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Valorization of dredged dam sediment as partial cement substitute in pervious concrete

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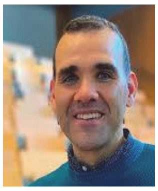

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Research Paper

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Valorization of dredged dam sediment as partial cement substitute in pervious concrete

The purpose of this study was to investigate the mechanical and hydraulic properties of pervious concrete made with calcined dredged dam sediments (CDDS) as a partial cement replacement. Three calcination temperature scales were considered (700, 750, and 800 °C), for each temperature scale three incorporation rates of (CDDS) were adopted (5, 10, and 15 %), with a single water to cement ratio (E/C) of 0.36. The effects of the (CDDS) calcination temperature and its substitution rate on the compressive strength, flexural strength, water permeability, and porosity were evaluated. The results revealed that pervious concrete containing 10 % of (CDDS) calcined at a temperature of 750 °C shows a notable enhancement in compressive strength with acceptable permeability coefficient recommended for pervious concrete.

Key words:

pervious concrete, dredged dam sediment, calcination, pozzolanic effect, cement replacement

Prethodno priopćenje

Farida Amiar, Ourdia Fedaoui-Akmoussi, Ourdia Haddad, Nordine Leklou, Shaswat Kumar Das

Valorizacija sedimenta izvađenog iz akumulacije brane kao djelomične zamjene cementa u propusnom betonu

Svrha ovog istraživanja bila je ispitati mehanička i hidraulička svojstva propusnog betona izrađenog s kalciniranim sedimentom izvađenim iz akumulacije brane (eng. *calcined dredged dam sediments* - CDDS) kao djelomičnom zamjenom cementa. Razmatrane su tri temperature kalcinacije (700, 750 i 800 °C), za svaku temperaturu primijenjena su tri udjela dodatka CDDS-a (5, 10 i 15 %), uz jedinstveni vodocementni omjer (v/c) od 0,36. Ocijenjeni su učinci temperature kalcinacije CDDS-a i njegova udjela zamjene na tlačnu čvrstoću, čvrstoću na savijanje, propusnost vode i poroznost. Rezultati su pokazali da propusni beton koji sadrži 10 % CDDS-a kalciniranog pri temperaturi od 750 °C pokazuje značajno poboljšanje tlačne čvrstoće uz prihvatljiv koeficijent propusnosti preporučen za propusni beton.

Ključne riječi:

propusni beton, sediment iz akumulacije brane, kalcinacija, pucolanski učinak, zamjena cementa

1. Introduction

The construction field, particularly Portland cement (PC) manufacturing, is renowned for its high carbon footprint [1]. It is responsible for approximately 22 % (2.2 Gt) of the worldwide greenhouse gas emissions from manufacturing processes [2, 3]. Moreover, owing to the rapid growth of the construction industry, the demand for cement (including low carbon PC) is predicted to rise by 12 to 23 % by 2050, in comparison to 2014 [2, 3]. This causes a proportional increase in carbon emissions; hence, there is a need to implement effective strategies to achieve carbon neutrality of concrete. Among the solutions suggested by the IEA technological roadmap to mitigate this challenge, is the partial substitution of PC in concrete with pozzolanic materials, widely known as supplementary cementitious materials (SCMs) [3–6].

On the other hand, reservoir sedimentation is a higher threat to dams in many parts of the world [7, 8]. This causes a loss in the global reservoir capacity that ranges between 13 % and 19 % [7-9]. Therefore, this waste is frequently extracted, but its storage requires a large volume of space which could otherwise be dedicated to other activities. In light of this, the valorisation of dredged sediment as an additive for concrete is an effective environmental solution that can meet the sustainability of the water supply, ensure the safety of dams, avoid the need for landfill disposal [7-11], and lower cement usage. In this context, many researchers have studied the use of calcined dredged dam sediments (CDDS) as partial substitutes for binders [9]. In the study [7] conducted by Touhami K et al, a 10 % replacement rate of CDDS at 750 °C is considered ideal for the usage of CDDS as SCMs. Another study [12], revealed that, the dredged dam sediments (DDS) heated at 600 °C at a heating rate of 20 °C/min, added at the range of 10 % to cement clinker, enhances the strength of the binder.

DDS are predominantly clay, which commonly contains minerals such as Kaolinte, Smectite, Illite, and Montmorillonite, and impurities including Quartz and Feldspar with different Kaolin contents [7, 13]. Various studies have shown that these clays behave as pozzolanic materials after going through an activating process with different temperature ranges (between 600 and 900 °C) for a given period of time. This temperature range is generally much lower than the temperature used for cement clinker formation, which reduces the subsequent carbon (CO_2) emissions associated with the calcination energy [14]. Crucially, the calcination process of clay generates an estimated 393 Kg of CO_2 per ton, which is only 40 % of the total emissions linked to the cement manufacturing process. This is partialy due to their lower calcination temperatures and lime contents compared to typical cement clinkers [4, 7, 14, 15].

Until now, most studies have focused on the behaviour of clay minerals in cement paste and concentrated their research on their Kaolin content because of the wider acceptance that it has the highest pozzolanic reactivity among other clay minerals [16-18]. Therefore, many researchers estimated that the use of sediments as SCMs requires at least 40 % of Kaolin content [4, 7, 13, 15]. However, high-quality clays are depleted because of their widespread use in ceramic and paper manufacturing, as they are more economical than cement [7, 13]. In recent years, the use of low-kaolin-content clays, known as heterogeneous clays or (2:1) clay minerals, as SCMs has gained prominence because of their low production cost and significant worldwide availability. Several studies have investigated the possibility of using low-grade deposits in Ordinary Portland Cement (OPC) [7, 13, 15].

Another environmental concern is urban flooding. In 2001, intense rains caused 781 deaths and had a terrible impact on the economy of Algeria's capital, Algiers [19]. This disaster was a consequence of a combination of climate change, the expansion of impermeable surfaces in urban areas, and an ineffective conventional drainage system [20]. Thus, to avoid such a catastrophe, it is necessary to introduce pervious concrete into Algerian urban landscapes, such as paving sidewalks, parking lots, and roadways [21]. This porous material is characterised by a network of interconnected pores that allows water to percolate into subgrade layers at high rates [22]. Additionally, it enhances groundwater recharge, minimises water and soil pollution, and mitigates the heat island effect [23, 24], as well as other environmental benefits that make it a sustainable material recommended for pavement use. Furthermore, pervious concrete constitutes a crucial component of pavements used in sponge city programs in China [22, 25, 26]. Additionally, it was selected by the US Environmental Protection Agency (EPA) as one of the best urban management practices [27, 28].

Pervious concrete is obtained by mixing coarse aggregates with a narrow particle size distribution and carefully monitoring the amount of cement, water, and sand [21, 28, 29]. Its porosity is typically ranging from 15 % to 35 % by volume, while its compressive strength is ranged between 2,8 to 28 MPa, [21-24, 28, 30, 31]. Owing to its high porosity, this sustainable material is characterised by weaker mechanical properties compared to conventional concrete, which restricts its use to lightly loaded surfaces [20, 28] [30, 31]. Differently, the mechanical properties and permeability of PC are significantly influenced by factors such as water-to-binder ratio. Thus, in order to achieve optimal aggregate coating and paste stability in pervious concrete, a water-to-cement ratio of 0.26-0.45 is recommended [23, 24]. The integrity of pervious mixtures is mainly affected by the thickness of the cement paste layer coating and the connection of the aggregate particles [20, 32]. In this context, the quality of the cement paste layer is significantly affected by the rheological properties of the binder [33]. To enhance the strength, workability, and durability of PC while simultaneously maintaining an acceptable permeability, researchers have explored numerous strategies, such as the incorporation of chemical and mineral admixtures.

Various studies investigated the effects of adding SCMs to pervious concrete, relvealing that the partial replacement of cement with Fly Ash (FA) and Silica Fume (SF) enhances the workability of fresh concrete, as well as the mechanical strength and durability of pervious concrete [34, 35]. Meanwhile, [36] reported a modest increase in the porosity of pervious concrete mixes using ground granulated blast-furnace slag and FA as partial replacements for

Figure 1. Geographical situation of the K'sob dam from Goggle earth

cement. Moreover, a study conducted in [37] indicated that adding 2 % of Metakaolin to pervious concrete considerably enhanced the density and mechanical strength while decreasing the porosity. Kwabena et al. [38] investigated the properties of pervious concrete containing calcined clay pozzolan and they found that the optimum content of these SCMs that can enhance strength and maintain adequate permeability was 20 % by weight.

In the present research, we develop suitable pervious concrete mixtures utilising locally available resources such as dredged dam sediments. This study focuses on the potential use of deposits from K'sob Dam as SCMs for the development of pervious concrete recipes. This dam is situated on the K'sob River in Hamman, between the Kef El Ouerad and Djebel El Gruon mountains, 15 km north of M'sila, a province located on the high plateaus of north-central Algeria (Figure 1). This dam covers an area of 1460 km² with a circumference of approximately 180 km [12]. According to the ANB (National Dam Agency), the K'sob Dam had a sedimentation rate of 59.90 % in 2011. The annual sedimentation of this structure is about 8105 m³ of sediments. The sludge is typically dredged and pumped into settling basins on uncultivated land. This practice has harmful effects on the surrounding environment and requires additional storage resources, thus posing an urgent need for their reuse in an ecological and sustainable way. In this study, the DDS was first calcined and then incorporated into the compositions of permeable concrete as a partial replacement for the binder (PC), with the aim of optimising the mechanical characteristics of pervious concrete samples while maintaining an appropriate permeability coefficient. This not only helps to reduce PC usage and hence its carbon footprint but also provides a sustainable way to reuse locally available secondary resources, paving the way for a more integrated circular economy [39].

2. Experimental part

2.1. Materials

Pure PC CEM I 42.5 R from a cement plant in Lafarge Algeria, commonly known as Matine, was used in this study. The PC used had a blaine-specific surface area of 4290 cm^2/g according to the standard NF EN 196-6 [40] and a density of 3.0 g/cm^3; its chemical composition is shown in Table 1.

The aggregates used in this study were crushed limestone aggregates free from impurities with a particle size of 3-8 mm, meeting the requirements of ASTM D448 [41]. A percentage of 10 % (by coarse aggregate mass) of fine aggregates 0/3 mm, was also used. The aggregate grading curve, determined according to ASTM C 33 [42], is shown in Figure 2.

The superplasticiser (SP) marked under the brand "Sicaplast 40 Pro" (Sica Algeria) was used as a water reducing agent to improve the workability of pervious concrete mixes.

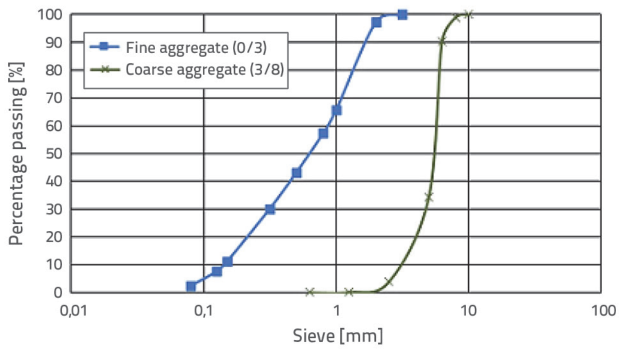

Figure 2. The aggregate grading curve

2.1.1. Preparation of calcined DDS

The DDS was collected downstream of the K'sob Dam in the landfill zone. After homogenisation, the sediment was dried at 105 °C for 24 hrs. It was then manually crushed and subsequently underwent intense grinding in a disc mill before passing through an 80 μm sieve. Calcination was performed in a static oven at a ramp rate of 5 °C/min for 5 hrs. Three temperatures were considered for the calcination, i.e., 700, 750, and 800 °C. The calcined sediment was stored away from air and moisture in an airtight container before use. Figure 3 provides a pictorial representation of the methods used to obtain the calcined DDS.

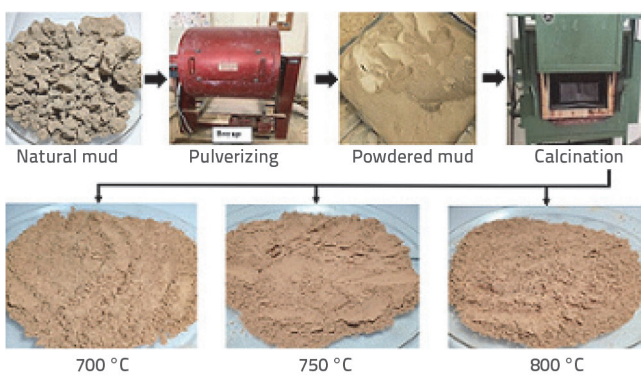

Figure 3. DDS treatment process followed before using it for concrete formulations

2.1.2. Granulometric analysis

Laser granulometry examinations were conducted to determine the potential changes in clay particle size distributions (PSD). The analysis was conducted using a CILAS 1180 SEC in wet dispersion mode with deionised water. An approximate weight of 0.1-1.0 g of dry powder sample was fed into the hopper and dispersed using compressed air at 200-300 kPa to minimize the agglomeration and optimal results.

According to the PSD curves, the diameter gradually decreased with increasing temperature. The maximum value of fineness is obtained for an activation temperature of 800 °C with a relative increase of about 3.57 % compared to the dredged dam sediment calcined at 750 °C. Nonetheless, this one (750 °C) has registered a rise of fineness of 0.15 % compared to the sludge calcined at a temperature of 700 °C. Comparable facts have been reported in the literature [43-45], and it is well known that an increase in fineness provides a greater surface area, accelerating hydration kinetics, and thus increasing reactivity [46, 12]. Furthermore, from these curves, it can be observed that the residue on the 45-micron sieve is less than 10 % for the three temperatures, which represents the maximum permissible value for the usage of pozzolan and metakaolin as SCMs according to [43].

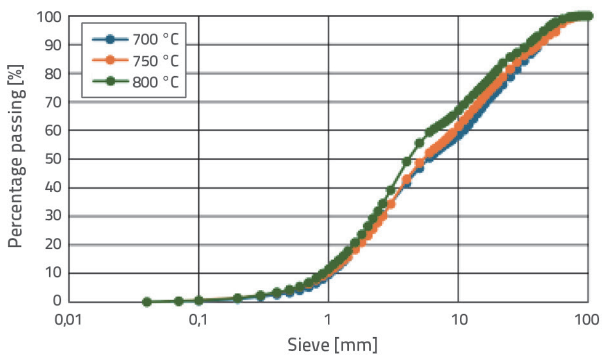

Figure 4. PSD of (CDDS) calcined at different temperatures

2.1.3. Material characterization

Natural dredged dam sediments (NDDS) and CDDS were studied using various characterisation techniques to determine their physical, chemical, and mineralogical properties.

The XRF analysis: XRF analysis was performed using an analyser EPSILON 4 manufactured by Mlvern Panalytical. The results of different sediments used in this study are tabulated in Table 1.

Relevant literature reports that a clay is considered as high-quality clay (containing at least 40 % Kaolin), when the subsequent criteria are fulfilled: (1) % Al_2O_3 > 18; (2) % Al_2O_3/ SiO_2 > 3.0; (3) Na_2O ≤ 3 [47, 48]. The clay composition in the current study, according to the chemical analysis, was NDDS % Al_2O_3 = 12,21 < 18; Al_2O_3/ SiO_2 = 0.3; Na_2O = 0.29 ≤ 3. It can be clearly observed that the first condition was not satisfied. Therefore, this clay can be classified as low-grade clay.

The results from laser particle size analysis for the three different CDDS used in this study, are shown in (Figure 5) for the three temperatures of activation (700, 750, and 800 °C). The calcination of DDS induces the release of structural hydroxide ions (OH^-), which is known as dihydroxylation. This results in a weight loss and a change in colour (Figure 3) and grain diameter, as shown in Figure 4 [7, 43].

X-ray diffraction analysis: The mineralogical composition of DDS at the three temperature levels was determined by the XRD X-ray diffraction analysis. An Empyrean diffractometer manufactured by Malvern Panalytical was used. The source of X-ray was Cu-Kα and the test was conducted out from 5 to 60 ° with a step size of 1.2 °/min with a rotating speed of 60 rpm. The sample preparation involved powdered sample passing 75 μm standard sieve without any additives. The XRD patterns of the three different CDDS are shown in Figure 5. The diffractogram indicated that the most abundant clay minerals in these samples were Quartz, Calcite, and Illite. The analysis results indicate that certain Illite peaks have disappeared when the temperature rose from 700 to 750 °C, which is due to the partial dihydroxylation of Illite, thus the observed disappearance of the peak at 25.5 ° (2θ). This finding aligns with the results of [4]. Moreover, certain calcite peaks became more pronounced as the temperature increased from 700 to 750 °C, such as the peak at 29.4 °(2θ). However, there was no apparent change in the quartzite peaks, as they remained unaltered in this temperature range.

Table 1. Chemical composition of different sediments and cement

Components	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	SO_3	K_2O	Na_2O	P_2O_5	TiO_2	MnO	PF
Cement	17.28	3.89	4.38	60.82	3.34	2.03	0.57	0.16	0.14	0.20	0.05	8.67
NDDS	37.87	12.17	2.87	18.98	2.00	0.1	1.34	0.32	0.21	0.58	0.04	22
CDDS 700	45.70	14.03	4.93	20.62	2.39	0.81	1.68	0.39	0.22	0.68	0.06	8.49
CDDS 750	43.69	13.55	4.83	20.13	2.27	0.56	1.61	0.35	0.22	0.66	0.05	12.09
CDDS 800	43.53	13.80	4.81	19.90	2.31	0.65	1.60	0.24	0.22	0.66	0.05	12.23

Note: NDDS indicates "natural dredged dam sediment" (NDDS) and (CDDS) indicates "calcined dredged dam sediment". The numbers next to(CDDS) indicate the calcination temperature.

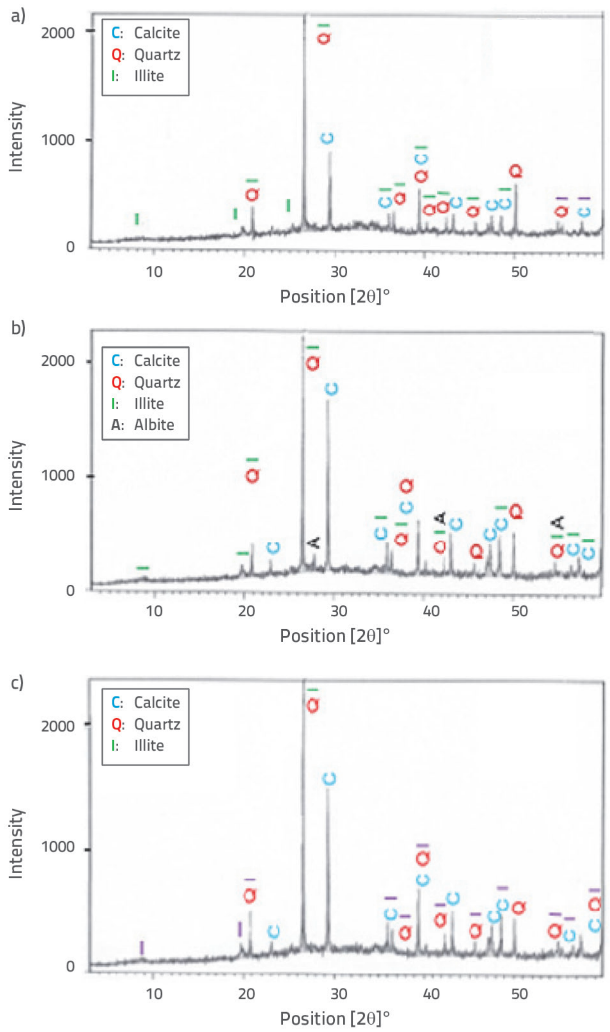

Figure 5. XRD patterns of CDDS at different temperatures: a) 700 °C; b) 750 °C; c) 800 °C

2.1.4. Mix proportions

The pervious concrete mix ratio was designed according to ACI522R-10 [28]. In order to investigate the influence of DDS on pervious concrete characteristics, the substitution rates of cement with CDDS for each of the temperatures (700, 750, and 800 °C) was 5, 10, and 15 % (by cement mass). For all the specimens designed for this study, a water/binder ratio of 0.36 was adopted to achieve a good correlation between workability, strength, and permeability. This falls within the range of 0.26 to 0.45 that the ACI committee 522R [28] recommends for pervious concrete.

The superplasticiser content was kept 1.5 %, with a target porosity of 20 %. Concerning the fine aggregates, the percentage used was 10 % (by weight of coarse aggregates), whereas coarse aggregates were incorporated into the mixture under a saturated surface dry (SSD) condition. Four types of specimens were castted for this experiment. First, cylindrical specimens, measuring Ø100 mm and 200 mm in height, were constructed for compressive strength testing after 28 days. Second, cylindrical specimens measuring 100 mm and 130 mm in height were prepared for the permeability test. Third, prismatic specimens measuring 70 × 70 × 280 mm were used to determine the flexural strength. Finally, the porosity and density were determined using cubic specimens with dimensions of 100 × 100 × 100 mm^3. The pervious concrete was mixed and cured in a manner similar to that of ordinary concrete. First, a mixer was filled with weighed batches of coarse and fine aggregates. After adding cement and CDDS, dry mixing was done for three minutes. Two-thirds of the weighed water was added after adequate dry and wet mixing were completed. To guarantee adequate dispersion, the measured superplasticiser was combined with the remaining one-third of the water. Subsequently, the concrete was wetly added to the mixture.

After the components were properly mixed, fresh concrete was poured into the moulds in two layers, and each layer was crushed

Table 2. Mixture proportion [kg/m^3]

Mix type	Fine aggregate, 0/3 mm	Aggregate, 3/8 mm	OPC	Mud	Superplastizer	Water
CPC[a]	163.9	1639	222	-	3.33	81
C5MA[b]	163.9	1639	210.9	11.1	3.33	81
C10MA	163.9	1639	199.8	22.2	3.33	81
C15MA	163.9	1639	188.7	33.3	3.33	81
C5MB[c]	163.9	1639	210.9	11.1	3.33	81
C10MB	163.9	1639	199.8	22.2	3.33	81
C15MB	163.9	1639	188.7	33.3	3.33	81
C5MC[d]	163.9	1639	210.9	11.1	3.33	81
C10MC	163.9	1639	199.8	22.2	3.33	81
C15MC	163.9	1639	188.7	33.3	3.33	81

CPC[a]: Control pervious concrete with no"CDDS"
C5MA[b]: Pervious concrete with 5 % "DDS" calcined at 700 °C
C5MB[c]: Pervious concrete with 5 % "DDS" calcined at 750 °C
C5MC[d]: Pervious concrete with 5 % "DDS" calcined at 800 °C

with 20 blows from a 2.5 kg Proctor hammer. The moulds were then placed on a vibrating table. The power of the plate vibrator was 750 W, and the vibration time was controlled at approximately 10 s. After a day, the specimens were demoulded and allowed to cure in water in conditions of 20 ± 2 °C temperature and a relative humidity of over 95 %, until they reached the 28-day age. The PC mixture design and component proportions are listed in Table 2.

2.2. Methods

2.2.1. Mechanical tests

In this study, a computer-controlled hydraulic press with a maximum capacity of 2000 kN was used to investigate the compressive and flexural strengths of pervious concrete mixes. Compressive strength tests were conducted on cylindrical specimens with sizes of (Ø100 to 200 mm) at an age of 28 days and a loading rate of 0.5 kN/s. The test was performed following the standard NF-EN 12390-3 [49]. The flexural strength was determined using three-point bending tensile tests on 70 ×70 × 280 mm³ prisms. The prism was then placed in a computer-controlled hydraulic press. The distance "L" between supports was equal to 21 cm. To avoid parasitic effects caused by defects in the parallelism and flatness of the upper face of the specimen, we applied loading on the lateral faces of the specimen. The latter was subjected to increasing loads until failure occurred. Tests were conducted at a loading rate of 0.5k N/s. The test was performed according to the standard NF-EN 12390-5 [50]. Each crushing test was performed on three samples, and the average compressive and flexural strengths were recorded.

2.2.2. Permeability coefficient test

In this research, a permeability test was conducted using a falling head permeameter on cylindrical specimens cured for 28 days, measuring 100 mm in diameter and 130 mm in height. The apparatus used in this study is illustrated in (Figure 6). It was constructed according to the ACI522R-10 recommendations [28]. The lateral surface of each specimen was coated with a plastic warp. It was positioned between two pipes in the apparatus. Subsequently, it was carefully covered with latex tourniquets to prevent water leakage. This permitted water to enter the upper surface. Water was then added to the graduated cylinder and allowed to flow through the entire pipe while the valve was left open to remove air and conduct the permeability test. After closing the valve, water was poured into the permeameter to the level indicated by standard dimensions (initial head h_1 = 290 mm). The time required for the water-pressure head to decrease from this level to the final head (h_2 = 70 mm) was measured once the valve was opened. This was noted and used in the following equation given by Darcy's law:

$$K = \frac{\alpha \cdot L}{A \cdot t} \ln \frac{h_1}{h_2} \qquad (1)$$

In this equation, K is the permeability coefficient (mm/s). A (mm²) and L (mm) are, respectively the cross-sectional area and the length of the specimen, "a" is the cross-sectional area of the top graduated pipe, t (s) is the time required for water to decrease from h_1 to h_2.

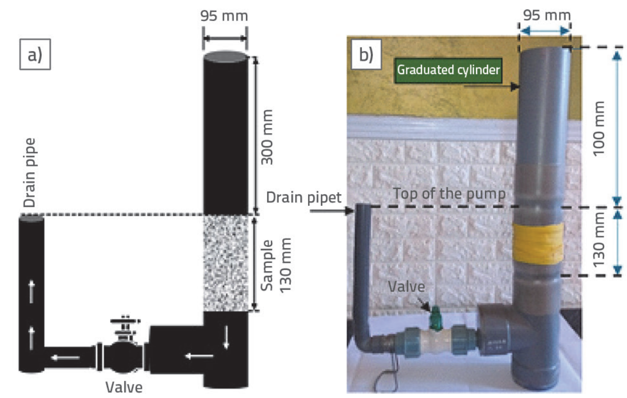

Figure 6. a) Schematic; b) pictorial representation of permeability coefficient apparatus

2.2.3 Porosity

The porosity of the pervious concrete was determined according to ASTM C1754–12 [51] using cubic specimens with dimensions of (100 × 100 × 100 mm). Firstly, the specimens were dried to a constant weight in a drying oven at 60 °C. Then, the weight of the specimens (W_1) in the air was measured. Subsequently, to fill the pores with water, the samples were submerged in water for 24 hours. Then, the specimens were placed in a hydrostatic balance. Subsequently, the submerged weights (W_2) of the pervious concrete specimens were measured. The total porosity (P%) of the specimens was determined as follows:

$$(P\%) = \left[1 - \frac{W_1 - W_2}{V \cdot \rho_W}\right] \cdot 100 \qquad (2)$$

where, W_1 is the dried weight of the specimens (g), W_2 is the submerged weight of the same specimens (g), V is the volume (cm³), and ρ_w is the density of water (1g/cm³).

3. Results and discussion

3.1. Compressive strength

The compressive strength development of pervious concrete samples with different CDDS content (5, 10, and 15 % by weight of PC) calcined at different temperature ranges (700, 750, and 800 °C), is shown in Figure 7. From these results, it is clear that the DDS calcined at 750 °C yields the highest compressive strength for the three consecutive percentages of clay content. This observation highlights the idea that the best pozzolanic character is attributed to the clay calcined at 750 °C, compared to the other tested temperatures (700 and 800 °C). This result is consistent with those reported previously [7, 52, 53]. Indeed, this temperature falls within the range in which the sediment is partially dehydroxylated and changes to an optimum amorphous state, in which its reactivity is at its highest [7]. For the calcination temperature of 800 °C, a decrease in compressive strength is observed. This could be due to a decrease in the material›s reactivity, which is related to the formation of vitreous structures in the calcined clay owing to high-temperature exposure. The values of compressive strengths for the pervious concrete samples with 0, 5, 10, and 15 % of CDDS at 750 °C are found to be 8.4, 8.7, 10.4 and 8.4 MPa, respectively. The strength was enhanced by 3.57 and 23.81 % respectively for 5 and 10 % of CDDS content compared with the reference mix. Furthermore, for 15 % CDDS content, the compressive strength recorded was the same as that of the control mix.

The modified pervious concrete achieved higher strength than the control mix for 5 and 10 % of CDDS. This progressive increase, depending on the CDDS substitution strength, was probably due to the pozzolanic reaction and the filler effect. First, the thermally activated DDS contains active SiO_2 and Al_2O_3 which react with $Ca(OH)_2$ (free lime) to produce an additional calcium silicate hydrate-(C-S-H) and calcium aluminosilicate hydrate (C-A-S-H)-type gel products. Therefore, these hydration products fill the pores and make the material denser, leading to enhanced mechanical strength [54]. However, the strength decreased when the substitution amount was 15 %. It is worth noting that 10% replacement was the optimal replacement level for calcined clay. This outcome aligns with previous findings [7, 12, 52]. Second, unreactive phases such as crystalline calcite and quartz could act as nucleation sites and filler phases to densify the matrix, which could improve the mechanical strength. For the mixture with 10 % CDDS, this possible dual effect could synergistically be responsible for observed strength enhancement. Beyond this substitution level, any further increase in CDDS in the mixture leads to a decrease in the cement (reactive) fraction (dilution effect) and a subsequent decrease in the hydration products (C-S-H-/C-A-S-H-type gels), which leads to overloading of the mixture with unreacted SiO_2/Al_2O_3 and other unreactive phases. This limits mechanical strength [7, 38, 56].

3.2. Flexural strength

The flexural strength results for the pervious concrete with different substitution levels of CDDS are presented in Figure 8. The overall trend in the flexural strength followed that of the compressive strength results; however, given that concrete is inherently weak under tension, certain anomalies were observed. For instance, while the mix containing 10 % CM calcined at 750 °C exhibited the highest compressive strength among all compositions, including the reference mix, its corresponding flexural strength displayed greater variability, as evidenced by the wider error bars for the CM10(750) mixture. Such discrepancies can be attributed to the heterogeneous nature of pervious concrete and the distinct stress distribution mechanisms under flexural loading compared with compression [55].

For mixes containing DDS calcined at 700 °C, the recorded flexural strength values for 5, 10, and 15 % CDDS replacements were 3.3, 2.8, and 2.5 MPa, respectively. A clear decreasing trend was observed with increasing CDDS content. Similar behaviour was noted for DDS calcined at 750 °C, where the respective flexural strengths were 3.2, 3.0, and 2.5 MPa for 5, 10, and 15 % replacement levels. For mixes incorporating DDS calcined at 800 °C, the corresponding values were 2.9, 3.2, and 2.7 MPa, suggesting that a 10 % CDDS replacement could represent an optimal dosage for mechanical performance.

Overall, all CDDS-modified mixes exhibited slightly lower flexural strength than the control specimen. Nevertheless, the recorded values remained within the acceptable range for pervious concrete intended for low-traffic pavement applications, as reported in previous studies [55]. According to literature, pervious concrete typically exhibits flexural strengths between 2 and 4 MPa, which are adequate for pedestrian zones, parking areas, and light traffic pavements [58].

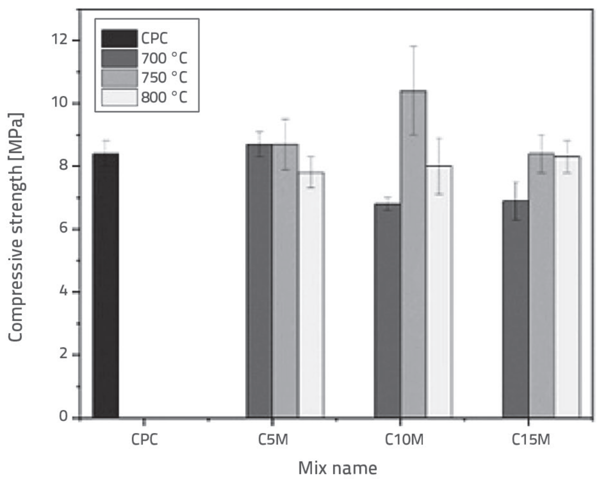

Figure 7. Compressive strength results of control and pervious concrete with different percentage of DDS calcined at different temperatures

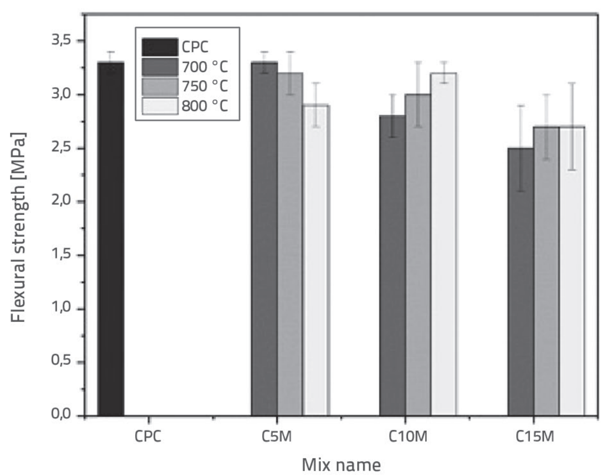

Figure 8. Flexural strength of control and pervious concrete with different percentage of CDDS calcined at different temperatures

3.3. Permeability

Figure 9 presents the permeability coefficient results of pervious concrete incorporating different substitution levels of CDDS (5, 10, and 15 %) and various calcination temperatures (700, 750, and 800 °C). It is evident that both the CDDS replacement level and calcination temperature significantly influence the permeability coefficient of the pervious concrete.

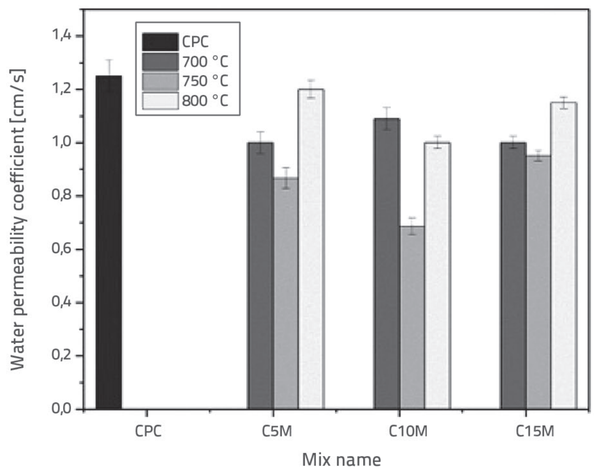

Figure 9. Water permeability coefficient of control and pervious concrete with different percentage of (CDDS) calcined at different temperatures

At a calcination temperature of 700 °C, the mixes with 5, 10, and 15 % CDDS replacement exhibited nearly identical permeability values of approximately 1.0 cm/s, corresponding to a 20 % reduction compared with the control value (1.25 cm/s). The mixture containing 10 % CDDS recorded a slightly higher value of 1.09 cm/s, though still lower than the control. This behaviour can be attributed to the filling effect of the CDDS and its moderate pozzolanic reactivity, which results in a slight densification of the pore structure without significantly obstructing the interconnected pore network or increasing its tortuosity [59].

At a calcination temperature of 750 °C, the permeability coefficient declined substantially across all substitution levels. The lowest recorded value was 0.69 cm/s for the 10 % CDDS mix, corresponding to a 44.8 % reduction compared to the control specimen, followed by 0.87 cm/s for 5 % CDDS (a 30.4 % decrease) and 0.95 cm/s for 15 % CM (a 24 % decrease). This pronounced reduction suggests an enhanced pozzolanic activity at 750 °C, leading to a denser microstructure and reduced pore interconnectivity, thereby limiting the flow of water through the matrix. These findings support the earlier observation that calcination at 750 °C yields the most reactive pozzolanic phase in the CDDS.

In contrast, the pervious concrete incorporating DDS calcined at 800 °C exhibited permeability coefficients of 1.20 cm/s and 1.15 cm/s for 5 and 15 % replacement levels, corresponding to only 4 and 8 % reductions relative to the control mix. The mix containing 10 % CDDS showed a more pronounced 20 % decrease in permeability, which may be attributed to the optimum packing density achieved at this replacement level, resulting in a denser microstructure and reduced pore connectivity.

Overall, the measured permeability coefficients ranged between 0.63 and 1.28 cm/s, which are well within the limits recommended by ACI 522R-10 [28], specifying that acceptable permeability for pervious concrete should exceed 0.1 cm/s for adequate drainage performance [28]. These results confirm that the partial replacement of cement with CDDS can be optimised to balance the mechanical performance and permeability characteristics suitable for low-traffic pavement applications.

3.4. Porosity

Figure 10 presents the porosity results of pervious concrete as influenced by the substitution level of CDDS (5, 10, and 15 %) and the calcination temperatures (700, 750, and 800 °C). The results clearly indicate that both parameters significantly affect the pore structure and overall porosity of the mixes.

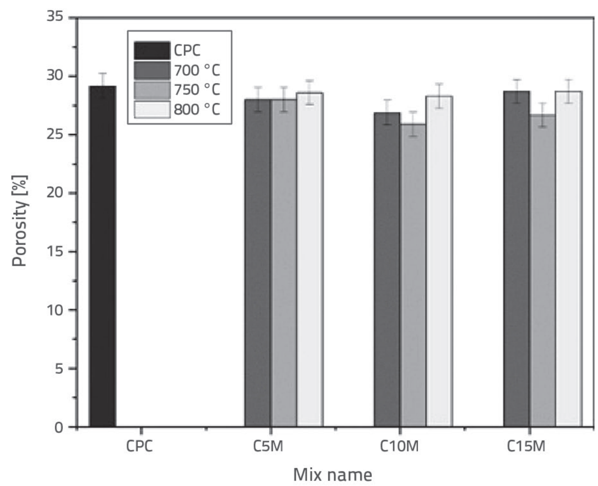

Figure 10. Average porosity of control and pervious concrete with different percentage of CDDS calcined at different temperatures Water permeability coefficient

A slight reduction in porosity was observed for the mixtures incorporating CDDS calcined at 700 °C. The decreases in the 5, 10, and 15 % replacement levels were approximately 4.0, 7.9, and 1.6 %, respectively, compared to the control specimen. This marginal reduction can be attributed to the slightly denser cement paste induced by the incorporation of CDDS. However, the differences relative to the control mix remain modest, likely because the DDS calcined at 700 °C exhibits lower pozzolanic reactivity compared with that at 750 °C, limiting its ability to significantly refine the pore structure.

A more pronounced reduction in porosity was observed for the mixtures containing DDS calcined at 750 °C, particularly at the 10 % replacement level, which recorded a porosity of 25.86 %, representing an 11.3 % reduction compared to the control. For the 5 and 15% CDDS mixes, the corresponding porosity values were 28 and 26.66 %, indicating 4 and 8.6 % decreases, respectively. This notable reduction in porosity is consistent with the observed decline in permeability at the same calcination temperature, and it is attributed to the enhanced pozzolanic activity of the calcined DDS at 750 °C. The increased reactivity contributes to a denser microstructure resulting from secondary calcium silicate hydrate (C-S-H-/C-A-S-H) formation, which effectively refines the pore network and reduces the total porosity [52].

For pervious concrete containing DDS calcined at 800 °C, the reduction in porosity was less significant compared to that observed at 750 °C, consistent with the reduced pozzolanic reactivity of DDS subjected to higher calcination temperatures. As previously noted, the diminished reactivity at 800 °C results in a less pronounced microstructural densification effect.

Overall, the porosity values obtained in this study ranged between 25.87 and 29.17 %, slightly above the target value of 20 %, This difference is probably due to the cement segregation toward the bottom of the mould owing to vibration. Consequently, the lower section becomes dense, whereas the upper part remains porous, distorting the measurements. However, these results remain within the recommended range of 15 to 35 % specified by ACI 522R-10 [28]. These findings confirm that all mixes maintained porosity levels compatible with the functional requirements of pervious concrete, ensuring adequate permeability for drainage applications while achieving improved compactness and mechanical performance.

4. Conclusion

This study investigated the potential use of calcined dredged sediments from K'sob Dam (Algeria) as a SCM for the partial replacement of cement in pervious concrete. Based on the experimental findings, the following conclusions can be drawn:

- The particle size of CDDS decreased progressively with increasing calcination temperature, as shown by granulometric analysis. The residue retained on the 45 μm sieve remained below 10 % for all calcination temperatures, indicating that the material's fineness meets the acceptable criteria for pozzolanic or metakaolin-type SCMs.
- X-ray diffraction (XRD) results revealed that calcination at 750 °C effectively dehydroxylated the Illite phase, producing amorphous aluminosilicate phases with enhanced reactivity. Thus, 750 °C is identified as the optimum calcination temperature to promote pozzolanic activity.
- The pervious concrete incorporating DDS calcined at 750 °C exhibited the highest compressive strength, whereas the lowest strength was recorded for DDS calcined at 700 °C. A 10 % replacement level was found to be optimal, attributed to the combined effects of enhanced pozzolanic reactivity and improved particle packing density within the cementitious matrix.
- The permeability coefficient decreases with increasing CDDS content and is strongly affected by the calcination temperature. The lowest permeability (≈0.69 cm/s) was recorded for the mix with 10 % DDS calcined at 750 °C, showing a 45 % reduction relative to the control due to increased pozzolanic activity and microstructural densification. Despite this reduction, all permeability values (0.63–1.28 cm/s) remained well above the ACI 522R-10[28] minimum requirement of 0.1 cm/s, ensuring sufficient drainage capacity for pervious concrete applications.
- The incorporation of CDDS resulted in a decrease in total porosity, particularly at 10 % DDS calcined at 750 °C, which exhibited a 11 % reduction compared to the control mix. Overall, the recorded porosity values (25.9 to 29.2 %) complied with the ACI 522R-10 [28] recommended range of 15 to 35 %, maintaining the functional balance between permeability and mechanical integrity.

The results demonstrate that calcined dredged sediments from the K'sob Dam can be effectively valorized as a partial cement replacement in pervious concrete. The developed mixes satisfied the mechanical and hydraulic performance standards while reducing cement consumption and utilising local waste resources. This valorization strategy not only addresses the sediment disposal challenges faced by dam authorities, but also promotes sustainable construction practices, resource efficiency, and the principles of the circular economy.

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