Effect of Coarse Ground Cement on the Strength Development of Mortar

Makoto HISADA, Dr. Eng.
Senior Researcher
Public Works Research Institute
Tsukuba, Japan

Hirotaka KAWANO
Chief Researcher
Public Works Research Institute
Tsukuba, Japan

Summary

Recently, the durability of concrete structures subject to chloride attack and carbonation has been examined in many studies and projects. For the long-term durability and strength of concrete, resistance to calcium leaching from cement hydration is one of the requirements for properties of hardened cement matrix. It is well known that the ratio of water to binder is one of key parameters affecting the performance of concrete. However, the new design concept should be extended from the mixture proportion to new cement based materials.

In this study, the authors examined the effect of grain size and chemical composition of cement on the properties of hardened cement mortar in order to design new sustainable cement based materials, with special focus on compressive strength.

It was found that the presence of large cement particles played a major role in the long-term strength and hydration improvement of cement matrix, and that such role would be improved in combination with the design of the mixture proportion and chemical composition of cement.

Keywords: coarse ground cement; ordinary Portland cement; Belite type cement; mixture proportion; compressive strength; long-term durability

1. Introduction

The durability of concrete structures has become increasingly important for the sustainability of infrastructure. In Japan, a performance verification system has been introduced into the guidelines for every stage of construction. For example, in the *Standard Specifications for Concrete Structures-2002, Materials and Construction*, published by the Japan Society for Civil Engineers, it is stipulated that the durability of concrete shall be verified at both the design and production stages.

Many studies on existing old concrete structures have therefore been conducted to obtain useful information about concrete durability. Some of these investigations have suggested that the qualities of cement, not only the chemical properties but also the physical properties such as fineness, may affect the durability of concrete. Some researchers pointed that the use of coarse ground cement improves the long-term durability of concrete structures.

This paper examines the latest knowledge on the historical changes of cement standards and the quality of cement in Japan. Past and present studies on coarse ground cement are also reviewed, and the possibility of a new approach to coarse ground cement is discussed. Finally, some test results are shown and new challenges are discussed.

2. Fineness and quality of cement

2.1 History of cement standards in Japan

The first cement standard in Japan was established in 1905. Since granulating techniques were not advanced at that time, cement needed to be fine in order to achieve the minimum soundness and strength. In the Japanese standard, the fineness of cement was determined by the sieve-remaining method, which was used until the 1950s.

The fineness and strength of cement stipulated in the Japanese standard are summarized in Table 1. As shown, the standard progressively required finer and stronger cement. These changes resulted from advances in clinker granulating techniques in Japan.

Table 1 Summary of Fineness and Strength of Cement Stipulated in the Japanese Standard

Year	Fineness		Compressive strength, kgf/cm^2			Bending strength, kgf/cm^2		
	Sieve remaining, %	Blaine, cm^2/g	3 days	7 days	28 days	3 days	7 days	28 days
1905	< 10 (*1)	---	---	---	> 120	---	> 7	> 15
1909	< 5 (*1)	---	---	---	---	---	> 8	> 16
1919	< 3 (*1)	---	---	---	> 140	---	> 10	> 18
1927	< 17 (*2)	---	---	---	> 210	---	> 14	> 21
1930	< 12 (*2)	---	> 150	> 220	> 300	---	> 20	> 25
1941	---	---	> 35 (*3)	> 70 (*3)	> 150 (*3)	> 10	> 20	> 30
1950	*********************** JIS A 5201 established ***********************							
1953	---	> 2300	> 45	> 90	> 200	> 12	> 25	> 36
1960	---	> 2300	> 55	> 110	> 220	> 15	> 25	> 40
1973	---	> 2500	> 70	> 150	> 300	requirement abolished		
1995	---	> 2500	> 7.0 (*4)	> 15.0 (*4)	> 30.0 (*4)	---	---	---

*1 Sieve size: 0.2 mm (= 210 µm).
*2 Sieve size: 0.088 mm (= 88 µm).
*3 Mixture proportion changed (Before 1941: W/C=0.24-32, After 1941: W/C=0.65).
*4 SI unit (N/mm^2) applied. W/C=0.50 set for mixture proportion.

2.2 History of cement quality in Japan

Ordinary Portland cement was imported to Japan for the first time in 1865. Domestic production of cement started in 1873, and peaked at 99.56 million tons per year in 1996. In addition, eco-cement, which is produced by using refuse or waste, has recently been developed for one of the solutions for waste problem in many cities.

The physical properties of cement in Japan are summarized in Table 2. As shown, the physical properties of Japanese cement have become finer and stronger, according to the Japanese standard shown in Table 1. These changes of cement quality reflected advances in granulating methods in Japan. In addition, finer and stronger cement has been required at construction sites, where

Table 2 Summary of Physical Properties of Cement in Japan

Year	Density, g/cm^3	Sieve remaining, %		Blaine, cm^2/g	Compressive strength, kgf/cm^2			Bending strength, kgf/cm^2		
		210 µm	88 µm		3 days	7 days	28 days	3 days	7 days	28 days
1905	2.99	0.9	29.0	---	---	61	138	---	14.0	24.2
1908	3.08	0.3	---	---	---	73	117	---	19.1	33.3
1911	3.01	0.5	9.2	---	---	67	119	---	21.4	34.9
1916	3.03	0.3	6.7	---	---	117	213	---	28.5	50.5
1921	3.09	0.2	12.6	---	---	67	141	---	24.0	41.1
1926	3.13	0.2	7.0	---	---	127	225	---	33.0	52.4
1935	3.15	---	2.1	---	107	180	325	24.1	36.8	54.2
1945	3.09	---	4.6	---	62	102	188	16.0	26.3	41.4
1955	3.15	---	2.8	3340	119	215	385	31.0	48.4	72.1
1965	3.16	---	1.5	3300	123	220	392	30.7	47.0	69.5
1975	3.17	---	1.4	3210	139	242	411	34.3	52.0	74.2
1985	3.16	---	0.7	3310	153	253	417	34.0	49.0	70.0
1991	3.15	---	0.6	3390	155	251	415	37.0	51.0	72.0

Fig. 1 More than 100-year-old concrete samples from Otaru, Hokkaido, Japan

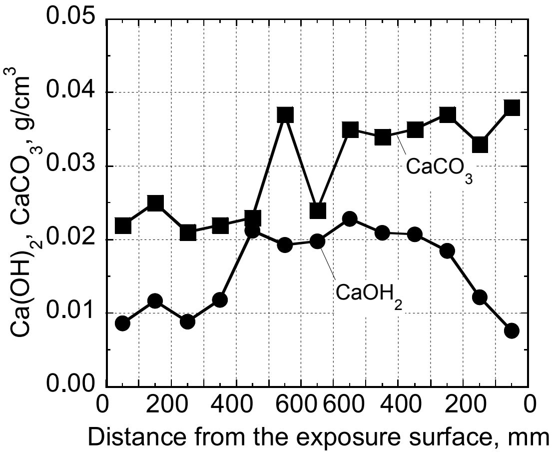

Fig. 2 Measurement results of $Ca(OH)_2$ and $CaCO_3$ in 80-year-old concrete

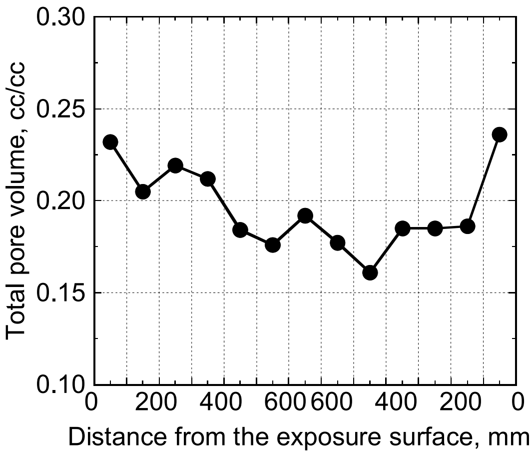

Fig. 3 Measurement results of pore volume in 80-year-old concrete

structures need to be put into service as quickly as possible.

2.3 Previous studies on coarse ground cement

As described in the introduction, investigations of old concrete structures yield useful information as to concrete durability. In Japan, Nagataki reported the measurement results for more than 100-year-old concrete located at Otaru port, Hokkaido, Japan [1, Fig. 1]. The report noted that the old concrete was still durable since it had been made with a small amount of water, coarse ground cement and cast properly, and that fine ground cement contributes only to early strength, and that hydration of such fine ground cement finishes at an early age.

The authors investigated an old concrete structure, which was constructed in 1923 and always exposed to river water, in Niigata, Japan [2]. The chemical and physical properties of the concrete, such as cement hydrates and pore volume, were analyzed. Fig. 2 shows the measurements of $Ca(OH)_2$, $CaCO_3$ and pore volume in the concrete. Although these figures show that calcium leaching occurs at the surface of the concrete, it has sufficient resistance against chloride ingress.

In addition, Yamada et al. reported on the beneficial effects of low fineness cement (2200-2800 cm^2/g) on the durability of hardened concrete, compared to present fine cement concrete [3].

Idorn reported the measurement results of 136-year-old concrete sampled from Portland Hall, Kent, UK, which was constructed in memory of W. Aspdin, the son of J. Aspdin[4]. He described that the coarse ground cement had been hydrating for a long time, and so the concrete was still dense and durable.

Halord et al. investigated the drying shrinkage and freeze-thaw resistance of concrete using cement with various grinding level [5]. He reported that concrete made with coarse ground cement had better resistance to drying shrinkage and freeze-thaw resistance compared to concrete made with finer ground cement. He also pointed out that the adhesion between coarse aggregate and cement particles was improved by coarse ground cement.

These reports suggest that coarse ground cement has good properties such as long-term durability and strength.

3. Investigation on the application of coarse ground cement

3.1 New approach to coarse ground cement

In general, fine ground cement chemically reacts and hydrates with water faster than coarse ground cement, if the total volume of cement is constant, because the surface area of fine ground cement is larger than that of coarse ground cement. Therefore, the hardened cement matrix quickly develops strength when fine ground cement is used. However, this also means that fine ground cement may finish its hydration at an early age.

On the other hand, with coarse ground cement, the hardened cement matrix cannot develop strength at an early age since its reaction is slower than that of fine ground cement. However, coarse ground cement may continue long-term hydration and therefore be able to more strength improvement.

If these two types of cement characteristics can be combined, a hardened cement matrix can quickly develop strengthen by fine ground cement and yet offer long-term hydration and durability by continuous hydration by coarse ground cement. Therefore, the author blended both fine and coarse ground cements to produce a new mixture proportion. In addition, High C_2S (Belite) type cement was tested and the possibility of longer hydration effect was investigated.

3.2 Test procedure

3.2.1 Materials

In this study, ordinary Portland cement (OPC) and high C_2S type cement (CLC) were prepared. Each cement clinker were granulated for targeting 600, 1200, 2000 and 3400 cm^2/g. As a result, ordinary Portland cement clinker were granulated to 700, 1260, 1940 and 3300 cm^2/g of Blaine fineness, and the high C_2S type cement clinker was granulated to 560, 1140, 2060 and 3520 cm^2/g of Blaine fineness. Note that ordinary Portland cement with fineness of 3300 cm^2/g and Belite type cement with fineness of 3510 cm^2/g have the same fineness as normal cement used in Japan. The basic properties of these cement clinkers are summarized in Table 3.

Table 3 Basic properties of cement clinker

Cement	Density g/cm^3	L.O.I %	Chemical composition, %							Mineral composition, %			
			SiO_2	Al_2O_3	CaO	MgO	SO_3	Na_2O	K_2O	C_3S	C_2S	C_3A	C_4AF
OPC	3.16	1.30	21.40	5.40	64.30	2.00	2.00	0.29	0.48	49.36	24.31	9.74	8.22
CLC	3.22	0.92	26.35	2.68	63.71	0.59	2.18	0.19	0.40	29.30	55.20	2.73	7.84

Table 4 Mixture proportions of mortar (Volume %)

No.	*	Binder								Fine aggregate		
		OPC				CLC				OPC	CLC	sand
		3400	1940	1260	700	3520	2060	1140	560	700	560	
1	1)	100	0	0	0	0	0	0	0	0	0	100
2	1)	0	100	0	0	0	0	0	0	0	0	100
3	1)	0	0	100	0	0	0	0	0	0	0	100
4	1)	0	0	0	100	0	0	0	0	0	0	100
5	1)	0	0	0	0	100	0	0	0	0	0	100
6	1)	0	0	0	0	0	100	0	0	0	0	100
7	1)	0	0	0	0	0	0	100	0	0	0	100
8	1)	0	0	0	0	0	0	0	100	0	0	100
9	2)	75	0	0	25	0	0	0	0	0	0	100
10	2)	50	0	0	50	0	0	0	0	0	0	100
11	2)	0	0	0	0	75	0	0	25	0	0	100
12	2)	0	0	0	0	50	0	0	50	0	0	100
13	3)	100	0	0	0	0	0	0	0	6.25	0	93.25
14	3)	100	0	0	0	0	0	0	0	12.5	0	87.5
15	3)	100	0	0	0	0	0	0	0	25.0	0	75.0
16	3)	100	0	0	0	0	0	0	0	50.0	0	50.0
17	3)	0	0	0	0	100	0	0	0	0	6.25	93.25
18	3)	0	0	0	0	100	0	0	0	0	12.5	87.5
19	3)	0	0	0	0	100	0	0	0	0	25.0	75.0
20	3)	0	0	0	0	100	0	0	0	0	50.0	50.0

*Design concept (see next page)

As fine aggregate, Japanese local natural sand was used. The fineness modulus, density with SSD condition and absorption capacity of fine aggregate were 2.71, 2.61 g/cm^3 and 1.78%, respectively.

3.2.2 Specimens

Mortar specimens with W/C of 0.55 and S/C of 2.0 were prepared in this study. The mixture proportions of mortar are summarized in Table 4. As shown, the mixture proportions were designed according to the following three concepts.

1) Each ground cement used alone as binder

2) Coarse ground cement used as replacement material of cement

3) Coarse ground cement used as replacement material of fine aggregate

Mortar specimens were immediately cast into a 40 x 40 x 160 mm prism formwork after mixing. After casting, specimens were demolded and continuously cured under water at a constant temperature (20±2°C).

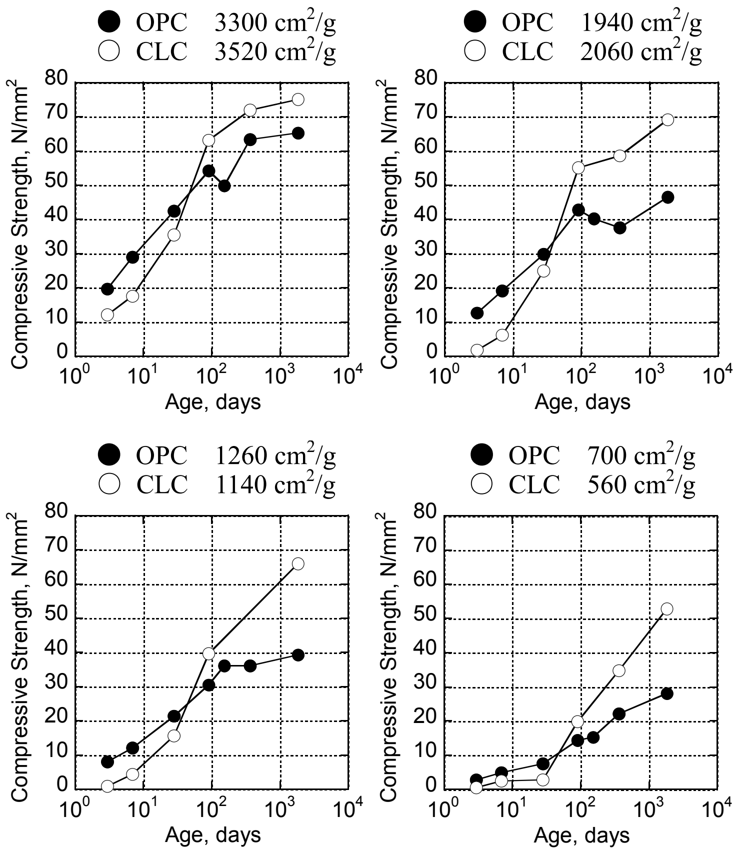

Fig. 4 Compressive strength of hardened cement mortar - Effect of the cement type and fineness -

3.2.3 Measurement

The compressive strength of mortar specimens was measured at the ages of 3, 7, 14, 28, 91, 154, 365 and 1825 days (= 5 years).

3.3 Results and discussion

Fig. 4 show the compressive strength of hardened mortar for each fineness of cement. As shown, high C_2S type cement improves the compressive strength more than ordinary Portland cement up to 5 years.

The compressive strength of cement mortar at 5 years did not improve further when the fineness of cement was high, such as 3000 cm^2/g, whereas it was still improving at 5 years with coarse ground cement. This tendency is more remarkable in the case of CLC 560 cm^2/g, although the strength did not improve until 28 days.

Unfortunately, other tests, such as pore volume or water penetration, could not be conducted in this study. However, the results suggest that coarse ground cement, particularly the high C_2S type cement has possibilities which would bring concrete structures more durability. This advantage, *the continuous hydration of coarse ground cement*, can be adapted in the new design concept.

Fig. 5 show the compressive strength of hardened mortar when the base cement was replaced by the coarse ground cement. It is clear that when the binder was replaced by the coarse ground cement, the compressive strength of the hardened mortar decreased at every age. This tendency was recognized in both types of cement clinker.

As a result, coarse ground cement may not be a suitable as a replacement material for base binder when the higher strength is needed. However, even when 50% of base cement was replaced by the coarse ground cement, the compressive strength of each mortar at 5 years was more than 40 N/mm^2. Therefore, the coarse ground cement can be used as a replacement material for base binder when

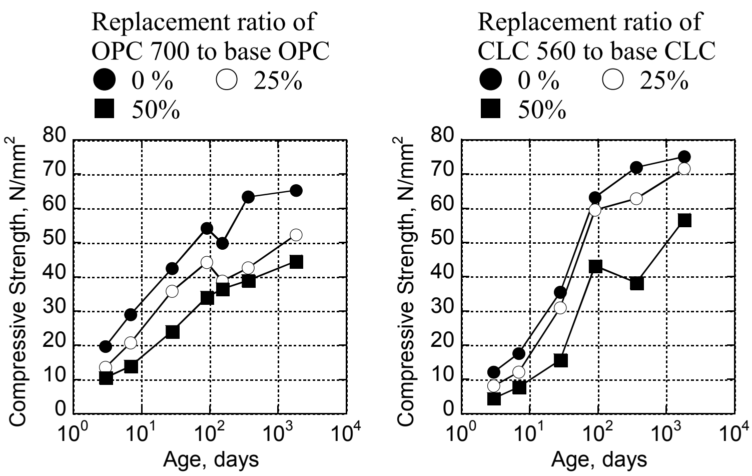

Fig. 5 Compressive strength of hardened cement mortar - Effect of replacement for binder -

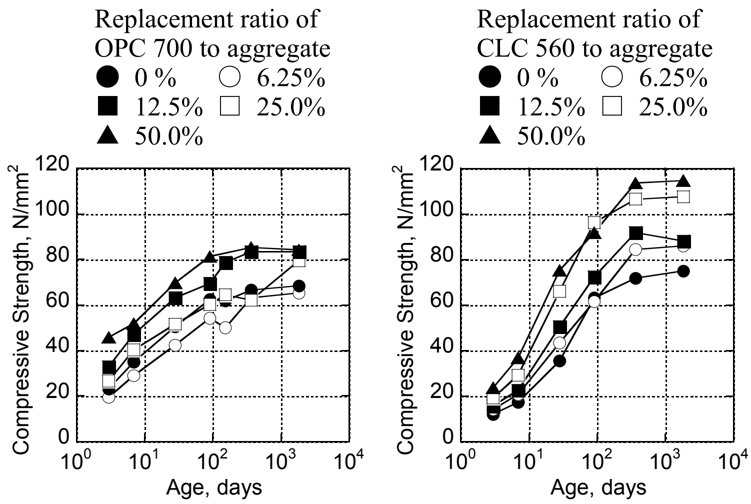

Fig. 6 Compressive strength of hardened cement mortar - Effect of replacement for aggregate -

only normal strength is required.

Fig. 6 shows the compressive strength of hardened mortar when the fine aggregate was replaced by the coarse ground cement. Unlike Fig. 5, it is clear that when the fine aggregate was replaced by the coarse ground cement, the compressive strength of the hardened mortar increased at every age. This tendency was clearer with C_2S type cement than that with ordinary Portland cement.

It should be noted that heat generation due to cement hydration did not occur when coarse ground cement was used since the hydration ratio is quite low. Therefore, coarse ground cement can be perform as a aggregate replacement material for the improvement of compressive strength.

4. Concluding remarks

Cement granulation techniques have been developed from the need for fast construction, and hence rapid cement hydration, and so cement has been made progressively finer and stronger. In Japan, however, the expectation for construction has been changing from "speed and quantity" to "certainty, durability and sustainability".

In this paper, the effects of the coarse ground cement on strength development of mortar was experimentally investigated. The authors therefore believe that coarse ground cement can be considered as a new design concept for cement based materials.

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