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Energy Procedia 50 (2014) 421 – 428

Energy Procedia

The International Conference on Technologies and Materials for Renewable Energy, Environment and Sustainability, TMREES14

Morinda lucida effects on steel-reinforced concrete in 3.5% NaCl: Implications for corrosion-protection of wind-energy structures in saline/marine environments

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Abstract

This paper studies effects of the leaf-extract of *Morinda lucida* on the corrosion-degradation of steel-reinforced concrete in 3.5% NaCl, simulating saline/marine environment (prevalent in offshore environments for wind-energy structures/installations). Electrochemical monitoring techniques and compressive-strength testing were employed for different concentrations of the leaf-extract admixture in duplicates of steel-reinforced concrete specimens, partially immersed in the corrosive-medium. Analyses of the experimental test-results according to specification ASTM G16-95 R04 showed that *Morinda lucida* leaf-extract combined highly-efficient corrosion inhibition, $84.82\pm7.76\% \leq \eta \leq 95.64\pm1.50\%$, with good compressive-strength improvements in their admixed steel-reinforced concretes. These bear implications for corrosion-protection of wind-energy structures in saline/marine environments.

Selection and peer-review under responsibility of the Euro-Mediterranean Institute for Sustainable Development (EUMISD)

Keywords: corrosion inhibition efficieny; concrete steel-reinforcement; non-toxic and environmentally-frendly admixture; offshore saline/marine environment; compressive strength change effects; sustainable/durable wind-energy structures/installations

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1876-6102
Selection and peer-review under responsibility of the Euro-Mediterranean Institute for Sustainable Development (EUMISD)
doi:10.1016/j.egypro.2014.06.051

1. Introduction

Curbing energy crisis, environmental pollutions and hazardousness of deleterious emissions from fossil fuel sources [1-3] and the consequent search for sustainable, abundantly available, clean and renewable energy are drawing attentions of energy stakeholders worldwide towards wind-power developments [4-6]. Increased demands from this, for increasing wind-energy capacity, have led to global growth of wind-power installations [4]. Militating against this growth are issues of land availability, wind turbine noise and ecological impact of wind farms to the natural environments all of which are driving wind-power installation from the onshore, that is closer to residential areas, to the coastal offshore regions prevalent with saline/marine environments [4,7].

In spite of its advantages, the offshore wind power installations are not without its own challenges. A major of these include costly construction materials, especially, for wind towers, required for ensuring wind turbines are at suitable heights for accessing higher wind speed to generate more power [4,7-8], and foundations, for securing stability and uprightness of wind-turbines [9-10]. For reducing these material costs, in the trend of growing capacity of offshore wind-power installations, steel-reinforced concrete has been identified as a competitive material for wind towers and foundations that is durable, reliable and potent with lesser maintenance requirement [4,7,9-10].

Installations of wind-energy structures, using steel-reinforced concretes, in aggressive chloride contaminated coastal, i.e. saline/marine, environments engender susceptibility of the steel-reinforced concrete to corrosion attacks. Chloride ingress into the concrete, from the ambient saline/marine prevalent in offshore environments, affects concrete durability through the destruction of the thin passive oxide layer protecting the concrete steel-reinforcement from corrosion degradation [11-13]. Rusts, the byproduct from chloride attacks of concrete steel-rebar, are expansive within the concrete structure leading to cracks, spalling, delamination and loss of structural integrity of the concrete [12,14]. Avoiding insidious catastrophe that could ensue from this stipulates that sustainable designs of steel-reinforced wind-power installations in offshore environments involve adequate corrosion protection policies [10,15].

The use of admixtures in concrete for wind-energy installation has been identified as a potent mean of not only improving strength of the concrete but for also improving its resistance to corrosion [7]. Well-known substances for inhibiting steel-rebar corrosion in chloride contaminated environment include compounds of chromates and of nitrites [12,16-18]. However, limitations on the use of these compounds are increasing in many countries due to the toxicity and hazardousness of the compounds to the environmental ecosystem thus leading to formulations of policies restricting the toxic substances [18-19]. Current research trends include the search for non-toxic and environmentally-friendly admixtures as alternative inhibitors of corrosion in steel-reinforced concretes for replacing the toxic chemicals. Although, leaf-extract of *Morinda lucida* has been found in recent toxicological study [20] as not having toxic effect on bio-functional organs, no study have been done on the effect of the leaf-extract on the corrosion of steel-reinforced concrete in saline/marine environment. Therefore, the objective of this paper was to investigate the effects of the leaf-extract of *Morinda lucida* on the corrosion of steel-reinforced concrete in 3.5% NaCl, simulating saline/marine environment (prevalent in the offshore environments) for durable and sustainable offshore wind-energy structures/installations.

Nomenclature

μ	mean value of dataset
HCP	half cell potential (mV)
CR	Corrosion rate (mm/y)
η	inhibition efficiency (%)
blank	steel-reinforced concrete sample without (i.e. 0%) admixture
blank in W_28	steel-reinforced concrete not used in corrosion experiment but that was cured in water for 28 days
_Dup	the duplicate of steel-reinforced concrete sample
K-S GoF	Kolmogorov-Smirnov goodness of fit test
K-S *p*-value	probability of the Kolmogorov-Smirnov goodness of fit test
_hom	homoscedastic (equal variance) of the student's *t*-test assumption
_het	heteroscedastic (unequal variance) of the student's *t*-test assumption

2. Experimental materials and methods

2.1. Experimental Materials

Leaves of *Morinda lucida* (*M. lucida*) *Rubiaceae* were collected fresh from the Forestry Research Institute, Nigeria. The leaves were identified at the Herbarium of the institute where a sample had been deposited with the voucher FHI. No. 109500. Methanolic extract from the blended dried leaves were varied from 0%, for blank concrete samples, in increments of 0.0833% (i.e. a part by weight of *M. lucida* in 1200 parts by weight of cement) up to 0.4167% and admixed in duplicates of steel reinforced concrete samples, of size 100 mm × 100 mm × 200 mm. These constitute six duplicated (i.e. twelve, in total) steel-reinforced concrete blocks. Centrally embedded, in each block, was 150mm of Ø12mm by 190 mm rod of reinforcing-steel, leaving the remaining 40 mm protrusion for electrochemical monitoring connections. The steel-reinforced concrete blocks were prepared according to standard procedures prescribed in literature [21-22] and in the specifications of [23-24].

2.2. Experimental Methods

Each steel-reinforced concrete specimen was partially immersed, longitudinally, in plastic bowls containing test-solution of 3.5% NaCl, which was made up to just below, but without touching the embedded steel-rebar. Electrochemical measurements [13,25-26] were taken from these, in five days interval for 40 days, then in seven days interval for eight weeks. These constitute 17-point measurements in 96 days. The electrochemical measurements taken from each specimen of steel-reinforced concrete block include:

- Half-cell potential, HCP, versus Cu/$CuSO_4$ electrode, CSE (Tinker & Rasor®) using high impedance multimeter (Mastech®) [16] according to ASTM C876-91 R99 [27]; and
- Corrosion rate, CR, using 3-electrode LPR Data Logger (Metal Samples®) [28], with direct instrument read-out of mpy [29], and which was connected to the concrete test-system as had been described in [14,17,25].

After the ninety-six day electrochemical measurement, compressive-strength testing of each block of steel-reinforced concrete was done [30] using hydraulically powered, Compression Testing Machine, Model YES 2000 (Eccles Technical Engineering Ltd, England) [14]. By this, compressive-strength from the *M. lucida* admixed concretes, including the blank concrete samples, were compared with the compressive-strength of three additionally cast blank steel-reinforced concretes, that were cured in water for 28 days [14] as per the specifications of ASTM C39/C39M-03 [11,31] and ASTM C267-01 [32].

2.3. Data Analyses

For detailing performance of the *M. lucida* admixtures, experimental dataset of the electrochemical monitoring methods from each specimen were subjected to the statistical analyses of the Normal and the Weibull probability distribution functions, pdf's [14,25,33-34]. Also, the Kolmogorov-Smirnov goodness-of-fit test-statistics [35-36] was used for ascertaining compatibility of each dataset to each distribution function, while the student's *t*-test statistics, of the homoscedastic and the heteroscedastic assumptions, was used for studying significance of between-duplicate differences in test-data response. These statistical tests were at $\alpha = 0.05$ level of significance. According to specifications of ASTM G16-95 R04 [37], the compatibility test of dataset with the distribution functions were done for avoiding grossly erroneous conclusions, while the between-duplicate test of significant difference in corrosion test-data were done for studying repeatability, of the performance of *M. lucida* admixture in the corrosive medium.

Mean values, μ, from the probability distribution function that fits the of corrosion rate datasets better find usefulness for estimating inhibition efficiency, η, using the formula [14,17-18,25]:

$$\eta = \frac{\mu_{(blank)} - \mu_{(admixed)}}{\mu_{(blank)}} \times 100 \quad (1)$$

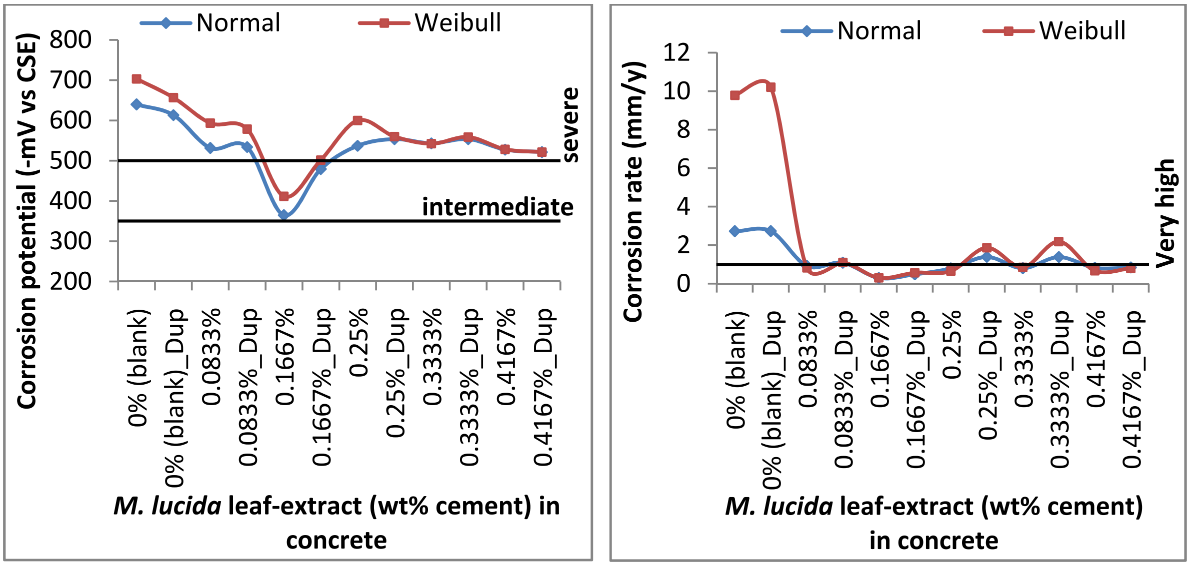
Compressive strength change factor, $CSCF_{(\%)}$, was estimated, for each *M. lucida* admixed concentration in concrete, using relationship described in [14] as per ASTM C267-01 [32]:

$$CSCF_{(\%)} = \frac{f'_{c_{w,28}} - f'_{c_{after\ corrosion}}}{f'_{c_{w,28}}} \times 100 \qquad (2)$$

3. Results and discussion

3.1. Analysed corrosion test-results

Fig. 1 showed the results from the analyses of the corrosion test-data by the Normal and the Weibull distribution functions. Also shown in the figure were linear plots for directly interpreting HCP according to specification ASTM C876-91 R99 [27] in Fig. 1(a), and for directly classifying CR according to [38-39] in Fig. 1(b). Notable from these include the fact that electrochemical test-results from the blank samples without admixture ranged well into the severe condition of corrosive test-systems from both interpretation criteria of the electrochemical monitoring methods. By this, it could be inferred that the test-system represent severe corrosive condition. This followed the preferred practice prescribed by [34] for reducing the time for effects to be observed such that the dominant factor could be used as the rank ordering factor for detailing *M. lucida* performance in the corrosive test-medium.



(a) (b)

Fig. 1. Results from the analyses of corrosion test-data by the Normal and Weibull distributions (a) HCP with corrosion risks interpreting linear plots according to ASTM C876-91 R99 [27]; (b) CR with classifying linear plot according to [38-39].

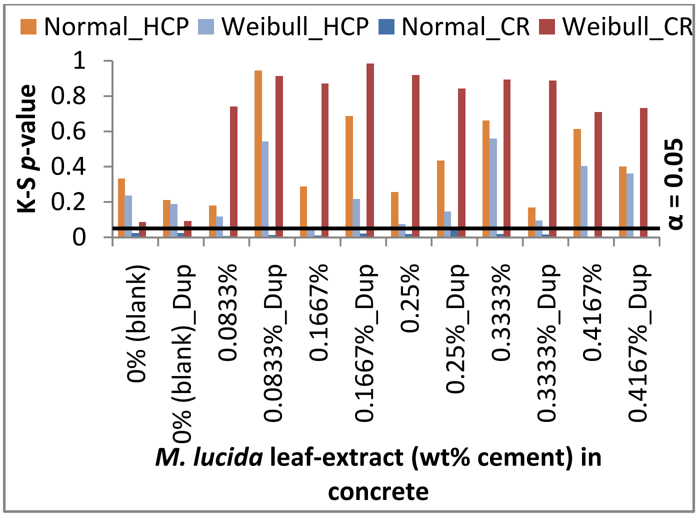
3.2. Results of statistical tests of significance

Results of the K-S GoF test-statistics, on the scattering of measured corrosion test-data like the pdf's, were presented in Fig. 2(a) while the student's *t*-test results on the significance of differences between test-data of duplicate samples were presented in Fig. 2(b). Both of these include the linear plot of $\alpha = 0.05$ for direct interpretations of distribution function compatibility and significance of differences, as appropriate.

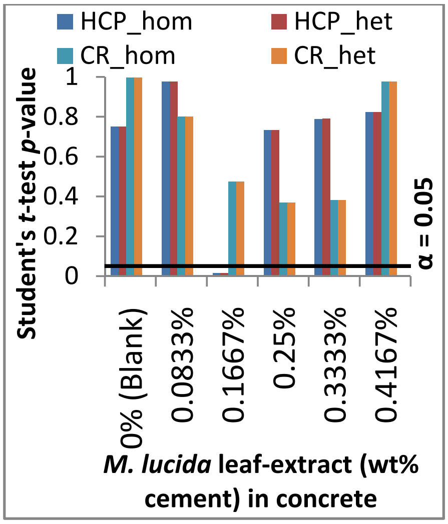
All the datasets of HCP scattered like the Normal and the Weibull distributions, according to the K-S GoF criteria, Fig. 2(a). However, eleven datasets of corrosion rate, out of the twelve corrosion rate datasets, were not distributed like the Normal pdf, whereas all the twelve datasets of corrosion rate distributed like the Weibull pdf according to the K-S GoF test-statistics. These, and the consideration from literature, on the use of CR rather than

HCP for indicating absolute corrosion activities [13,40], support the use of the Weibull pdf as the descriptive statistics for detailing *M. lucida* performance in the saline/marine simulating test-medium.

With the exception of the HCP test-data of the 0.1667% *M. lucida* duplicates, all the differences encountered between the corrosion test-data of the steel-reinforced concrete duplicates studied were just due to chance but were not significant as per the student *t*-test statistics, at $\alpha = 0.05$ level significance. The HCP datasets from the duplicate samples admixed with 0.1667% *M. lucida* exhibited differences that were not due to chance but that were significant by both the homoscedastic and the heteroscedastic student's *t*-test statistics.



(a)



(b)

Fig. 2. Testing statistical significance of corrosion test-data (a) K-S GoF test of test-data scatter like the Normal and the Weibull pdf's (b) student's *t*-test of significance of differences between test-data of duplicate samples.

3.3. Inhibition efficiency performance

The corrosion rate test-data of concrete samples exhibited no significant difference in the test-results from duplicate samples. This fosters estimations of averaged inhibition efficiency of *M. lucida* on steel-reinforced concrete in the 3.5% NaCl corrosive test-medium. Graphical plots of the results of these averaged inhibition efficiencies were presented in Fig. 3, in ranking order of performance by the concentrations of *M. lucida* admixtures.

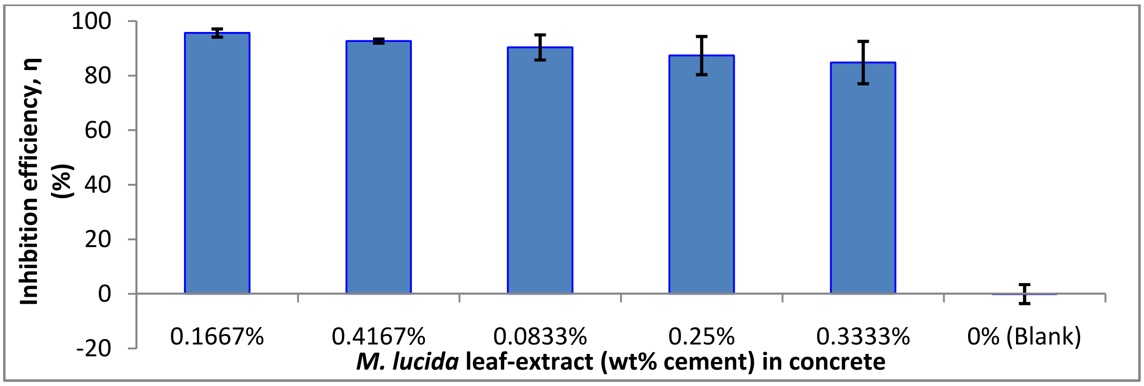


Fig. 3. Ranking order of inhibition efficiency performance by *M. lucida* on concrete steel-reinforcement corrosion.

From the figure, the 0.1667% *M. lucida* admixture exhibited optimal inhibition efficiency, η = 95.64±1.50%. This, according to the efficiency model classification criteria in [41], indicates "excellent" efficiency at inhibiting concrete steel reinforcement corrosion in the corrosive test-system. Also, both 0.4167% *M. lucida* and 0.0833% *M. lucida* admixtures exhibited excellent models of efficiencies at inhibiting concrete steel-reinforcement corrosion by exhibiting η = 92.68±0.74% and η = 90.36±4.61% respectively. The 0.25% *M. lucida* admixture exhibited η = 87.39±7.01% while the least effective 0.333% *M. lucida* admixture exhibited η = 84.82±7.76%. These latter efficiencies both translate to "very good" model of efficiency at inhibiting concrete steel reinforcement corrosion in the 3.5% NaCl, simulating saline/marine environment, as per the efficiency model classifications from [41].

3.4. Compressive strength change effect

Fig. 4 showed the compressive strength change effect, in ranking order of steel-reinforced concrete load-bearing performance, by the *M. lucida* admixture. This identified 0.1667% *M. lucida* as combining optimal inhibition efficiency with optimal compressive strength improvement advantage on steel-reinforced concrete in the saline/marine test-environment. The 0.1667% *M. lucida*, 0.4167% *M. lucida* and the 0.0833% *M. lucida* admixtures exhibited compressive-strength improvement in their admixed steel-reinforced concrete samples that surpassed that of the blank samples that were not part of the 96 days corrosion immersion testing but that were only cured in water for 28 days. Even the 0.3333% *M. lucida* admixture exhibited compressive-strength improvement that surpassed that of the 0% *M. lucida* blank samples which were part of the 96 days corrosion immersion testing. These bear implications that these admixtures combined their effectiveness at inhibiting steel-reinforcement corrosion with load-bearing/compressive-strength improvement in the concretes of their admixtures. Thus, only the 0.25% *M. lucida* admixture exhibited compressive-strength reduction relative to the 0% *M. lucida* blank samples in the study.

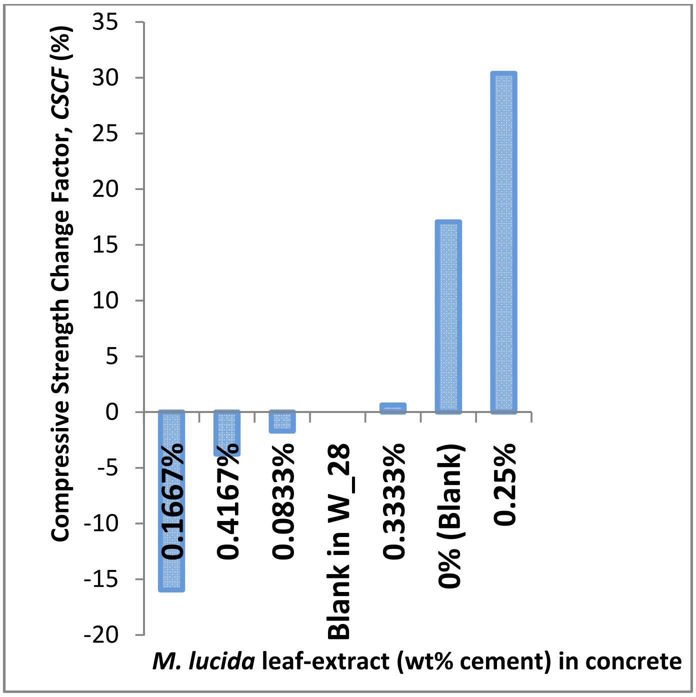


Fig. 4. Compressive-strength change in ranking order of steel-reinforced concrete load-bearing improvement performance by *Morinda lucida* admixtures.

These bear implications on the corrosion-protection wind-energy structures utilising steel-reinforced concrete for the wind-power installations in saline/marine (prevalent in offshore) environments, which include:

- Application of non-toxic, environmentally-friendly *M. lucida* admixture in steel-reinforced concrete, at suitable concentration, is potent for attaining excellent inhibition on the corrosion of the concrete steel-reinforcement in saline/marine service environments, i.e. the prevalent environments in offshore wind-power installations;
- Such application of suitable concentration of the non-toxic, environmentally-friendly *M. lucida* admixture is also potent for attaining load-bearing/compressive-strength improvement in the steel-reinforced concrete for wind-power installation in offshore saline/marine environment;
- While all the concentrations in wt% of cement studied in this work were efficient at inhibiting steel-reinforcement corrosion, choice of suitable concentration, e.g. the 0.1667% *M. lucida*, the 0.41667% *M. lucida* and the 0.0833% *M. lucida*, still remain of high importance for avoiding *M. lucida* admixture concentration that will engender compressive-strength reduction in the steel-reinforced concrete for durable and sustainable wind-power installations in the offshore, saline/marine, service-environment.

4. Conclusion

Morinda lucida effects on the corrosion-degradation of steel-reinforced concrete in 3.5% NaCl, simulating saline/marine environment (prevalent in offshore environments for wind-energy structures/installations) has been studied. From this, the following conclusions could be drawn:

- Analyses of the scatter of corrosion test-data, according to the K-S GoF statistics, showed that the HCP test-data distributed like both the Normal and the Weibull distribution but the fitting of the corrosion rate test-data by the Normal pdf was very poor for almost all the CR datasets, rather, the corrosion rate test-data scattered like the Weibull distribution for all the CR datasets of the steel-reinforced concretes studied;
- Except for the HCP test-data of the 0.1667% *M. lucida* admixture that exhibited between-duplicate difference that was significant, the monitored corrosion test-data exhibited between-duplicate sample differences that were only due to chance but that were not significant, according to the student's *t*-test statistics;
- The 0.1667% *Morinda lucida* admixture exhibited optimal inhibition efficiency, η = 95.64±1.50%, which classifies as "excellent" efficiency model with the inhibition efficiencies by the 0.4167% *M. lucida* and the 0.0833% *M. lucida* admixtures, while the 0.25% *M. lucida* and the 0.3333% *M. lucida* admixtures exhibited "very good" efficiencies at inhibiting reinforcing-steel corrosion in the 3.5% NaCl (saline/marine) environment;
- The 0.1667% *M. lucida* combined optimal corrosion inhibition effectiveness with optimal compressive-strength improvement in concretes of its admixture in the study, the 0.4167% *M. lucida*, and the 0.0833% *M. lucida* also exhibited similar manner of compressive-strength improvement that surpassed that of the blank samples cured in water for 28 days (but not part of the corrosion immersion testing), while only the 0.25% *M. lucida* exhibited compressive strength reduction relative to the 0% *M. lucida* blank samples of the corrosion immersion testing;
- Implications from these identify potency of attaining efficient inhibition of steel-reinforcement corrosion combined with improved compressive-strength advantage through suitable application of environmentally-friendly *M. lucida* leaf-extract admixture in steel-reinforced concrete for saline/marine environment, for durable and sustainable wind-energy structures/installations in the offshore environments.

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