>
</tr>
</tbody>
</table>

Source: Authors.

The particle size curves of the aggregates are given in Figure 8.

Figure 8: Grain size curves of the different aggregates used.

2.4 THE ADJUVANT

The adjuvant used to make our concrete is PLASTIMENT® BV 40 (SIKA); Plasticizer/Water Reducer for high mechanical resistance in order to have concretes with the same consistency (plastic) while keeping the same W/L ratio.

PLASTIMENT® BV 40 is an energetic water-reducing plasticizer which:

- the compactness of concrete, thus leading to an improvement in mechanical resistance and impermeability;
- facilitates the placement of concrete;
- possibly allows the cement dosage to be reduced;
allows you to obtain a more or less significant start-of-setting delay by increasing the normal dosage of high-performance concrete used, both in the fresh state and in the hardened state.

The characteristics of the adjuvant used are given in Table 8:

<table>
<thead>
<tr>
<th>Characteristics</th>
<th>PLASTIMENT® BV 40.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Colors</td>
<td>Dark brown</td>
</tr>
<tr>
<td>Density</td>
<td>1.180 ± 0.015</td>
</tr>
<tr>
<td>PH</td>
<td>4.5 ± 1</td>
</tr>
<tr>
<td>Extract</td>
<td>38.5 ± 1.9 %</td>
</tr>
<tr>
<td>Cl– ion content</td>
<td>≤ 0.1%</td>
</tr>
<tr>
<td>Na₂O content</td>
<td>≤ 2%</td>
</tr>
<tr>
<td>Range of use</td>
<td>0.3 to 1%</td>
</tr>
</tbody>
</table>

Source: Authors.

2.5 FORMULATIONS STUDIED

Four concrete formulations were developed (Calcined Sediment – Cement Concrete, CSCC). Three of them involved various proportions of mud (CSCC 10%, CSCC 20% and CSCC 30%), and the fourth one is control concrete (CC 00%) for the need of comparison. Table 9 gives the compositions of the different concretes under study. [52]

<table>
<thead>
<tr>
<th>Designation</th>
<th>Cement kg/m³</th>
<th>P/B (Plasticizer/Binder) (%)</th>
<th>Addition kg/m³</th>
<th>Gravel kg/m³</th>
<th>Sand kg/m³</th>
<th>Water kg/m³</th>
<th>W/B Water/Binder</th>
<th>P kg/m³</th>
</tr>
</thead>
<tbody>
<tr>
<td>CC 00%</td>
<td>402</td>
<td>0.0</td>
<td>0.0</td>
<td>179</td>
<td>912</td>
<td>663</td>
<td>201</td>
<td>0.5</td>
</tr>
<tr>
<td>CSCC 10%</td>
<td>363.6</td>
<td>0.3</td>
<td>35.33</td>
<td>179</td>
<td>912</td>
<td>663</td>
<td>199.4</td>
<td>0.5</td>
</tr>
<tr>
<td>CSCC 20%</td>
<td>324.8</td>
<td>0.4</td>
<td>71.02</td>
<td>179</td>
<td>912</td>
<td>663</td>
<td>197.9</td>
<td>0.5</td>
</tr>
<tr>
<td>CSCC 30%</td>
<td>286.3</td>
<td>0.65</td>
<td>107.31</td>
<td>179</td>
<td>912</td>
<td>663</td>
<td>196.8</td>
<td>0.5</td>
</tr>
</tbody>
</table>

Source: Authors.

The characterizations of the concretes are given in Table 10.

<table>
<thead>
<tr>
<th>Characteristics</th>
<th>CC 00%</th>
<th>CSCC 10%</th>
<th>CSCC 20%</th>
<th>CSCC 30%</th>
</tr>
</thead>
<tbody>
<tr>
<td>W/B</td>
<td>0.5</td>
<td>0.5</td>
<td>0.5</td>
<td>0.5</td>
</tr>
<tr>
<td>Addition/Cement (%)</td>
<td>00</td>
<td>10</td>
<td>20</td>
<td>30</td>
</tr>
<tr>
<td>Dough Volume (l/m³)</td>
<td>334</td>
<td>334</td>
<td>334</td>
<td>334</td>
</tr>
<tr>
<td>G/S</td>
<td>1.65</td>
<td>1.65</td>
<td>1.65</td>
<td>1.65</td>
</tr>
<tr>
<td>Granular skeleton volume (l/m³)</td>
<td>666</td>
<td>666</td>
<td>666</td>
<td>666</td>
</tr>
<tr>
<td>Theoretical density (Kg/m³)</td>
<td>2357</td>
<td>2353.7</td>
<td>2349.3</td>
<td>2347</td>
</tr>
<tr>
<td>Actual density (Kg/m³)</td>
<td>Fresh 2475.6</td>
<td>2468.9</td>
<td>2454.5</td>
<td>2441.6</td>
</tr>
<tr>
<td></td>
<td>Hardened 2461.7</td>
<td>2448.1</td>
<td>2433.0</td>
<td>2421.2</td>
</tr>
</tbody>
</table>

Source: Authors.
3 TEST METHODS

3.1 SLUMP TEST

Consistency is the parameter that requires special attention to ensure the quality of a plastic concrete, it is determined by the use of the Abrams cone (NF P18-451) which measures the slump in the concrete. The test steps are determined in Figure 9.

![Figure 9: Slump test.](image)

Source: Authors.

3.2 COMPRESSION TESTING

The simple compression test is carried out in the laboratory on cubic specimens (10 × 10 × 10) cm³, using a press with a maximum capacity of 3000 kN, and a loading speed of approximately 0.5 MPa/s (NF P 18-406). Figure 10 shows the different made concretes (Figure 10).

![Figure 10: Differents made concretes: a) CC 00%, b) CSCC 10%, c) CSCC 20%, d) CSCC 30%.](image)
3.3 NATURAL CARBONATION

Carbonation results from the action of atmospheric carbon dioxide on concrete, and affects the durability of concrete structures, because it can lead to corrosion of the reinforcements. [24] [39]

The CO₂ content of ambient air is between 0.03% and 1%. It is under these conditions that natural carbonation occurs. [50] [25]

The test pieces used are prismatic in shape, with dimensions of 7 x 7 x 28 cm³. [10]

The action of carbon dioxide on concrete is a process which begins with the penetration of the first (carbon dioxide) into the concrete matrix through the pores of the latter. Once penetrated, the CO₂ dissolves in water and reacts with the calcium hydroxide Ca(OH)₂ contained in the cement paste. [4]

The result is an acid with the chemical formula H₂CO₃, which reacts with the cement hydrates in a reaction called Carbonation. The chemical writing of this reaction is given by equation (I-1):

\[
\text{Ca (OH)}_2 + \text{CO}_2 + \text{H}_2\text{O} \rightarrow \text{CaCO}_3 + 2\text{H}_2\text{O} \quad (I-1)
\]

The test tubes were placed in the open air in the laboratory to monitor the evolution of natural carbonation. The measurement deadline for this conservation environment is 6 years. (Figure 11).
To measure the depth of carbonation, spraying a colored indicator such as phenolphthalein allows carbonated areas to be visualized on split surfaces of concrete. It is colorless on carbonated areas and pink on healthy areas, it changes at a pH of around 9.

To do this, the 7×7×28 cm³ specimens were broken by splitting using a manual press (Figure 12).

Measurements of the thickness of carbonated concrete are carried out after wetting the surfaces and spraying with a phenolphthalein solution. The latter reveals the interface between the healthy zone and the carbonate zone (Figure 13a and 13b).
The value of the carbonation thickness corresponding to a given time is the average of the measurements taken on the four sides of the sample.

**Figure 13 a:** Carbon sequestration in concrete to mitigate environmental impact [26]

**Figure 13 b:** Diagram illustrating the principle of measurements [12]

<table>
<thead>
<tr>
<th>Concretes</th>
<th>CC 00%</th>
<th>CSCC 10%</th>
<th>CSCC 20%</th>
<th>CSCC 30%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Subsidence (cm)</td>
<td>8.5</td>
<td>8.0</td>
<td>7.0</td>
<td>7.0</td>
</tr>
</tbody>
</table>

Source: Authors.

**4 RESULTS AND DISCUSSIONS**

**4.1 SLUMP TEST**

Concrete was mixed in such a way that the plasticizer gives concrete the same workability, with a plastic consistency. The value of the Abrams cone slump for all concrete is given in Table 11 and Figure 14.
The slump in the study concrete conforms to standard NF P 18-451 and the slump required for the formulation of our concrete (8 ± 1cm).

### 4.2 COMPRESSION STRENGTH

Figure 15 displays the compressive strengths of the concretes in MPa, as a function of time.

Source: Authors.
The results indicate that the control concrete achieves good compression performance, because it did not show compression strength smaller than 57 MPa at 3 years. The mechanical strengths of concrete with 10 % of cement replaced by calcined sediment are obviously the best of all calcined sediment-based concretes. At the end of the course, they tend to exceed those of control concrete. This concrete reaches a compressive strength around 70 MPa at 3 years. [53] The other concretes with calcined sediment contents of 20, and 30% also give very satisfactory results. [65]

To better visualize the strength evolution, the strengths of calcined sediment-based concretes are compared with that of control concrete (0% calcined sediment), at different ages (Figure 16).

Figure 16: Evolution of the strength of calcined sediment -based concretes with respect to control concrete.

Source: Authors.

It can easily be noted from the results obtained that, relatively to the control concrete, the compressive strengths of all tested concretes increase continuously with age and show no drop.[31]

Indeed, the concretes with calcined sediment contents of 20 and 30% are likely to develop mechanical performances that are higher by 87 and 80% at 7 days, and 85 and 76% at 28 days, respectively, as compared to control concrete. Beyond 90 days, CSCC 10% and CSCC 20% develop compressive strengths superior to those of control concrete. At 3 years, they are higher than that of control
concrete by about 119% and 107%, respectively. This can be attributed to the slow pozzolanic activity at the young age, but which grows later.

Moreover, the mechanical behavior of concrete containing 30% of calcined sediment also exhibits high strengths, which eventually tend to approach those of control concrete. This concrete reaches a compressive strength around 70% at 7 days, 68% at 28 days, and about 97% at 3 years of hardening, as compared to that of control concrete. [51, 52]

Incorporating calcinated sediment in concrete induces a rapid increase in the mechanical strength, at all maturities. When the particles of calcinated sediment are well deflocculated by the plasticizer, they promote the hydration of cement and calcined sediment, mainly through a physical process, and lead to a cementitious matrix with a denser structure, all the more since calcined sediment has a high fineness. These effects have a visible influence on the mechanical strength in the medium to long term. [13]

4.3 NATURAL CARBONATION

The measurement of carbonate depth was made after 6 years of exposure [8]. The carbonated zones are highlighted with phenolphthalein: photos of the sections of the test pieces are presented in Figures 17a and 17b.

Figure 17a: Natural carbonation after 12 months of exposure.
b: Natural carbonation after 6 years of exposure.

The carbonate depths after 12 months and 6 years of testing are shown in Figure 18.

Figure 18: Depth of natural carbonation of study concretes, after 12 months and 6 years in the open air of the laboratory.

The results obtained (Figure 18) show the comparison between the concretes studied after 1 and 6 years of conservation in the open area.

We note the good resistivity of all the concretes containing the calcined sediment, the carbonate depths of the latter are very low or almost similar. [33]
The substitution rate of 20 and 30% of calcined sediment would improve resistance to carbonation in the long term (6 years). [63]

The carbonation depth of CSCC 30% and CSCC 20% are significantly greater than that of CSCC 10% and the control concrete (difference of 4.23 mm at 6 years).

The results show more clearly the positive effect of calcined sediment on the resistivity of concrete with respect to carbonation.

Figure 19a, 19b and 19c shows the difference in carbonation fronts between 1 and 6 years of testing.

Figure 19a: Difference in carbonation fronts between 1 and 6 years of testing.
Comparison of the results of natural carbonation at ages 1 and 6 years shows that the substitution of 20 and 30% of silt gives the lowest value of carbonation compared to other concretes. [58] [34]

Comparing the results, a difference of 4.95 mm for CC 00%, 4.60 mm for CSCC 10%, 4.52 mm for CSCC 20% and 4.23 mm for CSCC 30% are recorded after six years of storage in the open air. [23] [12]

Other research such as that of report the positive effect of pozzolanic additions such as fly ash and natural pozzolana and which may be due to the great densification of the porous structure in the presence of pozzolanic additions which makes the effect of Consumption of portlandite a side effect. [62]

In addition, we can explain this, by the Rozière hypothesis, which shows that the additions intervene on the carbonation by the dilution of the lime of the clinker and the additions, and not by consumption of the portlandite by pozzolanic reaction. [40] [49]

This seems to justify the small difference observed in the carbonation kinetics of silt-based concretes which is significantly lower than that of the control concrete. [54] [55]
5 CONCLUSION

This study made it possible to show the possibility of valorizing the sediment, resulting from dam stripping operations, as a material partly substitutable for cement. This could partly resolve the problem of its storage and contribute to the ecological and economic development of certain regions of the Mediterranean.

We have highlighted the effects of the introduction of calcined sediment on the behavior of cementitious matrix materials and we have developed the first elements allowing us to understand the main mechanisms of action.

The main conclusions we reached are:

• concerning the compressive strength, all the concretes follow the same kinetics with a slight advantage for the control concrete up to 90 days due to the dilution phenomenon;

• generally, all se-based concrete formulations give good mechanical performances;

• the calcined sediment enhances the long-term compressive strength of concrete, as it gives rise to a second hydrated calcium silicate (H-C-S) which helps to fill in the pores, and increases the mechanical strength beyond 90 days;

• the proportions of 10 and 20% of calcined sediment, for partial replacement of cement in concrete, are found to be optimal for developing high strength in the short term, that are higher by 85% and 76% at 28 days, respectively, as compared to control concrete. Beyond 90 days, CSCC 10% and CSCC 20% develop compressive strength superior to those of control concrete;

• the diffusion of CO₂ depends on relative humidity and its uncertainty. Water is an essential element in the carbonation reaction. It is necessary to have a certain amount of water to dissolve the CO₂; it must be limited to facilitate its access to the solid surface, and therefore carbonation will take place quickly;

• the results of our experimental study on natural carbonation showed that there is a relationship between the addition of silt to concrete paste and the risk of carbonation and its effect on concrete strength. By comparing the results of different concretes, we see that the replacement rate of 20 and
30% of calcined sediment improves resistance to carbonation in the long term (6 years);

- the presence of silt in the concrete paste significantly reduces the risk of carbonation of these concretes;

- research results on the transfer properties of concrete based on calcined sediment have shown the reduction in the values of sorptivity and porosity coefficients with the addition of calcined sediment up to 30%. Consequently, this concrete develops good mechanical performance and better behavior in terms of durability and in particular carbonation;

- the possibility of valorizing the sediment (thermally activated in order to transform the mineral structures which are in their natural state stable, into amorphous structures) with the aim of manufacturing a substitute for the hydraulic binders in common use seems feasible. The results obtained in this research demonstrate significant potential for societal and academic benefits through the valorization of calcined sediment as a partial substitute for cement in concrete. Here’s how the findings can assist society and academia:

  1. **environmental benefits**: the reduction of cement usage by incorporating calcined sediment directly addresses environmental concerns. Cement production is a major contributor to carbon dioxide emissions, and using alternative materials like calcined sediment can significantly reduce the carbon footprint of the construction industry. This aligns with global efforts to mitigate climate change;

  2. **sustainable sediment management**: the study provides a practical solution to the problem of sediment accumulation in dam reservoirs, which is a pressing issue in semi-arid regions like Algeria. By converting sediment into a valuable resource for construction, the research offers a sustainable approach to managing siltation and reducing the need for costly and environmentally damaging dredging operations;

  3. **economic development**: utilizing locally available sediment as a construction material can reduce the dependence on imported cement and lower construction costs. This can spur economic development, particularly
in rural and semi-arid regions, by making building materials more affordable and promoting local industries;
4. **enhanced material properties**: the research highlights that concrete incorporating calcined sediment exhibits good mechanical performance, particularly in terms of long-term compressive strength and resistance to carbonation. This makes it a viable and attractive option for various construction applications, ensuring durability and longevity of structures;
5. **academic contributions**: the study advances the understanding of the mechanisms by which calcined sediment enhances concrete properties. It contributes to the body of knowledge in materials science and civil engineering, particularly in the field of sustainable construction materials. The findings can serve as a foundation for further research on the use of alternative pozzolanic materials in concrete;
6. **policy and practice implications**: The positive outcomes of using calcined sediment in concrete can inform policy decisions and industry practices. Policymakers can promote the use of such sustainable materials through regulations and incentives, while construction companies can adopt these practices to improve their environmental credentials and comply with sustainability standards.

In conclusion, the research demonstrates a viable pathway for the valorization of dam sediment, turning a waste material into a valuable resource. This not only addresses environmental and economic challenges but also enhances the durability and performance of construction materials, thereby benefiting both society and the academic community.

6 PERSPECTIVES

The possibility of valorizing the silt with the aim of manufacturing a substitute for commonly used hydraulic binders seems feasible. Given the results of this study, new parameters could follow this work by considering replacing a part of cement with the calcined mud and studying the optimal and/or maximum percentage of substitution as well as their influence on the physical parameters. - mechanical such as static and dynamic elasticity moduli, and concrete durability
by gas permeability and mercury porosity tests, associated with scanning electron microscope and mineralogical analyzes by X-ray diffraction.

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