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Optimizing Sand Concrete Properties Through Partial Substitution of Natural Sand with Cement Kiln Dust

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ABSTRACT

This study investigated the impact of substituting ordinary sand with cement kiln dust (CKD) as sand on the rheological, mechanical characteristics and some aspects of durability of sand concrete, formulated according to the experimental method of SABLOCRETE. Concrete mixtures were prepared with different CKD replacement rates: 0%, 5%, 10%, 15%, and 20%, while the quantities of cement, water, limestone fines, and adjuvant still constant. Different concrete mixtures were tested to measure: density, workability, air content, compressive and flexural strengths. Moreover, capillarity and immersion tests were performed to evaluate water absorption, and resistance to sulfuric acid exposure was assessed to estimate chemical durability. Results demonstrate that substitution rates had a significant influence on the properties of sand concrete. The optimal mechanical performance was around 15% of CKD sand. In contrast, the highest water absorption rates (both by immersion and capillarity), were observed in the concrete with 20% of CKD sand. However, the mass loss due to sulfuric acid, was lower in concrete containing 10% CKD sand. This investigation underlined the role of CKD's proportion in determining the mechanical and durability characteristics of sand concrete, offering valuable insights for sustainable construction practices.

1. INTRODUCTION

The building materials industry always generates secondary products or waste that have an impact on the environment. However, with the fairly significant development marked in recent years and the scarcity of landfill space, the use of this waste has become an attractive alternative to disposal. The most common modality of upgrading these materials involves their use in applications that do not require high performance. Several studies have indeed confirmed the viability of concretes composed of recycled aggregates, with promising results obtained from various materials such as blast furnace slag, recycled glass, used tires, hardened cement, and demolition waste [1-4].

The cement industry, in particular, generates a type of waste known as "Cement Kiln Dust" (CKD). This highly alkaline solid substance is extracted from the cement kiln with fumes and collected through bag filters or electrostatic precipitators. Annually, millions of tons of CKD are produced, with most of the generated CKD and bypass dust (an odorless substance found in lumps or powder form, ranging from white to grey in color) recycled directly into the cement oven or the clinker crusher. In these processes, CKD partially substitutes materials such as limestone and natural rock constituents, thereby conserving energy and moderating emissions associated with the extraction and processing of these minerals.

However, the direct recycling of dust into the oven often results in a gradual increase in the alkaline content of the produced dust. This can damage cement kiln coatings, reduce cement production, and increase particle emissions due to handling and elimination. Current solutions to this challenge include the addition of CKD directly to the cement produced and/or the use of an alkali diversion system (a method to decrease the alkaline content for oven coating protection) [5].

Researchers worldwide have explored the potential of this waste by incorporating it partially or wholly into new cementations' materials such as mortars and concretes. Kunal et al. [6] replaced Portland cement with CKD (10%, 20%, and 30%), observing an increase in consistency and a decrease in setting time up to 10% CKD addition. Maslehuddin et al. [5] investigated the performance of cement concrete combined with CKD, preparing cementitious concrete samples with 0%, 5%, 10%, and 15% CKD. They noted that the quantity of CKD impacted the compressive strength of the concrete sample. Al-Harthy et al. [7] found that the correct addition of CKD did not adversely affect strength properties and that mortars built with moderate levels of CKD exhibited improved absorption properties. Kherraf et al. [8] and Mohamed El Gamal [9] also conducted studies that demonstrated positive results with the use of CKD.

Finally, all these studies have employed CKD as a partial substitute in cement, but the current study used it as a sand substitute.

2. EXPERIMENTAL PROGRAM

2.1 Resources

Several resources were employed:

- A CEM I 42.5 cement from Ain-Elkebira (Sétif) cement factory (Algeria), (Algerian standard NA 442-2003). Its absolute density is 3.06g/cm^3, its specific surface is 3200cm²/g;

- Class 0/1 dune sand (SD) from the Oued Z'hor quarry (Skikda-East of Algeria);

- Class 0/2 cement kiln dust sand (CKD) from industrial residues recovered by electrostatic filters during clinker production at the Hadjar-Soud/Azzaba cement plant (Skikda-East of Algeria);

- Fine limestone collected at the Ben Azzouz quarry (Skikda-Algeria) with an absolute density of 2.7g/cm^3 and a specific area of 3200cm²/g;

- A poly flow SR 5400 super plasticizer adjuvant with a density of 1.07g/cm3; the specificity of sand concrete favors the use of plasticizers or superplasticizers: they improve handling, more often with an increase in strength as a result of a decrease in water content and deflocculating of fine elements.

- Tap water (T°=28°C) for mixing.

2.2 Material identification

2.2.1 Chemical composition

The chemical composition of the cement and the two sands (Table 1) were determined by X ray fluorescence spectroscopy (XRF), according to NF EN ISO 12677: 2004 and the mineralogical compositions by the BOGUE formula.

Table 1. Chemical and mineralogical composition of the different components

	Dune Sand	CKD Sand	Cement	Limestone Fines
Chemical Composition				
CaO	0.80	65.50	62.66	55.80
Al_2O_3	2.36	6.25	4.32	0.01
Fe_2O_3	1.15	3.86	4.05	0.01
SiO_2	94.09	22.21	22.64	0.14
MgO	0.14	1.27	1.28	0.01
Na_2O	0.2	0.27	0.14	0.01
K_2O	0.58	0.61	0.28	0.01
SO_3	0.01	0.29	1.53	--
Cl^-	--	0.01	0.004	0.21
Mineralogical Composition				
C3S	--	58	43.78	--
C2S	--	19.94	28.61	--
C3A	--	10.03	4.60	--
C4AF	--	11.75	12.31	--

From the results shown in Table 1, it can be seen that ordinary sand is siliceous in nature while the CKD sand is calcareous.

Chemical properties of CKD, are similar to those of cement. It is relatively high in alkaline content (K_2O and Na_2O).

2.2.2 Physical properties

Table 2 lists the physical features that were established using the standards and test results.

We see that:

CKD sand has a higher absolute density than sand from dunes, so it occurs more compacity to the concrete.

CKD sand has a lower sand equivalent (but it is considered clean) than regular sand that is considered to be exceptionally clean sand; both of them are admissible to be used in concrete.

CKD and dune sand are fine. The CKD sand contains more fine particles than the natural sand; it's why it absorbs more water.

Table 2. Physical properties of sands

	Dune Sand	CKD Sand	Standards
Bulk Density g/cm^3	1.52	2.173	NF EN 1097-3
Density g/cm^3	2.591	3.125	NF EN 1097-6
VB %	0.70	--	NF EN 933-9
SE %	86.30	70.50	NF EN 933-8
Ab %	3.35	13.4	NF EN 1097-6
Mf	1.67	1.71	NF EN 933-1
Fines (%)	0.54	7.77	NF EN 933-1

2.2.3 Grain size analysis

According to the Standard NF EN 933-1: 2012, Granulometric analysis of the employed sands was performed, as indicated in Figure 1.

Figure 1 shows that both dune and CKD sand trends are homogeneous and largely comparable.

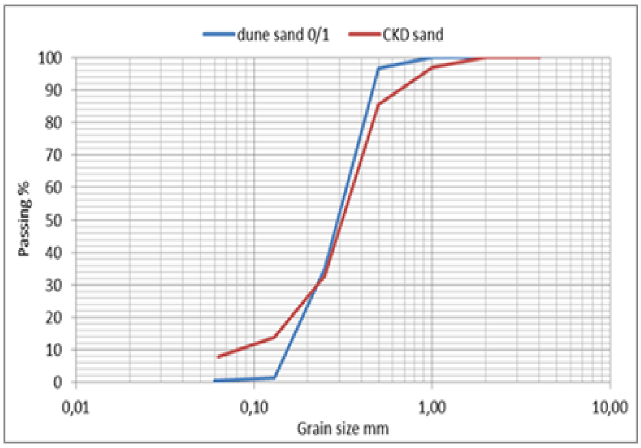

Figure 1. Grain size curves of CKD sand and dune sand

3. METHODOLOGY

The impact of the incorporation of CKD sand in the granular skeleton on the properties of concrete was studied on five compositions (Table 3). The formulation of the control mixture was produced according to the SABLOCRETE experimental method, taking as basic data: constant quantities of cement, water, fine limestone and that of the adjuvant presenting 1% of the cement dosage. The partial substitution of ordinary sand is carried out by replacing a volume of dune sand by the same volume of CKD sand using the rates of 5, 10, 15 and 20%, the choice of these rates is based on literature. The performances of the mixtures thus obtained are evaluated in the both of fresh state and in the hardened one. The outcomes are contrasted with those of the control concrete. The mixes were named as follows:

- **SC0**: sand concrete with 100% dune sand (control mix);
- **SC5**: sand concrete with 95% of dune sand+5% of CKD sand;
- **SC10:** sand concrete with 90% of dune sand+10% of CKD sand;
- **SC15:** sand concrete with 85% of dune sand+15% of CKD sand;
- **SC20:** sand concrete with 80% of dune sand+20% of CKD sand.

Fixed parameters are: W/C=0.68; Cement=400Kg/m^3; Adjuvant=5,556 and limestone fines=252Kg/m^3.

Table 3. Concretes' composition when made using CKD sand

Mixtures	Substitution Rate (%)	Dune Sand (Kg/m^3)	CKD Sand (Kg/m^3)
SC0	0%	1171,246	0
SC5	25%	1112,684	58,5623
SC10	50%	1054,121	117,1246
SC15	75%	995,5591	175,6869
SC20	100%	936,9968	234,2492

The study's concretes were prepared using a 60 liter capacity electric cement mixer with an angled axis. All the materials are first mixed to homogenize them and the total mixing time is 05 minutes including 02 minutes of dry mixing. According to the specification NF P18-421: 1981, the produced concrete is put into molds measuring 15×15×15cm^3 and 7×7×28cm^3, and tightened in layers for 10 seconds. Demolding took place 24 hours after the casting phase. In compliance with standard NF EN 12390-2: 2012, the specimens are then kept in water and maintained at a temperature of 20°C to 2°C till being tested for age.

The following tests were run to describe how each concrete behaved:

• Consistency to measure the workability of concrete (NF EN 12350-5: 1999).
• Bulk density (NF EN 1015-6/A1: 2007).
• Air content (NF EN 12350-7: 2012).
• Compressive strength at 2, 7, 28 and 90 days (NF EN 12390-3: 2012).
• Flexural strength at 2, 7, 28 and 90days (NF EN 12390-5).
• Water Absorption by immersion (NBN B 15-215).
• Capillary Absorption (NF EN 480-5).

4. FINDINGS AND DEBATE

4.1 Fresh state of concrete

4.1.1 Density

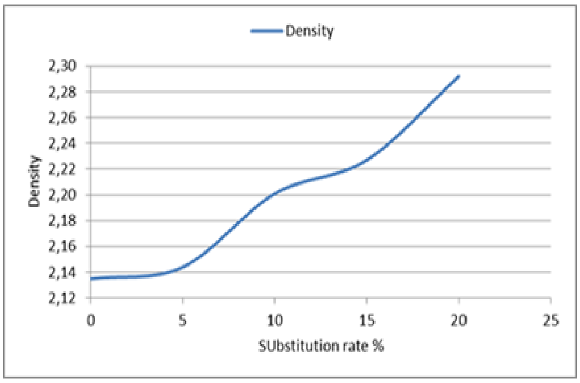

Figure 2. Variation in density as a function of CKD sand content

Figure 2 shows the evolution of density in the fresh stage of the concretes according to the volumetric percentage of CKD sand.

The data collected demonstrate that all of the concretes' densities are increasing. This development is more pronounced when increasing the rate of CKD sand. It is noted that the increase in the density of concrete SC20 compared to that of SC0 represents 7%. This increase is mostly owing to the CKD sand's higher actual density than regular sand, as well as the increased water content brought on by the waste's higher alkalinity's effect on water absorption.

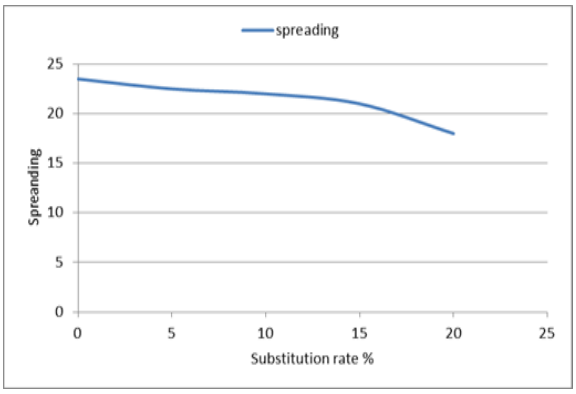

Figure 3. Variation in spread as a function of CKD sand content

4.1.2 Consistency

The concrete slump values are given in Figure 3. It is evident that less spreading occurs with higher CKD content. This workability can be explained by the rough quality of CKD sand, the spherical texture of ordinary sand and the percentage of water absorbed [10, 11].

4.1.3 Air content

The volumes of air occluded in the mixtures developed in our study are shown on Figure 4. The outcomes represent the middle measurement between three values.

It was noted that the addition of CKD sand tends to decrease the entrapment of air in the matrix. The quantity of entrained air declines from 1.56% for SC15 to 30% for SC5 and SC10 concretes, respectively. The decrease of air content in CKD sand concretes is undoubtedly related to the capacity of the fines of the CKD sand to react with the cement and to fill the voids available between the components of the cement matrix.

This may be explained by the high free lime (CaO) content of CKD, which absorbs more water and has a rapid ability to react with OPC (ordinary Portland cement) as found by Najim et al. [12].

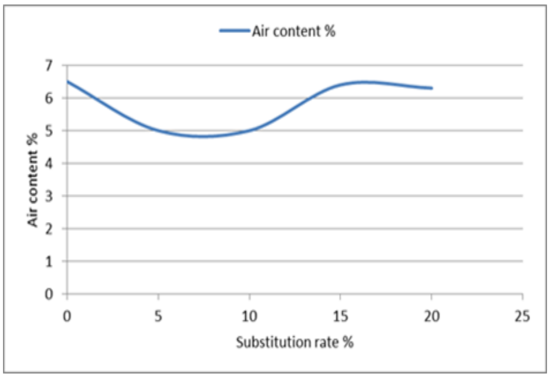

Figure 4. Variation in air content as a function of CKD sand rate

4.2 Hardened concrete

4.2.1 Compressive strength

Three prismatic specimens were used to assess the compressive strength in accordance with NF EN 12390-3:

2012. Figure 5 displays the outcomes for concrete mixtures at 2, 7, 28, and 90 days.

Figure 5 demonstrates that in each of the analysed concretes' instances, the compressive strengths of the CKD-based concretes evolve over time in a similar way to the control concrete. They also vary with increasing CKD dosage. Concrete with 15% of CKD (SC15) always shows the greatest resistance over time.

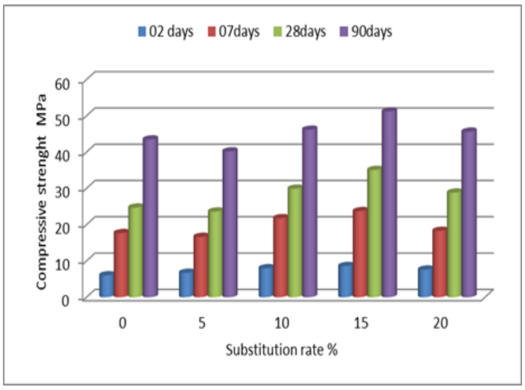

Figure 5. Compressive strength for hardened concrete with various cement kiln dust (CKD) percentages at cure times of 7, 28, and 91 days

Because the compressive strength is determined by a decline in the water/cement ratio as a result of the CKD sand's increased absorption, this behavior is expected. Also, it is attributed to the limestone chemical composition; CKD is rich in free lime (CaO) which raises the amount of C3S in the made-up mixtures and accelerates hydration of clinker (C3S) and consequently increase compressive strength values at young ages. At 28 days, the reactive siliceous fines present in the composition of CKD contribute to improve the compressive strength at this time frame, at the onset of hydration this component is inactive, and nonetheless, it might gradually combine with hydroxide of calcium, resulting from hydration of cement, to get insoluble compounds analogous to cement hydrates, as investigated by Kherraf et al. [8].

Long-term, the outcome is caused by the pozzolanic reaction, which produces an extra C-S-H and has the following formula:

$$SiO_2 + Ca\,(OH)_2 + H_2O \rightarrow C\text{-}S\text{-}H \qquad (1)$$

For SC20, the decrease in strength is presumably the result of the increase in alkalis.

Lot of alkali in cement decreased its quality and influenced the strength and cement paste microstructure; According to Maslehuddin et al. [5], more cement replacement with CKD may result in a decrease in compressive strength when compared to the control concrete mix.

4.2.2 Flexural strength

Using different rates of CKD sand, results in an increase in tensile strength (Figure 6). For the different test deadlines, the 15% CKD sand mixture yielded the most significant value, which presents a gain of 60.84, 39.85, 16.28 and 11.63%, comparing with the control sand concrete at 2, 7, 28 and 90 days, respectively. In fact, the interaction of limestone and CKD particles with the clinker can be used to explain the constant increase in the flexural strength of CKD sand-based mixes, which helps cement paste to adhere on the aggregates.

Also, the favorable effect of capillary depressions, when the concrete is subjected to tensile stress as observed by Kherraf et al. [8].

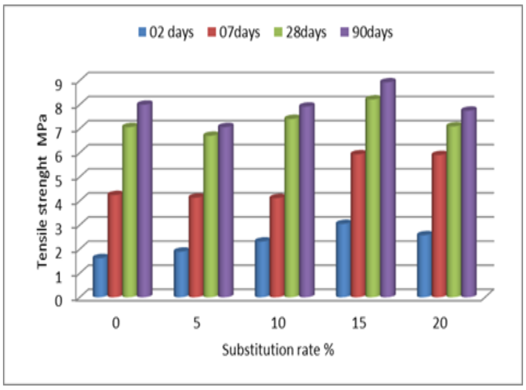

Figure 6. Variation in tensile strength by bending as a function of the CKD sand content at different ages

4.3 Durability

4.3.1 Absorption of water by immersion

It is clear from Figure 7 that the replacement of dune sand by CKD decreases water absorption by immersion. This finding explains why CKD's hydraulic characteristic fills spaces, resulting in less porous constructions as found by Kunal et al. [6].

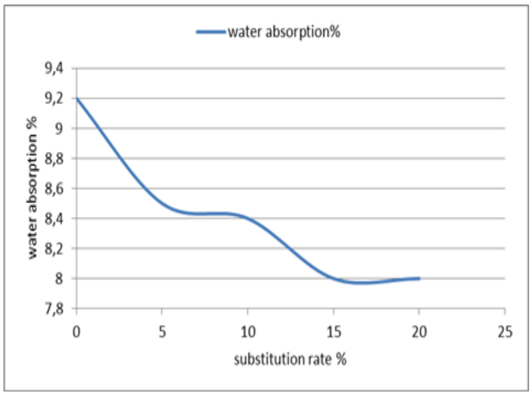

Figure 7. Variation in water absorption as a function of CKD sand rate

4.3.2 Capillary absorption

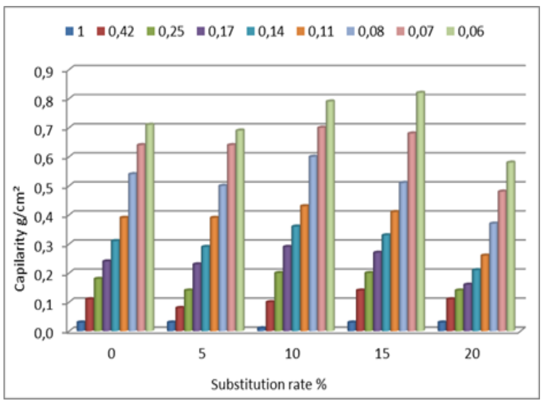

Figure 8. Absorption by capillarity of concretes according to the rate of substitution

The findings of the tests are shown in Figure 8.

It was found that absorption of water by capillarity rises with time. The capillary coefficient decreases for SC5 and grow-up for SC10 and SC15. The minimum absorption was established with the mixture SC20.

This outcome can be explained by the fine nature of CKD sand, which engendered a dense area of contact between cement pastes and granulates.

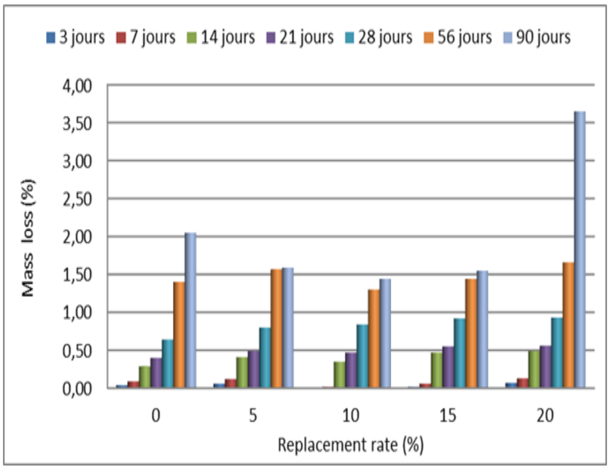

Figure 9. Mass loss of concretes according to the rate of substitution and conservation time in H_2SO_4

4.3.3 Chemical attack in aggressive environment (H_2SO_4)

Cubic samples of 5×5×5 of dimensions were made and conserved 28 days in water, after this period they were immerged in Sulfuric acid solution (concentration of 5%), during 90 days. We measure the weight of our samples at 03; 07; 14; 21; 28; 56 and 90 days. Results are represented by Figure 9.

It can be seen (Figure 9) that the mass loss is greater in the SC20 mixture especially at 90 days; it is more or less stable in the SC5; SC10 and SC15 mixtures. The SC10 mixture is the most resistant to the chemical attack of sulfuric acid.

When concrete is exposed to sulfuric acid, the calcium salt produced by the reaction of sulfuric acid and calcium hydroxide is calcium sulfate which in turn causes increased degradation due to sulfate attack. This process is illustrated below:

$$H_2SO_4+Ca(OH)_2Ca(SO4)+2H_2O$$

Sulfuric acid+calcium hydroxide calcium sulphate+water.

(The calcium sulphate product contributes to sulphate attack).

The dissolution of calcium hydroxide caused by the acid attack, proceeds in two phases. The first phase being the acid-calcium hydroxide reaction in the cement paste. The second phase being the acid-hydrated calcium silicate reaction, this phase will not begin until all the calcium hydroxide is consumed. Dissolution of hydrated calcium silicate, in the most advanced cases of acid attack, can significantly damage concrete [13].

4.3.4 Correlation between compressive strength and mass loss by sulfuric attack

In this part we will compare mechanical performance versus chemical resistance in Figure 10. Good compressive strength doesn't necessarily mean a good resistance to chemical attacks, because of the high content of CKD, SC20 had the highest value of mass loss in the sulfuric acid.

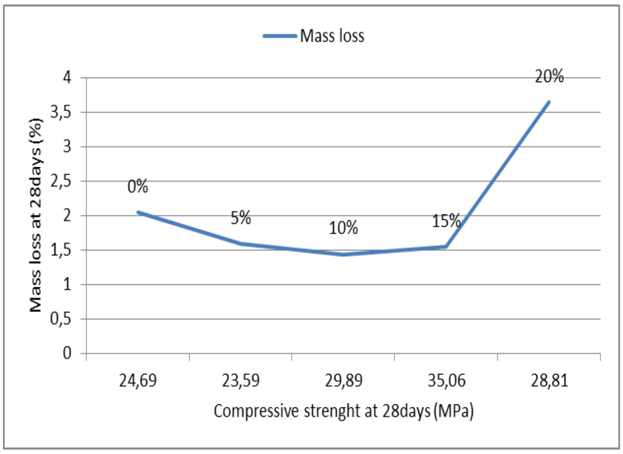

Figure 10. Mass loss at the end of attack cycle and compressive strength at 28 days

4.3.5 Correlation between tensile strength and mass loss by sulfuric attack

Figure 11 shows that the best tensile strength value gave less mass loss with SC15 mixture, whenever the same value (7 MPa) gave us two different behaviors for SC0 and SC20, the last one was more vulnerable to the sulfate attack, may be because of the high content of CKD so more absorption of the acid and more alteration. A study of the microstructure could explain more different phenomena.

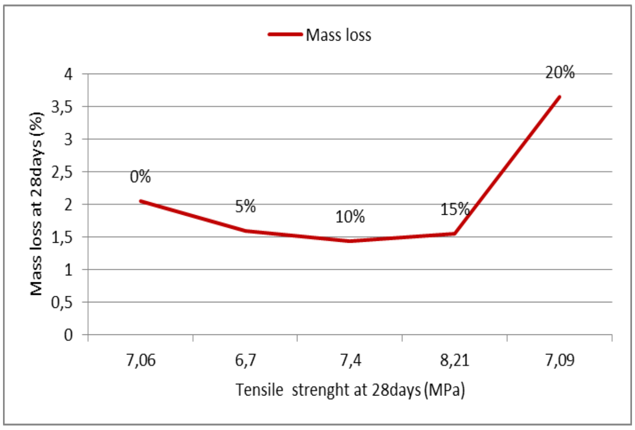

Figure 11. Mass loss at the end of attack cycle and tensile strength at 28 days

5. CONCLUSIONS

This research examined the viability of using sand made from cement kiln dust in the mix for sand concrete. Several conclusions are drawn from the results that are presented:

- CKD sand is characterized by a high level of fines (<63µm) greater than 5% and by very high water absorption: 13.4%, seven times greater.
- Substitution of natural granulates by CKD sand increases the density of the tested concretes, the highest value is observed for SC20.
- The incorporation of CKD sand in sand concretes causes a decrease in their workability.
- The entrained air content of fresh concrete increases

when CKD sand is incorporated. The minimum value is illustrated by the two concretes with 5 to 10% recycled sand.

- The mechanical performance in compression and bending at all measurement intervals, of concretes based on 10 and 15% CKD sand were the best comparing with concrete based on ordinary sand. An optimum is obtained by SC15.
- The water absorption of all the CKD sand-based concretes was lower than that of the control concrete.
- SC5 and SC20 gave the lower coefficient of capillarity than those of the control concrete.
- The mass loss by sulfuric attack was greater in the SC20 mixture especially at 90days; it is more or less stable in the SC5; SC10 and SC15 mixtures. The SC10 mixture is the most resistant to the chemical attack of sulfuric acid.

Finally, this study has shown that concretes based on CKD sand have acceptable characteristics in terms of resistance and durability, and the valorization of that kind of waste as sand, to manufacture concretes, seems to be a promising way. In another side we have to know more about the chemical and physical behavior of CKD when it is used as sand not a powder, infrastructure study, could explain lot of phenomena observed in the current study.

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