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Mechanical Properties and Corrosion Resistance of Cement Concrete Containing Sea Sand or Sea Water

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Abstract: Through the test of 27 groups of specimens, the influence law on compressive strength and expansion under sea salt corrosion by type of cement, fly ash substitute rate of cement, fly ash substitute rate of fine aggregate, water-binder ratio, type of fine aggregate, and immersion method were analyzed. The corrosion resistance of reinforced concrete under sea water attack was also studied in this research. The experimental results indicate that the influence of various factors on the compressive strength is correlative, and the interaction effects of the type of cement and type of fine aggregate, type of cement and immersion method on the compressive strength are correlative; fly ash substitute rate of fine aggregate, water-binder ratio, type of fine aggregate and immersion were all had significant effects on the expansion at each age. The immersion method had the most significant effect on the expansion. The type of fine aggregate has a significant effect on all tests, but other more correlative factors can be used to improve the deterioration of cement mortar caused by sea sand. Replacement of 10% or 20% aggregate by fly ash gives no apparent improvement in preventing the expansion of cement mortar in sea water exposure. The concrete test results indicate that no serious detrimental effect was found for the corrosion inhibitor in reinforced concrete.

Keywords: sea sand; corrosion; mechanical properties; fly ash.

1. Introduction

The performance of concrete structures in coastal areas is an important issue. Due to limited natural resources and inaccessibility, it is difficult to find clean water and satisfactory aggregates due to limited natural resources and inconvenient transportation. This paper attempts to explore the effect of seawater and unwashed sea sand on the properties of cement mortar with fly ash.

The early strength of concrete made from sea sand and seawater is higher than ordinary concrete, but the long-term strength of sea sand and seawater concrete is approximated to the ordinary concrete [1-6]. The use of sea sand has an adverse effect on the long-term compressive strength of concrete [7]. For the durability of concrete, the freeze-thaw resistance of sea sand concrete is slightly inferior to that of ordinary concrete [8]. The impact of sea sand and seawater on the carbonation process of concrete is negligible. The development trend of the carbonization depth

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of sea sand concrete is the same as that of river sand concrete [9]. The use of seawater as mixing water makes the rebar vulnerable to corrosion [10-11]. A corrosioninhibitor, mixed into the concrete, could react with steel forming a stable oxide film on the steel rebar surface, and prevent steel from corrosion [12].

The purpose of this study is to improve the strength and durability of cement mortar in the marine environment, study the impact of different factors on the properties of cement with fly ash, and evaluate the feasibility of sea sand as a concrete construction material.

2. Experiment Design

2.1. Experimental Material

Portland Type I, II, V Portland cement; bagged fly ash from Taiwan Power Company, the chemical composition of cement and fly ash is shown in Table 1; sea sand taken from Taoyuan, river sand taken from Shihmen Reservoir, the physical properties of aggregates are shown in Table 2. Artificial seawater is formulated according to ASTM D-1141 [13] and the components are shown in Table 3.

Table 1. Chemical composition of cement and fly ash.

Chemical composition/%	SiO_2	Al_2O_3	CaO	MgO	SO_3	Fe_2O_3	Na_2O	K_2O
Type I cement	21.02	5.78	65.01	1.65	2.35	3.2	0.21	0.63
Type II cement	21.48	4.84	63.69	3.58	1.91	4.44	-	-
Type V cement	20.94	4.38	66.91	0.78	1.86	4.8	0.20	0.53
Fly ash	56.14	22.26	3.26	1.36	0.58	7.48	-	-

Table 2. Physical properties of aggregate.

Physical properties	Coarse aggregate	River sand	Sea sand	Washed Sea sand
Fineness modulus	-	1.24	1.00	0.99
Surface dry density	2.61	2.66	2.70	2.71
Surface dry moisture content	1.38%	1.71%	1.97%	1.86%

Table 3. Main components of artificial sea water.

Chemical composition	Solution concentration（g/L）
NaCl	24.50
$MgCl_2 \cdot 6H_2O$	11.10
Na_2SO_4	4.10
$CaCl_2$	1.20
KCl	0.70

2.2. Proportion of Experiment

There are many factors influencing the sea sand specimens, it takes a lot of manpower and materials to make specimens, and the maintenance process takes up a lot of space. Therefore, the orthogonal design is used in this test, and the test quantity is reduced on the premise that the test result has analytical significance. The factors and levels are shown in Table 4. Orthogonal experimental design [16] is shown in Table 5 (wherein "RS" stands for "river sand", "SS" stands for "sea sand", "WS" stands for "washed sea sand", "SL" stands for "saturated lime water", "SW1" stands for "artificial seawater", and "SW2" stands for "double main components of artificial seawater").

Table 4. Factors and levels.

Factors / Levels	A Type of cement	B Fly ash substitute rate of cement	C Fly ash substitute rate of fine aggregate	D Water-binder ratio	E Type of fine aggregate	F immersion method
1	I	0/%	0/%	0.45	RS	SL
2	II	15/%	10/%	0.55	SS	SW1
3	V	30/%	20/%	0.65	WS	SW2

Note: "SW1" stands for "artificial seawater".
"SW2" stands for "double main components of artificial seawater".

Table 5. Mix design of orthogonal experiment（$L_{27}3^6$）.

Factors / No. of specimens	D Water-binder ratio	B Fly ash substitute rate of cement	C Fly ash substitute rate of fine aggregate	E Type of fine aggregate	F Immersion method	A Type of cement
1	1（0.45）	1（ 0%）	1（ 0%）	1 （RS）	1（ SL ）	1 （I）
2	1（0.45）	1（ 0%）	2（10%）	2 （SS）	2（SW1）	2（II）
3	1（0.45）	1（ 0%）	3（20%）	3（WS）	3（SW2）	3（V）
4	1（0.45）	2（15%）	1（ 0%）	2 （SS）	2（SW1）	3（V）
5	1（0.45）	2（15%）	2（10%）	3（WS）	3（SW2）	1 （I）
6	1（0.45）	2（15%）	3（20%）	1 （RS）	1（ SL ）	2（II）
7	1（0.45）	3（30%）	1（ 0%）	3（WS）	3（SW2）	2（II）
8	1（0.45）	3（30%）	2（10%）	1 （RS）	1（ SL ）	3（V）
9	1（0.45）	3（30%）	3（20%）	2 （SS）	2（SW1）	1 （I）
10	2（0.55）	1（ 0%）	1（ 0%）	2 （SS）	3（SW2）	1 （I）
11	2（0.55）	1（ 0%）	2（10%）	3（WS）	1（ SL ）	2（II）
12	2（0.55）	1（ 0%）	3（20%）	1 （RS）	2（SW1）	3（V）
13	2（0.55）	2（15%）	1（ 0%）	3（WS）	1（ SL ）	3（V）
14	2（0.55）	2（15%）	2（10%）	1 （RS）	2（SW1）	1 （I）
15	2（0.55）	2（15%）	3（20%）	2 （SS）	3（SW2）	2（II）
16	2（0.55）	3（30%）	1（ 0%）	1 （RS）	2（SW1）	2（II）
17	2（0.55）	3（30%）	2（10%）	2 （SS）	3（SW2）	3（V）
18	2（0.55）	3（30%）	3（20%）	3（WS）	1（ SL ）	1 （I）
19	3（0.65）	1（ 0%）	1（ 0%）	3（WS）	2（SW1）	1 （I）
20	3（0.65）	1（ 0%）	2（10%）	1 （RS）	3（SW2）	2（II）
21	3（0.65）	1（ 0%）	3（20%）	2 （SS）	1（ SL ）	3（V）
22	3（0.65）	2（15%）	1（ 0%）	1 （RS）	3（SW2）	3（V）
23	3（0.65）	2（15%）	2（10%）	2 （SS）	1（ SL ）	1 （I）
24	3（0.65）	2（15%）	3（20%）	3（WS）	2（SW1）	2（II）
25	3（0.65）	3（30%）	1（ 0%）	2 （SS）	1（ SL ）	2（II）
26	3（0.65）	3（30%）	2（10%）	3（WS）	2（SW1）	3（V）
27	3（0.65）	3（30%）	3（20%）	1 （RS）	3（SW2）	1 （I）

2.3. Test Piece Preparation and Experimental Method

In this study, the compressive strength and expansion of the specimens after artificial seawater immersion treatment were tested. According to ASTM C-109 [14], 50 mm cube mortar specimens were prepared and the compressive strength was measured. According to ASTM C-490 [15], 25 × 25 × 285 mm prismatic mortar specimens were prepared and the expansion was measured. The erosion degree of the cement mortar affected by sea salt was measured by the expansion. After demoulding, the specimens were soaked in saturated lime water and artificial seawater respectively. The saturated lime water was used to simulate the environment of general structures. Artificial seawater was used to simulate the environment of marine structures. Soaking solution was changed once a month. The test specimens were maintained until 7d, 14d, 28d, 56d, 90d, and 180d respectively.

A #6 steel rebar was inserted in the center of a concrete cylinder, 100 mm in diameter and 450 mm in height, used in the corrosion potential test. Electric potential was measured by using Ag/AgCl SCE potentiometer according to ASTM C876. The factors considered and the combinations of concrete samples are shown in Table 6.

Table 6. Factor Combinations of Concrete Samples.

Factors	Combinations
a. Water-binder ratio	0.60
b. Fly ash substitute rate of cement*	0%, 20% cement by volume
c. Fly ash substitute rate of fine aggregate	0%, 10% sand by volume
d. Mixing water	sea water
e. Corrosion inhibitor	0%, 3% by weight of cement
f. Immersion method	Saturated lime water, sea water

* Type I cement

3. Experimental Results and Analysis

3.1. Compressive Strength

Using the Duncan's Multiple Range Test [17], the order of compressive strength of the same factor at three levels can be seen, as shown in Table 7. The combination with the highest compressive strength is A3B1C2D1E1F2: type V cement, 0% fly ash substitute rate of cement, 10% fly ash substitute rate of fine aggregate, water-binder ratio 0.45, river sand, and seawater immersion in 180 days.

Table 7. Three levels range of compressive strength.

Factors	Range
A. Type of cement	V≈I>II
B. Fly ash substitute rate of cement	0%>15%>30%
C. Fly ash substitute rate of fine aggregate	10%≈20%>0%
D. Water-binder ratio	0.45>0.55>0.65
E. Type of fine aggregate	RS > SS > WS
F. Immersion method	SW1>SL>SW2

The changes in compressive strength at 180 days under the 6 factors at three levels are shown in Fig. 1 and Fig. 2, in which fly ash substitute rate of fine aggregate (C) and water-binder ratio (D) are the most significant factors. Compressive strength reaches the highest when the fly ash substitute rate of fine aggregate is 10%, while types of fine aggregate (E) and immersion method (F) have less impact on compressive strength. The interaction between the type of fine aggregate and the type of cement, and the interaction between the immersion method and the type of cement, respectively has a great influence on the compressive strength.

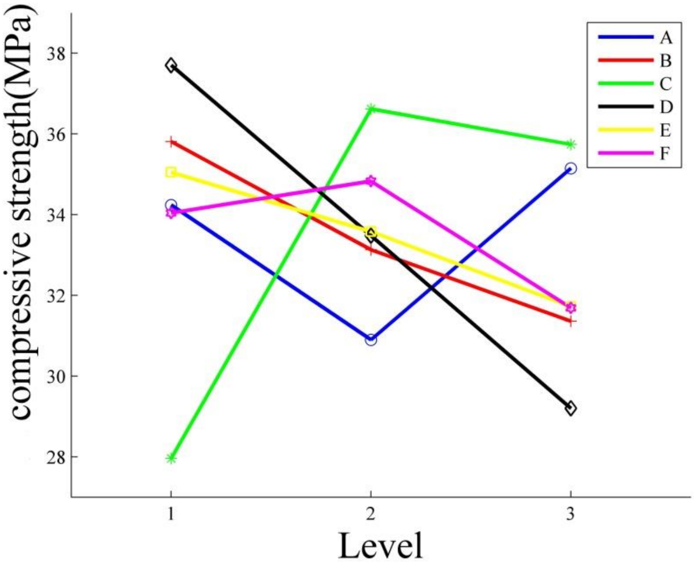

Figure 1. The influence of different factors on the compressive strength at 180 days.

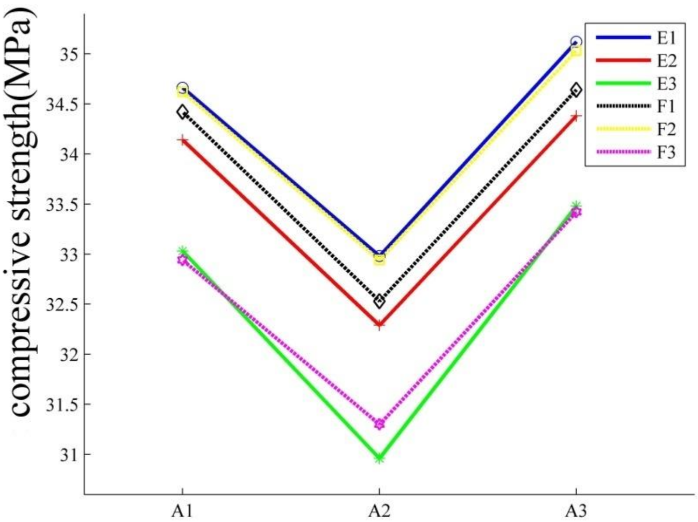

Figure 2. Interaction between A and E/F on the compressive strength at 180 days.

The variance results analysis of compressive strength at various ages for sea sand specimens are shown in Table 8. F test is a method to compare variance of two different sets of values. F test is applied on F distribution under null hypothesis. For calculating F value, first find the mean of two given observations and then calculate their variance [16]. F value is expressed as the ratio of variances of two observations in Table 8. It can be seen from the table that type of cement (A), fly ash substitute rate of cement (B), fly ash substitute rate of fine aggregate (C), water-binder ratio (D), type of fine aggregate (E) and immersion method (F) almost had highly significant effects on the compressive strength at each age. In the initial stage (no more than 28 days), the effect of fly ash substitute rate of cement (B) has a significant effect on compressive strength. For the same proportion of test pieces, the initial compressive strength is mainly affected by the fly ash substitute rate of cement (B), and the compressive strength at the later stage is mainly affected by the fly ash substitute rate of fine aggregate (C). The interaction effects of the type of cement (A) and type of fine aggregate (E) / immersion method (F) on the compressive strength are both significant, indicating that it may be for a certain type of cement and a certain type of fine aggregate, the combination of the two can get the highest compressive strength, that is, the combination of type V cement and river sand. Similarly, the combination of type V cement and double seawater can also achieve maximum strength.

Table 8. F value in variance analysis of compressive strength.

Properties / Variance origin	7d compressive strength	14 d compressive strength	28 d compressive strength	56 d compressive strength	90 d compressive strength	180 d compressive strength
A	16.41**	25.72**	14.27**	23.14**	27.97**	38.00
B	69.12**	127.69**	100.3**	72.75**	56.49**	37.99**
C	65.14**	106.32**	73.18**	117.28**	169.66**	174.71**
D	33.61**	72.08**	78.69**	91.44**	117.27**	139.67**
E	16.75**	27.34**	25.54**	19.01**	15.11**	21.25**
F	4.27*	8.23**	9.23**	15.39**	23.22**	22.14**
A*E	10.05**	23.94**	19.3**	24.17**	30.53**	31.99**
A*F	11.74**	18.96**	14.16**	18.34**	19.46**	21.39**

NOTE: ** Highly significant at α level of 0.01; * Significant at α level of 0.05.

3.2. Expansion

Using the Duncan's Multiple Range Test, the order of expansion of the same factor at three levels can be seen, as shown in Table 9. The combination with the highest compressive strength is A3C1D1E3F1: type V cement, 0% fly ash substitute rate of cement, water-binder ratio 0.45, washed sea sand, and saturated lime water immersion.

Table 9. Three levels range of expansion.

Factors	Range
A. Type of cement	I > II≈V
B. Fly ash substitute rate of cement	-
C. Fly ash substitute rate of fine aggregate	20% ≈10% > 0%
D. Water-binder ratio	0.65 ≈ 0.55 >0.45
E. Type of fine aggregate	RS ≈ SS > WS
F. Immersion method	SW2> SW1> SL

The changes of 180-day expansion under the 6 factors at three levels are shown in Fig. 3 and Fig. 4, in which the water-binder ratio (D) and the immersing method (F) have a great influence on the expansion. In particular, specimens soaked in double seawater are more severely attacked by sulfate. Fly ash substitute rate of cement (B) and the Type of fine aggregate (E) have little effect on expansion. The interaction effects of the type of cement (A) and type of fine aggregate (E) / immersing method (F), has little effect on the expansion.

The variance analysis results of the expansion at each age of the sea sand test specimens are shown in Table 10. It can be seen that the fly ash substitute rate of fine aggregate (C), the water-binder ratio (D), the type of fine aggregate (E) and the immersion method (F) almost had highly significant effects on the expansion of each age. Among them, the immersing method (F) has the most significant effect on the expansion. The influence of the type of cement (A) on the expansion is not obvious at the initial stage, and it has no significant effect until 14 days. It may be due to the different types of cement that the soaking solution has different hydration products.

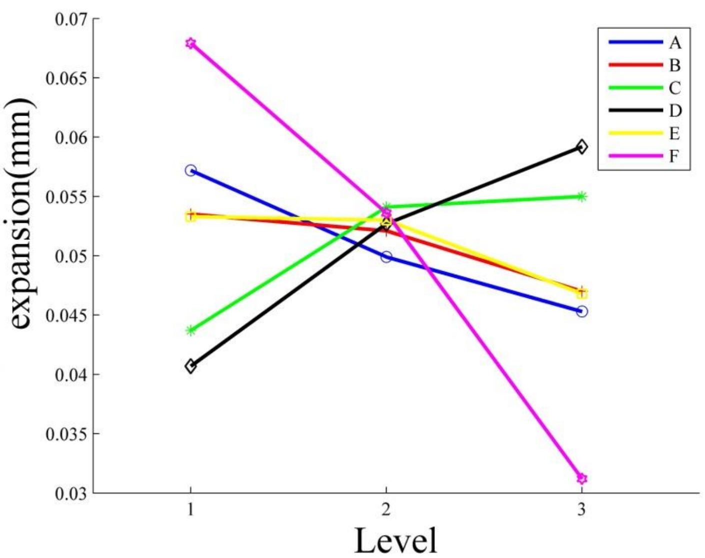

Figure 3. The influence of different factors on the expansion at 180 days.

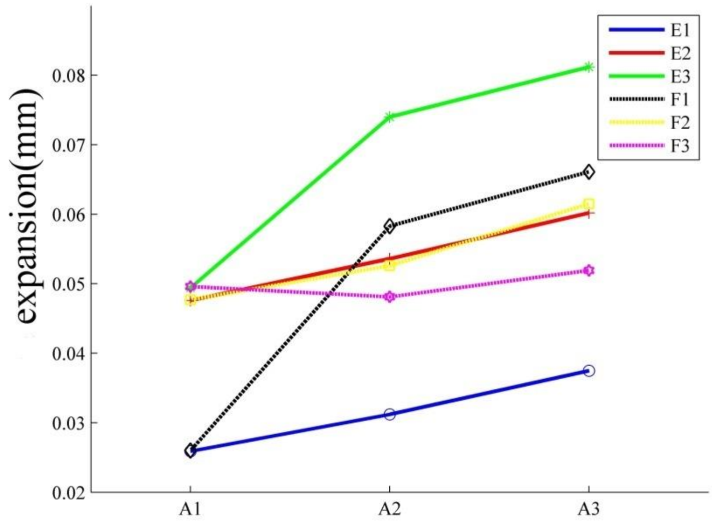

Figure 4. Interaction between A and E/F on the expansion at 180 days.

Table 10. F value in variance analysis of expansion.

Properties / Variance origin	7d Expansion	14 d Expansion	28 d Expansion	56 d Expansion	90 d Expansion	180 d Expansion
A	0.39	6.91**	6.93**	13.88**	18.73**	24.47**
B	0.71	0.80	0.78	2.64	3.92*	7.78**
C	5.76**	12.68**	13.60**	16.06**	21.86**	26.93**
D	14.17**	27.56**	38.95**	38.76**	49.22**	60.33**
E	5.11*	6.67**	12.04**	6.65**	9.27**	9.06**
F	21.08**	107.18**	148.39**	154.60**	190.56**	235.10**
A*E	0.56	2.41	1.20	1.87	2.36	3.05*
A*F	0.45	2.11	3.18	2.18	2.43	3.25*

3.3. Corrosion Potential Measurement

In accordance with ASTM C876, there is a probability greater than 90% that no reinforcing steel corrosion is occurring when the potential is numerically less than -200 mV CSE. Beyond the level of -350 mV CSE, the corrosion is occurring with a probability higher than 90%. However, a simple comparison of the half-cell potential data with the ASTM guideline on steel reinforcement corrosion probability could prove meaningless. For instance, a more negative reading of potential is generally considered to indicate a higher probability of corrosion [12]. Potentials of the reinforcing steel bars inserted in concrete cylinders, exposed to seawater and saturated lime water, are shown in Tables 11 and 12. Results show that the worst condition was the sea water mixed concretes soaking in sea water. However, when the sea water mixed concrete was placed in saturated lime water for 100 days, the potential increased from about -461 mV to -290 mV. This indicates that the alkaline environment in the concrete will protect the reinforcing bar if one more chloride ions penetrated from the environment. Results also show that the use of fly ash to replace 20% cement by volume gave no improvement in protection of steel rebar corrosion when the sample was mixed with and soaked in sea water. However, addition 3% corrosion inhibitor was effective in reducing the corrosion probability in all cases. The potential was gradually increased to a non-corrosion level. This indicates that a passive layer was formed to protect steel rebar from corrosion [12].

Table 11. Electric potential of steel rebars soaked in saturated lime water (mV).

Duration	0 day	20 days	50 days	80 days	100 days
b0c0e0[1]	-461	-427	-335	-306	-290
b2c0e0[2]	-474	-471	-360	-290	-298
b0c1e0[3]	-471	-405	-350	-307	-294
b0c0e3[4]	-375	-321	-245	-202	-152
b2c0e3[5]	-337	-330	-228	-211	-192
b0c1e3[6]	-330	-298	-260	-235	-211

Table 12. Electric potential of steel rebars soaked in sea water (mV).

Duration	0 day	20 days	50 days	80 days	100 days
b0c0e0[1]	-461	-407	-435	-476	-490
b2c0e0[2]	-474	-425	-470	-490	-538
b0c1e0[3]	-471	-365	-380	-387	-399
b0c0e3[4]	-375	-320	-230	-192	-145
b2c0e3[5]	-337	-310	-261	-241	-202
b0c1e3[6]	-330	-290	-265	-260	-251

[1]Control group.
[2]The specimen contains 20% replacement of cement by fly ash.
[3]The specimen contains 10% replacement of sand by fly ash.
[4]Control group contains 3% corrosion inhibitor.
[5]The specimen contains 20% replacement of cement by fly ash and 3% corrosion inhibitor.
[6] The specimen contains 10% replacement of sand by fly ash and 3% corrosion inhibitor.

4. Conclusion

The main findings from this study are summarized as follows:

The combination with the highest compressive strength is A3B1C2D1E1F2: type V cement, 0% fly ash substitute rate of cement, 10% fly ash substitute rate of fine aggregate, water-binder ratio 0.45, river sand, and seawater immersion. The type of cement (A), fly ash substitute rate of cement (B), fly ash substitute rate of fine aggregate (C), water-binder ratio (D), type of fine aggregate (E) and immersion ways (F) almost had highly significant effects on the compressive strength at each age. The interaction effects of the type of cement (A) and type of fine aggregate (E) / immersing ways (F) on the compressive strength are both highly significant.

(1)

The combination with the smallest elongation is A3C1D1E3F1: type V cement, 0% fly ash substitute rate of cement, water-binder ratio 0.45, washed sea sand, and saturated lime water immersion. This means that as long as the salt was washed out of the sea sand they could use it for concrete. The fly ash substitute rate of fine aggregate (C), the water-binder ratio (D), the type of fine aggregate (E) and Immersion method (F) almost had highly significant effects on the expansion of each age. Among them, the immersion method (F) has the most significant effect on the expansion. The influence of the type of cement (A) on the expansion is not obvious at the initial stage, and it has no significant effect until 14 days.

(2)

The results of variance analysis showed that the type of fine aggregate (E) has a significant effect on each test, but other more significant factors can be used to improve the deterioration of cement mortar caused by sea sand. For the sea sand cement mortar with fly ash, the research result could be used for reference. It also could raise the reuse percentage of sea sand reduce the lack of aggregate.

(3)

The use of fly ash to replace 20% cement by volume gave no improvement in protection of steel rebar corrosion under an aggressive sea water environment.

(4)

The addition of 3% corrosion inhibitor in concrete was effective in reducing the corrosion probability under an aggressive sea water environment. The potential was gradually increased from corrosion level to a non-corrosion level.

(5)

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