Journal of Advanced Concrete Technology

Materials, Structures and Environment

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Journal of Advanced Concrete Technology, volume 14 (2016), pp. 163-171

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Scientific paper

Study on Concrete for Civil Engineering Structures Using High Volume Blast Furnace Slag Cement

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Received 20 August 2015, accepted 14 April 2016

doi:10.3151/jact.14.163

Abstract

The use of “Energy CO₂ Minimum (ECM)” cement incorporating high amount of blast-furnace slag contributes to reduction of energy consumption and CO₂ emission. In this paper, results of experiments which were conducted in the purpose of applying the concrete using the ECM cement for civil engineering structures are presented. The Results of experiments show that the fundamental properties of fresh and hardened ECM concrete with water-cement ratio of 50% are equivalent to those of concrete using blast-furnace cement type B (BB) with water-cement ratio of 55%. In addition, the excellent performance of durability was verified by the tests using large-scale wall members.

1. Introduction

In response to global warming, greater efforts are being made to reduce CO₂ emissions by establishing goals for each country. Various measures are being taken in Japan, and a major challenge in the construction industry is to reduce the CO₂ generated in the process of manufacturing cement, which accounts for 4% of total emissions in Japan (JSCE 2012).

One way of reducing cement-derived CO₂ is to utilize blast-furnace slag powder, which is a by-product from steel plants. Since the raw material emits no CO₂, nearly 100% of the slag contributes to CO₂ reduction when mixed with Portland cement.

Commercial blast-furnace cement class B (“BB” hereafter) contains 40% blast-furnace slag powder and is widely used at present. Blast-furnace cement class C has a higher content of slag powder, which is desirable from the viewpoint of CO₂ reduction, but it is seldom used due to challenges such as the large amount of bleeding, low initial strength, significant autogenous and/or drying shrinkage, and tendency for rapidly progressing carbonation.

To resolve the issues specific to cement with a high content of blast-furnace slag, recent studies have focused on improvement methods such as increasing the content of SO₃ in cement or adjusting the water-cement ratio

(Nito *et al* 2008; Kanai 2011; Wachi 2011).

Against this background, we are studying the application of cement with a high content of blast-furnace slag (“ECM” hereafter, reported by Yonezawa *et al* 2010) to civil engineering structures. As part of the study, we examined the application of ECM to RC structures, which have relatively massive components including box culverts for road tunnels or substructures of bridges. In the study, we established a set of conditions for ordinary concrete using BB for these structures: slump of 8 cm, water-cement ratio of 55%, and unit cement content of 300 kg/m³ (“BB mix proportion” hereafter), and conducted the study with the aim of developing ECM concrete with equivalent performance. This report describes how the basic properties of the concrete for civil engineering structures using ECM (“ECM mix proportion” hereafter) were obtained and how specimens at the same scale as actual structures were constructed. The results of evaluating the hardening properties are also presented.

2. Considerations on the basic properties of concrete for civil engineering structures

2.1 Summary of considerations

First, the ECM mix proportion, which has a carbonation resistance equivalent to the BB mix proportion, was selected based on the results of accelerated carbonation tests on the concrete using an ECM mix proportion with a slump of 8 cm. In the tests, while the water-cement ratio was lowered to ensure carbonation resistance, the unit cement content was kept at 300 kg/m³ since the purpose of using ECM is to reduce CO₂. Given the reduced water-cement ratio due to the decrease in unit water content, it was not possible to ensure a slump of 8 cm; therefore, we newly developed and applied an AE water reducing agent with high dispersibility of blast-furnace slag powder and high slump retention performance.

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Table 1 Chemical composition and physical properties of the cement.

Cement	Density (g/cm ³)	Specific surface area (cm ² /g)	Chemical composition of cement (%)										
			SiO ₂	Al ₂ O ₃	FE ₂ O ₃	CaO	MgO	SO ₃	Na ₂ O	K ₂ O	TiO ₂	P ₂ O ₅	MnO
ECM	2.98	4000	28.13	10.90	1.22	49.12	4.62	3.59	0.27	0.30	0.48	0.08	0.23
BB	3.04	3850	26.05	9.17	1.87	54.06	3.57	2.26	0.29	0.31	0.40	0.08	0.32

Table 2 Materials used of concrete.

Item	Symbol	Type
Water	W	Tap water
Cement	BB	Blast-furnace cement class B, commercial product, density: 3.04g/cm ³
	ECM	Cement with high amount of blast-furnace slag Prototype cement Slag content: 60~65%, Density: 2.98g/cm ³ , SO ₃ amount: 3.60%
Fine aggregate	S1	Crushed sand from Hachioji-shi, Tokyo, Density in saturated surface-dry condition: 2.64g/cm ³ , Fineness modulus: 3.04, Coefficient of water absorption: 0.98%
	S2	Mountain sand from Tsuruoka, Futsu-shi, Chiba Density in saturated surface-dry condition: 2.61g/cm ³ , Fineness modulus: 1.44, Coefficient of water absorption: 1.35%
Coarse aggregate	G	Crushed stone from Okutama, Tokyo, Density in saturated surface-dry condition: 2.65g/cm ³ , Percentage of absolute volume: 61.1%, Coefficient of water absorption: 0.60%
Admixture	AE	AE agent Resinate based anionic surfactant
	AD-1	AE water reducing agent (standard form), Complex of modified lignin sulfonic acid compound and polycarboxylic acid based compound
	AD-2	AE water reducing agent (standard form) Organic acid based derivative and aromatic polymer compound
	AD-N	AE water reducing agent (ECM multifunction type, standard form), Complex of modified lignin sulfonic acid compound and polycarboxylic acid based compound

Table 3 Concrete mix proportions for carbonation test.

Type of cement	Maximum size of coarse aggregate (mm)	W/C (%)	s/a (%)	Target air amount (%)	Unit amount (kg/m ³)					AE water reducing agent ^{*1} (C×%)	AE agent ^{*2} (A)
					W	C	S1	S2	G		
ECM	20	45	43.6	4.5	135	300	662	166	1075	2.0	1.5
ECM		55	43.6		165	300	635	159	1030	0.2	4.0
BB		45	43.6		135	300	664	166	1078	2.0	1.5
BB		50	43.6		150	300	650	163	1056	1.2	1.5
BB		55	43.6		165	300	637	159	1033	0.3	4.0

*1 AD-1 and AD-N were used for ECM mix proportion and BB mix proportion respectively.

*2 1A=C×0.001%

The basic properties of the concrete with the selected ECM mix proportion including setting time, bleeding amount, compressive strength, static modulus of elasticity, autogenous shrinkage and adiabatic temperature rise were confirmed, and were compared with the properties of the concrete with the BB mix proportion. Regarding the adiabatic temperature rise, temperature stress analysis was implemented based on the test results, and the thermal crack resistance when the concrete using ECM was applied to civil engineering structures was provisionally calculated.

2.2 Outline of the tests

(1) Materials used

Table 1 shows the physical property values and chemical composition of the cements used in the study. Table 2 lists the materials used. Here, “AD-N” is the AE water reducing agent experimentally developed for ECM.

(2) Method for accelerated carbonation tests

Accelerated carbonation tests complying with JIS A 1153

“Method of accelerated carbonation test for concrete” were implemented and the carbonation rate coefficients during the acceleration period were calculated.

Table 3 shows the mix proportions of the concrete used for the accelerated carbonation tests. Here, the water-cement ratio of the concrete using ECM was changed by changing the unit water content, while the unit cement content was kept unchanged, as mentioned above.

(3) Method for basic property tests

As the basic property test for the ECM mix proportion, the items listed in Table 4 were tested.

2.3 Results of the tests

(1) Results of accelerated carbonation tests

Figure 1 shows the relationship between the water-cement ratio and carbonation rate coefficients.

As shown in this figure, the carbonation rate coefficient of the concrete using BB increased from 0.69 to 3.60 (mm/√week) as the water-cement ratio increased from 45% to 55%. On the other hand, the carbonation

Table 4 Test items.

Test item	Test method
Accelerated carbonation test	JIS A 1153
Setting time test	JIS A 1147
Bleeding test	JIS A 1123
Compressive strength test	JIS A 1108 Material age of specimen: 1, 3, 7, 28, 56, 91 days
Coefficient of thermal expansion test	JIS A 1149 Material age of specimen: 1, 3, 7, 28, 56, 91 days
Autogenous shrinkage test	JCI-SAS2
Thermal expansion test	Method using buried type strain meter
Adiabatic temperature rise test	JCI-SQA3

Table 5 Concrete mix proportions and test results.

Type of cement	Maximum size of coarse aggregate (mm)	W/C (%)	s/a (%)	Target air amount (%)	Unit amount (kg/m ³)					AE water reducing agent *1 (C×%)	AE agent *2 (A)	Test result			
					W	C	S1	S2	G			Slump (cm)	Air amount (%)	Bulk density (kg/m ³)	Temperature (°C)
ECM	20	50	43.1	4.5	150	300	641	160	1062	1.0	3.0	8.0	4.0	2324	19.5
BB		55	44.1		165	300	642	161	1021	0.1	4.0	9.0	4.1	2307	19.8

*1 AD-1 and AD-N were used for ECM mix proportion and BB mix proportion respectively.

*2 1A=C×0.001%

rate coefficient of the concrete using ECM increased from 2.01 to 4.76 (mm/√week) corresponding to the same range of the water-cement ratio.

The carbonation rate coefficients obtained from this test are comparable to those shown in previous research (Wachi *et al* 2011) as well as in technical data provided by cement manufacturers (Technical Data of Cement by TAIHEIYO Corp.), and therefore these values are considered to be reasonable as the carbonation rate coefficients of ordinary concrete for civil engineering structures. According to the test results, the water-cement ratio of the concrete using ECM was about 51% and that for the concrete using BB, having the equivalent carbonation rate coefficient, was 55%. Therefore, it is considered that the carbonation resistance for ordinary concrete for civil engineering structures would be ensured by setting the water-cement ratio of the ECM mix proportion at 50%.

2.4 Results of basic property tests

(1) Properties of fresh concrete

Table 5 shows the settings for the concrete mix proportions and the test results. Even in the case of the ECM mix proportion, it was possible to achieve the targeted slump and air amount by using the AE water reducing agent for ECM.

(2) Setting time

Figure 2 shows the setting times for the ECM and BB mix proportions. The initial and final setting times for the ECM mix proportion were 9 h 35 min and 15 h 30 min, respectively. Those for the BB mix proportion were 2 h and 4 h later, respectively. It is considered that this was because the initial hydrate reaction of ECM was delayed due to the high content of blast-furnace

slag powder as well as the relatively large amount of AE water reducing agent (AD-N) in which a polycarboxylic acid based compound was used. In the future, it is necessary to improve the practicality of ECM by speeding up the setting times to be comparable with the BB mix proportion, including improving the chemical admixture and increasing the specific surface area of ECM.

Fig. 1 Relationship of the rate of carbonation coefficient and water-cement ratio.

Fig. 2 Setting time test results.

(3) Bleeding

Figure 3 shows the bleeding amounts for the ECM and BB mix proportions. The bleeding amount for the ECM mix proportion was $0.12 \text{ cm}^3/\text{cm}^2$, which was less than that for the BB mix proportion, $0.21 \text{ cm}^3/\text{cm}^2$. In addition, these values were also less than the target value of $0.30 \text{ cm}^3/\text{cm}^2$ specified in JASS 5. Generally, the higher the replacement rate of blast-furnace slag powder, the greater the bleeding amount tends to be. It is considered that the bleeding amount resulted in smaller values because the unit water content of the ECM mix proportion compared to that of the BB mix proportion was set smaller by $15 \text{ kg}/\text{m}^3$.

(4) Compressive strength

Figure 4 shows the relationship between the material age and compressive strength. The compressive strength of the ECM mix proportion at the material age of 28 days was $40.6 \text{ N}/\text{mm}^2$. In addition, the strength development

Fig. 3 Bleeding amount test results.

Fig. 4 Relationship of compressive strength and the age.

Fig. 5 Relationship of autogenous shrinkage and the age.

of the ECM and BB mix proportions were comparable. It is considered that this was partly due to the high content of blast-furnace slag powder of ECM as well as the lower water-cement ratio of the ECM mix proportion compared to that of the BB mix proportion.

(5) Autogenous shrinkage

Figure 5 shows the relationship between the material age and autogenous shrinkage strain. It was confirmed that the autogenous shrinkage strain of the ECM mix proportion at the material age of 28 days was 88.3μ , which was comparable with 92.0μ for the BB mix proportion.

(6) Coefficient of thermal expansion

Figure 6 shows the relationship between the temperature change amount and strain. The coefficient of thermal expansion of the ECM mix proportion was $9.80 \mu/^\circ\text{C}$ as the average of the values during temperature rise and temperature fall, and that of the BB mix proportion was similarly $9.70 \mu/^\circ\text{C}$. Both values were comparable with that of ordinary concrete, $10 \mu/^\circ\text{C}$.

(7) Adiabatic temperature rise

Figure 7 shows the relationship between material age and adiabatic temperature rise. Although the histories of adiabatic temperature rise of the ECM and BB mix proportions up to the material age of 2 days were comparable, the final temperature of the ECM mix proportion was 41.0°C , which was about 10°C lower than that of the BB mix proportion at 51.6°C . It is considered that this was due to the smaller heat generation amount of the

Fig. 6 Relationship of temperature and strain variation.

Fig. 7 Relationship of the adiabatic temperature rise and the age.

Table 6 Temperature stress analysis Input Value.

Item	Symbol	Ground
Initial temperature (°C)	Ambient temperature	Ambient temperature
Specific heat (kJ/kg °C)	1.15	0.79
Density (kg/m ³)	2400	2650
Thermal conductivity (W/m°C)	2.85	3.45
Static modulus of elasticity, E (N/mm ²)	$E=6300 \times f_c^{0.45}$	50.0
Tensile strength, f_t (N/mm ²)	$f_t=0.13 \times f_c^{0.85}$	1.96
Surface heat transfer coefficient (W/m°C)	Upper surface: 14 Form surface, with form up to 7 days: 8 without form after 7 days: 14	14
Ambient temperature	Data by the Meteorological Agency: monthly mean temperature of Tokyo Pref.	

ECM mix proportion, which included less clinker than the BB mix proportion, since the unit cement contents of the ECM and BB mix proportions were equalized.

(8) Temperature stress analyses

Using the results obtained from the basic property tests, temperature stress analyses using the three-dimensional finite element method (STANDARD SPECIFICATIONS FOR CONCRETE STRUCTURES-Design- 2013) were implemented. Table 6 shows the input values used in the analyses. As shown in Fig. 8, a quarter-scale model of a wall structure with dimensions of 10 m (length) $\times$ 0.7 m (width) $\times$ 2 m (height) was used. Two cases of concrete placement, one in summer (August) and one in winter (January), were assumed for the analyses. Concrete placement temperature was set at 25°C for summer, assuming daytime work was avoided, and at ambient temperature for winter.

Figures 9 and 10 show the histories of the crack indexes obtained from the temperature stress analyses. The data was extracted for the element where the crack index was the least at the surface and central parts of the wall component. A comparison of the BB and ECM mix proportions confirmed the crack reduction effect by using ECM. In the case of the ECM mix proportion, the crack index at the surface part in summer was 1.45, which showed that the occurrence of cracks could be optically controlled.

3. Confirmation of the hardening properties through full-scale experiments

3.1 Outline of the full-scale experiments

Since it was confirmed that the basic properties of the ECM mix proportion were equivalent to those of the BB mix proportion, full-scale specimens were constructed and then the hardening properties of each part were confirmed.

In each construction, the concrete was placed without any segregation or non-filling of concrete. In the winter test, which was implemented first, the target slump was set at 8 cm. On the other hand, in the following summer test, the target slump was set at 14 cm for improved workability (Hashimoto *et al* 2014). The change in target slump from 8 cm to 14 cm was achieved by adjusting

only the admixture amount without changing any unit contents in the mix proportion.

Tables 7 and 8 show the materials used and the mix proportions of the concrete, respectively.

Fig. 8 Analysis model.

Fig. 9 Temperature stress analysis results in summer.

Fig. 10 Temperature stress analysis results in winter.

Table 7 Materials used of concrete.

Item	Symbol	Type
Water	W	Tap water
Cement	BB	Blast-furnace cement class B (Density ;3.04g/cm ³)
	ECM	Cement with high amount of blast-furnace slag (Density ;2.98g/cm ³)
Fine aggregate	S1	Crushed sand from Okutamamacho, Nishitama-gun, Tokyo Density in saturated surface-dry condition ;2.65g/cm ³ , Fineness modulus ;3.00
	S2	Mountain sand from Mandano, Ichihara-shi, Chiba Density in saturated surface-dry condition ;2.58g/cm ³ , Fineness modulus ;2.00
	S3	Crushed sand from Yokose-cho, Chichibu-gun, Saitama Density in saturated surface-dry condition ;2.65g/cm ³ , Fineness modulus ;3.00
Coarse aggregate	G	Crushed stone from Okutama, Nishitama-gun, Tokyo Density in saturated surface-dry condition ;2.66g/cm ³ , Fineness modulus ;60.0%
Admixture	AD-N1	Prototype AE water reducing agent (ECM multifunction type, standard form, complex of modified lignin sulfonic acid compound and polycarboxylic acid based compound)
	AD-N2	Commercial AE water reducing agent (Complex of modified lignin sulfonic acid compound and polycarboxylic acid based compound)

Table 8 Concrete mix proportions and test results.

Type	Maximum size of coarse aggregate (mm)	W/C (%)	s/a (%)	Target slump (cm)	Target air amount (%)	Unit amount (kg/m ³)						AE water reducing agent ^{*1} (C×%)	AE agent ^{*2} (A)
						W	C	S1	S2	S3	G		
ECM (Winter)	20	50	48.0	8.0	4.5	150	300	267	311	311	974	1.0	4.0
ECM (Summer)		50	48.0	14.0		150	300	267	311	311	974	1.45	4.5
BB		55	48.0	8.0		165	300	262	306	305	1021	0.7	4.0

*1 AD-1 and AD-N were used for ECM mix proportion and BB mix proportion respectively.

*2 1A=C×0.001%

3.2 Outline of the experiments

(1) Shapes of the specimens

Figures 11 and 12 show the shapes of the full-scale components. In the experiment, a portion of the wall component of a box culvert was simulated. The wall thickness of the specimens was set at 0.7 to 1.0 m, and the total length of the specimen for winter was set at 1.5 m and that for summer at 10.0 m. The bar arrangement of the specimen for winter was set as D13 main reinforcement and D13 distribution bars at intervals of 150 mm, and that for summer as D25 main reinforcement and D19 distribution bars at intervals of 150 mm.

Fig. 11 Full scale specimens in winter.

(2) Time and place of the experiments

Both the winter and summer tests were implemented in Tokyo Prefecture (Chofu). Concrete placement for the winter test was implemented in mid-December (highest temperature on the placement day: 10.1°C) and for the summer test in mid-September (highest temperature on the placement day: 31.7°C).

(3) Execution method

Concrete placement for the winter test was implemented using buckets and consisted of 7 layers, each 50 cm thick. Placement for the summer test was implemented using

Fig. 12 Full scale specimens in summer.

concrete pumping vehicles and consisted of 4 layers, each 50 cm thick. The form of each specimen was removed at the material age of 7 days after which the specimen was covered with a sheet to prevent drying until the material age of 28 days.

(4) Test items

To test the hardening properties, compressive strength tests and air permeability test suggested by Torrents were implemented. **Figures 13** and **14** show the measurement positions in each test.

In the compressive strength tests, the cores were sampled from the full-scale specimens, and the tests were implemented according to JIS A1108. The cores for the winter test were sampled at three positions on three levels in the vertical direction, that is, nine positions in total, and the mean value at each level was shown as the compressive strength. For the summer test, on the other hand, cores with a diameter of 100 mm were sampled at two positions (the center and an edge) in the longitudinal direction on levels in the vertical direction, and each core was cut into pieces with a length of 200 mm, giving a total of eight specimens.

Regarding the sampling positions for the air permeability test suggested by Torrents, the specimens for the winter test were sampled at three positions on six levels in the vertical direction, that is, eighteen positions in total, and the mean value at each level was shown as the coefficient of air permeability. Regarding those of summer, on the other hand, sampling positions were set at four levels in the vertical direction.

Fig. 13 Measuring the position of the curing test in winter.

Fig. 15 Fresh concrete properties test results in winter.

Table 9 Fresh concrete properties test results.

Mix proportion	Slump (cm)	Air amount (%)	Concrete temperature (°C)
Mix proportion for winter	8.0	4.8	12.8
Mix proportion for summer	15.0	6.0	27.2

3.3 Results of the experiments

(1) Fresh properties

Upon constructing the specimen, concrete was placed after confirming that the slump and the air amount were within standard value ranges. **Table 9** and **Fig. 15** and **16** show the slump and air amount when the specimens arrived at the site.

In addition, **Figs. 17** and **18** show the construction situations.

(2) Results of compressive strength test

Figures 19 and **20** show the compressive strengths at the material age of 28 days. Those of the winter specimens were within the range of 36 to 40 N/mm², and differences in the vertical direction that remained were not found. On the other hand, those of the summer specimens were within the range of 40 to 60 N/mm², and it was confirmed that the lower the position the higher the value tended to be. This tendency was also true for both the center and the edge of the component. The considerable difference in compressive strength magnitude between the winter and summer specimens is thought to be mainly due to the difference in ambient temperature. On the other hand, regarding the considerable difference in distribution tendencies in the vertical direction, it is inferred that greater consolidation (lateral pressure on the form) oc-

Fig. 14 Measuring the position of the curing test in summer.

Fig. 16 Fresh concrete properties test results in summer.

cured at lower positions in the summer specimen, which had been constructed using concrete with a large slump and high filling performance.

As a result, it was confirmed that the compressive strength at the material age of 28 days of actual structures constructed with the ECM mix proportion exceeds 36 N/mm^2 even when the concrete was placed in mid-December at an ambient temperature of around 10°C .

(3) Results of air permeability test suggested by Torrent

Figure 21 shows the mean coefficient of air permeability of the air permeability test suggested by Torrent. The coefficients of air permeability obtained from the specimen with the mix proportion for winter were in the range of “good,” while those obtained from the summer specimen were mostly in the range of “excellent” and the lower value as the higher positions. It is considered that this was partly because the mix proportion for summer resulted in higher strength development at the material age of 28 days and lower porosity of the surface layer, as well as partly because the filling performance of the surface layer from the mix proportion for summer was greater than that for winter since the target slump of the mix proportion for summer was 14 cm compared to 8 cm for winter (Kohno and Ujike 1998). And it was confirmed that a sufficient compaction is performed as the higher positions from the lower positions. At any rate, it was confirmed by both the winter and summer speci-

mens that the structures could be built with a high surface layer quality by placing concrete with a water-cement ratio of 50%.

In this experiment, the compressive strength and the coefficients of air permeability was not obtained correlation.

4. Conclusions

As a result of considering the application of ECM to civil engineering structures, the following findings were obtained.

- (1) By setting the water-cement ratio at 50% for concrete using ECM, carbonation resistance equivalent to concrete using BB with a water-cement ratio of 55% for ordinary civil engineering structures can be obtained.
- (2) The setting time for concrete using ECM with a wa-

Fig. 20 Strength of the concrete core in summer.

Fig. 19 Strength of the concrete core in winter.

Fig. 21 Surface air permeability test results.

Fig. 17 Full scale construction experiment situation in winter.

Fig. 18 Full scale construction experiment situation in summer.

ter-cement ratio of 50% tends to be longer compared to that of concrete using BB with a water-cement ratio of 55%. The former produces less bleeding than the latter. Regarding strength development, amount of autogenous shrinkage and coefficient of thermal expansion, both the former and latter are comparable.

- (3) When the environmental temperature is set as 20°C and the unit cement content of concrete as 300 kg/m³, adiabatic temperature rise in the case of BB was greater than that of ECM by about 10°C. By implementing temperature stress analyses assuming an urban central area in summer and winter based on this result, it was confirmed that reduction of thermal cracks can be expected by using ECM.
- (4) The compressive strength of the structure constructed with concrete using ECM was greater than 36 N/mm² even in the case of concrete placement at an ambient temperature of 10°C in mid-December. Regarding the structure constructed with concrete using ECM and with a slump of 14 cm, it was confirmed that the lower the position, the higher the compressive strength tended to be.
- (5) The coefficients of surface layer air permeability of the structure constructed with concrete using ECM were within a range determined as “good” or “excellent,” and therefore it was confirmed that structures with a high-quality surface layer can be built using ECM.

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