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Sustainability Assessment of LC³-based Reinforced Concrete in Simulated Corrosive Semi-arid Environment of Morocco

Aadil Ejbouh[1*], Adil Ech-chebab[1], Sara Hassi[1,2], M. Galai[1], H. Benqlilou[3] and Mohamed Ebn Touhami[1]

[1]*Advanced Materials and Process Engineering Laboratory, Faculty of Science, University Ibn Tofail BP. 133-14000, Kenitra, Morocco*
[2]*Department of Civil Engineering, Fuzhou University, 2 Xue Yuan Road University Town, Fuzhou, Fujian, P. R. China*
[3]*International Institute for Water and Sanitation (IEA), National Office of Electricity and the Potable Water, Rabat, Morocco*

[*]Correspondence to:
Aadil Ejbouh
Advanced Materials and Process Engineering Laboratory,
Faculty of Science, University Ibn Tofail BP. 133-14000, Kenitra, Morocco.
E-mail: adil.ejbouh@uit.ac.ma

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Abstract

This study investigates the sustainability performance of local common raw clay as a supplementary cementitious material (SCM) in concrete in simulated semi-arid environment of Morocco. The service life of the underground concrete pipe is shorter in this harsh environment because of aggressive corrosive soil, and cyclical variation of temperature and humidity. Limestone cement calcined clay (LC^3) and limestone cement fly ash (LCF) and traditional OPC (Ordinary Portland cement) have been investigated. The electrochemical resistance, environmental, and economical performances have been evaluated. In the simulated condition, the LC^3 improve good concrete performance (R_c) in simulated condition by approximately 25 and 3 times compared to LCF and OPC, respectively. The environmental and economical assessments of LC^3 and LCF binder showed a similar cost and embodied CO_2, and both concrete mixes were lower by 38% and 38%, respectively, than the traditional concrete. Ultimately, the LC^3 technology seems to improve eco-friendly sustainability performance in the simulated aggressive semi-arid environment.

Keywords

Calcined clay, Limestone cement calcined clay, Fly ash, Sustainability, Corrosion, Aggressive soil, Wetting drying cycles, Chloride, Sulfate

Introduction

Cement fabrication contributes about 7% to the global CO_2 footprint [1]. However, the demand for building material is advancing due to the rapid development in the construction sector. Blended cement with SCMs which replace a part of clinker is the most interesting solution nowadays. The most SCMs materials used in Morocco are Silica fume and fly ash [2, 3] although these industrial products have a production limitation of only 15% global availability [4]. It is stated in previous research that calcined clay as SCMs improves the durability and sustainability of concrete blends [5, 6]. A study in Cuba shows that LC^3 allows sustainability increase by reducing the climate and social impacts per cost [7], as well as carbon emission, and energy consumption [8]. Also, a recent study in Brazil opened a new perspective for the production of alternative low-carbon and eco-friendly LC^3 cement [9].

In this paper, the sustainability performance of the calcined clay and fly ash was evaluated by comparing the LC^3 and LCF blend to the traditional concrete.

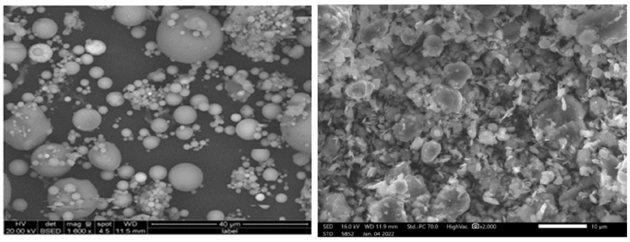
The aim of this study is to evaluate the environmental impact and economic potential of LC^3 and LCF compared to the OPC in simulated harsh environment of aggressive corrosive soil, and cyclical variation of temperature and humidity.

Our findings may encourage both the researchers and industrials in Morocco and in other counties to use calcined clay as SCMs.

Experimentation

Materials proprieties

Portland cement CEM I, limestone and clinker were sourced locally LafargeHolcim Morocco. A common clay was calcined in a laboratory oven at 800 °C for 1 h to achieve high pozzolanic reactivity [10, 11], and fly ash class F obtained from Jorf Lasfer power Morocco were used as SCMs. LC^3-based concrete are nanoscale materials. The chemical compositions of the materials are listed in table 1. The scanning electron microscope images of fly ash and calcined clay particles are shown in figure 1.



(a) (b)

Figure 1: The SEM micrographs of **(a)** fly ash and **(b)** calcined clay.

Table 1: Chemical composition of clinker, calcined clay, fly ash, and limestone (wt.%).

	Clinker	OPC	Fly ash	Calcined clay	Limestone
SiO_2	20.69	15.18	39.5	37.06	8.37
Al_2O_3	5.60	3.68	33.4	10.38	1.87
CaO	64.98	58.42	8.36	23.62	45.83
Fe_2O_3	3.67	2.36	3.35	3.99	0.83
K_2O	0.83	0.56	0.81	1.64	0.13
MgO	2.51	2.55	2.06	2.88	3.56
Na_2O	-	0.09	1.13	-	0.04
SO_3	1.34	2.59	0.4	0.37	0.09
Cl	-	0.01	-	-	-
Na_2O_{eq}	-	0.45			
CaO_{free}	0.38	-	-	-	-
LOI	-	14.58	8.5	20.06	39.28

Mix proportions and test specimen preparation

The calcined clay was mixed with limestone, and clinker to prepare the LC^3 binder. As well fly ash was mixed with limestone and clinker to prepare LCF mix. The OPC was used as control. In order to have a good correlation and to compare the results, the two binders were prepared with same mass ratio of calcined clay (fly ash): limestone in LC^3 (LCF) mixtures of approximately 1:1. The mix compositions are listed in table 2. All the specimens were unmoulded after 24 h and left to cure at 24 ± 1 °C and 100% relative humidity for 28 days.

Environmental test

In this study soil with a concentration of 9 g chloride and 34 g/kg sulfate was used to simulate the environmental conditions of semi-arid area in Morocco. Specimens prepared from different mixes OPC, LC^3, and LCF were buried in this aggressive soil and exposed to 16 wetting and drying cycles as indicated in the previous study. The dry cycle takes 5 days in a laboratory oven at 60 °C, and the wet cycle takes 2 days under water saturation at ambient temperature, which set 7 days of each cycle [12].

Table 2: Concrete mix composition of the mixes.

	OPC	LC^3	LCF
CEM1 (kg/m^3)	450	0	0
Clinker (kg/m^3)	0	280	280
Calcined clay (kg/m^3)	0	76	0
Fly ash (kg/m^3)	0	0	76
Limestone (kg/m^3)	0	94	94
Aggregate (kg/m^3)	1284	1284	1284
Sand dune (kg/m^3)	536	536	536
Water (L/m^3)	172	172	172
W/B	0.38	0.38	0.38

Electrochemical measurements

The electrochemical concrete/reinforcement resistances against the chloride-sulfate penetration were measured by using three electrodes electrochemical cell Potentiostat (PGZ100) (Figure 2) following the methodology in the reference [6]. The measurements were performed at different wetting drying cycles under 10 mV alternating current signal from an initial frequency of 100 MHz to a final frequency of 10 mHz [13].

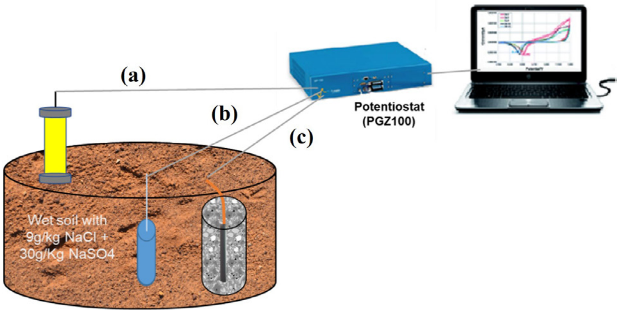


Figure 2: Experimental setup **(a)** reference electrode (Cu/CuSO$_4$), **(b)** counter electrode (stainless-steel), and **(c)** working electrode (reinforcement steel).

Results and Discussion

Electrochemical results

Figure 3 shows the ion transfer resistance R_c of the concrete mixes OPC, LCF, and LC^3 as a function of cyclic wetting drying got from electrochemical data modelling results. it can be seen that the electrochemical parameter R_e of the LCF blended cement is higher than the reference OPC, while LC^3 shows the highest value by approximately 3 times compared to the LCF. This indicates clearly that the concrete incorporated calcined clay can be limit the chloride-sulfate ion transport process in the LC^3 binder [14, 15]. Furthermore, the resistance evolution of LC^3 improves throughout the cyclic variation,

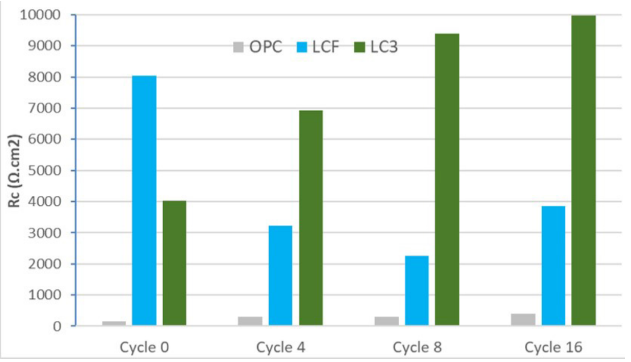


Figure 3: The ion transfer resistance of concrete R_c of the OPC, LCF, and LC^3.

while both OPC and LCF decrease as the wetting-drying cycles progress. the excellent resistance of LC^3 concrete against chloride ingress can be attributed to the pozzolanic reaction of amorphous aluminosilicate ($Al_2Si_2O_7$) product of the calcined clay with calcium hydroxide to form more silicate (CSAH) and alumina hydrate that fill the pore structure, outcoming to a denser structure matrix [16]. On other hand, the alumina of calcined clay reacts with the calcium carbonate of limestone to give hydrates product of carbo-aluminate (C_3ACcH) [6, 17].

Environmental evaluation of embodied carbon and material cost

In this study as all the mixes have the same proportion and composition formulation, the comparison of environmental and economic impacts focuses only on the binder effect, not including other ingredients (gravel, sand, and water). Emission factors Kilogram of CO_2 emitted per Kilogram of material produced was considered in the estimate of mitigation potential [18]. The average cost of LC^3 and OPC was estimated based on the average local market price in Morocco. The cost and CO_2 emission of different materials are listed in table 3. Based on equation (1) the results are presented in figure 4. In addition, the resistance of concrete R_c, was considered for the evaluation of the sustainability performance of each mix. The parameters of traditional OPC binders are considered as the reference. It can be seen in figure 4a that the total embodied carbon of LC^3 and LCF was approximately similar although the fly ash incorporated in LCF mix is considered negligible, and both were lower than OPC by approximately 32% and 38% respectively. Figure 4b presents the material cost of the three concrete mixes. Both LC^3 and LCF binders showed the same cost by contributing to about 67% of the total material cost for traditional concrete.

Table 3: Cost and CO_2 emission of ingredient (the average cost is estimated based of the local market price).

	CO_2 emission (kg/t)	Average market cost (USD/t)
OPC	912 [19]	125
Fly ash	8 [19]	20
Calcined clay	330 [20]	18
Limestone	10	15

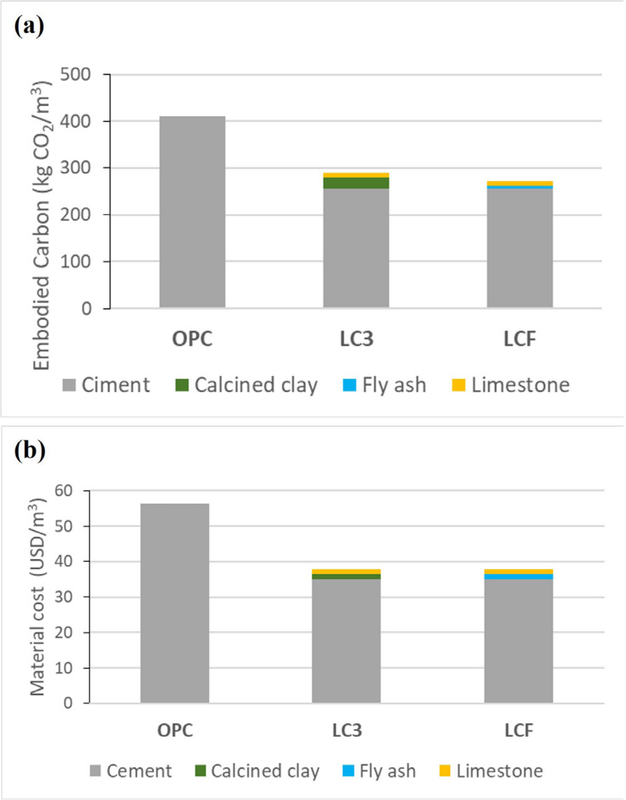


Figure 4: Environmental impacts and material cost of OPC, LCF and LC^3 concrete: **(a)** embodied carbon and **(b)** material cost.

To determine a relationship between these parameters and the environmental/economic impact, the indices below are calculated [19]:

$$R_c\ |\mathrm{Cos}\,t|\ embodied\ CO_2\ Index = \frac{Value\ for\ OPC}{Value\ for\ LC^3\,|\,LCF} \tag{1}$$

$$Global\ Performance\ Index = \frac{\sum_{i=3} Indices\ for\ LC^3\,|\,LCF}{\sum_{i=3} Indices\ for\ OPC} \tag{2}$$

A trade-off between the electrochemical resistance, and environmental/economic potential was considered to evaluate the sustainability of the OPC, LCF, and LC^3 binders. The sustainability performance of the three concrete mixes is quantified based on the equations (1 and 2) in the graph presented in figure 5. The higher the index value the higher performance. It is interesting to note that the LC^3 mark a higher global performance index by 2 times more than LCF

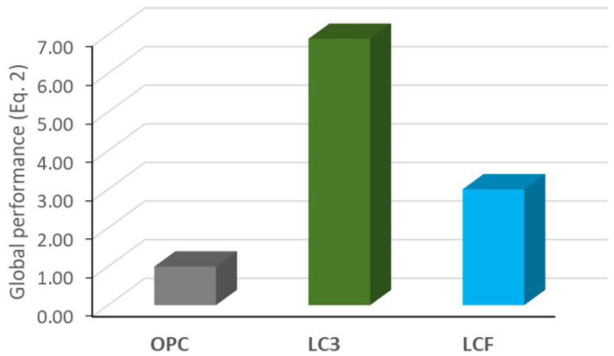


Figure 5: Global performance of OPC, LCF, and LC^3 concrete mixes.

mix, and approximately 7 times compared to the traditional OPC concrete.

Conclusions

In this study, the electrochemical resistance, environmental, and economical performances of OPC, LCF, and LC^3 concrete mixes were investigated. The three binders were tested in a simulated environment of semi-arid area under wetting-drying cycles. According to the experimental measurement, the following main results could be drawn:

- The resistance R_c of LC^3 was higher than LCF and OPC control.
- The total embodied carbon of LC^3 and LCF was approximately similar, and both were lower than OPC by approximately 32% and 38%, respectively.
- The LC^3 and LCF binder showed the same cost by contributing about 67% of the total material cost for traditional concrete.
- The sustainability of LC^3 compared to the OPC was approved by the higher global performance index, which is 2 times more than LCF mix, and approximately 7 times compared to the traditional OPC concrete.

Ultimately, the LC^3 technology seems to improve eco-friendly sustainability performance in the simulated aggressive semi-arid environment.

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Conflict of Interest

None.

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