IMPROVEMENT OF CONCRETE PROPERTY WITH CONTROLLED PERMEABILITY FORMWORK

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Controlled permeability formwork (CPF) has been used inner the steel and wood formwork to investigate the effect on surface properties improvement. The water-retaining ability of CPF under different lateral pressure, water requirement of cement paste and mortar in curing process, and surface hardness at different ages were measured, and the mechanism of surface concrete properties improved by CPF was researched. The results showed that lasting moisture curing of concrete can be realized with impounding type CPF. The carbonation resistance and chloride penetration resistance were also researched, and the results showed that CPF can significantly improve the surface concrete appearance quality, carbonation resistance, chloride penetration resistance. The morphological structure, porosity and pore size distribution of the composites were measured using mercury intrusion porosimetry and field emission scanning electron microscopy, and the results indicated that concrete using CPF had lower porosity and a more uniform pore size distribution.

Keywords: *controlled permeability formwork; water-retaining ability; surface hardness; carbonation resistance property; chloride penetration resistance*

1. Introduction

Corrosion of rebar in concrete is the main reason for structural degradation, the cover concrete plays an important role in suspending initial corrosion. The research performed by P.K. Mehta [1] showed that it is basically water tightness of which with well component, properly vibration and curing, as long as the channel has not been connected by the internal pore and fracture. The influence of structural load and the atmospheric environment such as alternate of cooling and heating or drying and watering cycle will make the crack develop and spread. Then concrete will lose water tightness and become water-saturated, thus giving rise to the invasion of harmful medium. Rebar corrosion expansion will arise under the effect of harmful medium, then cover concrete began crack, the effective steel cross section decreased, these are process of structural function deterioration. So, the measures which can extend the corrosive medium arrive at the rebar surface in time will improve the durability of the structure. Some technical measures such as improving the quality and thickness of cover concrete, and surface coatings are widely used in the practical engineering. While, increasing the thickness of cover concrete and coatings are seriously restrained by current specification, concrete properties, execution conditions and construction schedule requirements. Some rules and regulations of current design for cover concrete thickness is far lower than the developed countries [2]. It is a feasible way to improve the quality of cover concrete without increasing its thickness, so as to extend the time of corrosive medium reaching steel surface.

Controlled Permeability Formwork (CPF) is a kind of fiber product which can drainage downward and exhaust upward on account of its special composition and structure. The main products have the function of water storage or as a representative does not have water storage function. They can be used with conventional formwork fixed glue and nail. CPF can discharge the excess water and the bubbles near the structure surface, and it can eliminate the macro surface defects of the structure and improve the properties of concrete such as compactness [3, 4], carbonation resistance [5], rebound hardness [5, 6], wear-resistance [5], tensile strength [6], chloride penetration resistance [5] and frost resistance [7]. The first large-scale application of CPF in Shenzhen Yantian Port has achieved favorable effect. Now, it had been used in many important civil marine engineering, such as Zhoushan Islands Link Project [8], Donghai Bridge, Hangzhou Bay Sea-Crossing Bridge [9] and Qingdao Bay Bridge, and the effect is satisfactory.

Although CPF has been widely used in practical engineering, the improvement mechanism of CPF on surface concrete and the long-term performance of surface concrete with the use of CPF have not been unified [4-6]. Research [7, 10, 11] showed that CPF can improve the quality of

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Table 1

Chemical component and parameters of cement used in the research

SO_3, %	Na_2O_{eq}, %	Mass loss, %	water requirement of normal consistency, %	Setting time, s		Flexural strength, kPa		Compressive strength, kPa	
				Initial setting	Final setting	3 day	28 day	3 day	28 day
2.07	0.58	1.85	27.8	2700	26500	6800	8800	38400	62800

Table 2

Chemical component and parameters of fly-ash used in the research

SiO_2	Fe_2O_3	Al_2O_3	CaO	SO_3	Mass loss, %	Water demand ratio	Residue on sieve
60.8	5.8	24.1	3.0	0.6	2.6	94	9.7

Table 3

Chemical component and parameters of slag used in the research

Density, kg/m^3	Specific surface area, m^2/kg	Activity index, %		Fluidity ratio, %	SO_3, %	Loss on ignition, %
		7 day	28 day			
2.8×10^{-3}	370	68	103	105	0.2	1.2

Table 4

Proportion of concrete

Materials in 1 m^3 concrete								
Cement, kg	Fly-ash, kg	Slag, kg	Water, kg	Sand, kg	Coarse aggregate (5-10), kg	Coarse aggregate (10-20), kg	Super-plasticizer, kg	Air- entraining agent, kg
170	80	180	153	720	300	710	4.3	0.064

Table 5

Proportion of cement paste (mortar) and curing water usage

Samples	Mix proportion, kg/m^3					
	Cement	Fly-ash	Slag	River sand	Water	Water reducing agent
J0	1483	/	/	/	528	0
J1	823	549	/	/	488	0
J2	573	/	860	/	510	0
J3	716	179	522	/	504	0
S0	764	/	/	1280	271	1.5
S1	440	293	/	1228	261	1.3
S2	300	/	450	1257	267	1.4
S3	377	94	274	1250	265	1.3

concrete by reducing the water-binder ratio of surface concrete. Meanwhile, CPF has some water-holding capacity although it is compressed under the impact of lateral pressure of fresh concrete. The mixing water remained in CPF could provide moisture curing for some days, thus increasing the hydration extent of early-age concrete and improving the pore structure of the hydrates [12].

Marine concrete is characteristic of low water-binder ratio and large dosage of mineral admixture, its durability has been verified by a number of practical engineering, but the requirement of continuous moisture curing during adolescent period is strict. It could not match the expected durability without sufficient continuous moisture curing in the early-age [13]. CPF can meet the requirement of sufficient continuous moisture curing in the early-age, because of its continuous moisture curing ability. The experiment was conducted in this paper in order to exploratory improvement of concrete property with CPF and confirm its mechanism and obtain proper materials usage.

2. Material and methods

2.1. Materials

P•I type 52.5 Portland cement (Table 1), class I fly-ash (Table 2) and S95 slag (Table 3) were used in all experiments. The coarse aggregate was (5~10) ×10^{-3} m and (10~20) ×10^{-3} m single-grading crushed limestone, the silt content 0.3% and the apparent density 2700 kg/m^3. The fine aggregate was river sand, the fineness modulus 2.9, silt content 1.3% and

Table 6

Main properties of fresh concrete and hardened concrete

Fresh concrete			Hardened concrete					
Slump, m	Slump flow, m	Air content, %	Compressive strength, kPa		Electric flux		Frost resistance after 300 times circulation, %	
			7 day	28 day	28 day	90 day	28 day	90 day
0.22	0.52	4.5	40000	55000	900	400	94	95

apparent density 2640 kg/m^3. The chemical admixtures used were polycarboxylate super-plasticizer and air-entraining agent.

2.2. Specimens

The sample size, vibration, curing method and measure method of fresh concrete were conducted according to GB/T 50080-2002. Mechanical property test was performed by GB/T 50081-2002. Concrete electric flux test is carried out according to ASTM C1202-05. The sample with size of 1.4 m × 0.25 m × 0.80 m was prepared in order to simulate the practical status. Concrete was mixed with 60l single horizontal shaft mixer for 180 s, vibrated 30 s with 50 Hz, Φ 0.30 m vibrating rod, curing for 7 days, then kept in natural environment. The proportion of concrete used in the surface hardness test, carbonation resistance property test and chloride penetration resistance property test are shown in Table 4. Proportion of paste and mortar prepared for the water needed test is shown in Table 5.

2.3 Items of investigation

The main properties of hardened and fresh concrete in Table 6. After the strength tests the fractured samples were used for determining the porosity and pore size distribution. An AUTOPORE IV 9500 series MIP produced by MIC (Micrometrics) was used. This was able to determine the distribution of pores from 5.5×10^{-9} m to 360×10^{-6} m. The maximum pressure provided by this machine was 2.28×10^5 kPa. The morphology and microstructure of samples were assessed using FE SEM (Nova NanoSEM 450, FEI Co.) for samples at the age of 28 days after the strength test.

3. Results and discussion

3.1. Water-retaining ability

The water-retaining ability results was shown in Fig.1. When the structure casting height is 4 m per section, the CPF side pressure at the casting section bottom is about 96 kPa. Nine pieces of 0.10 m × 0.10 m CPF which had been completely water saturated be superimposed together to test its water-retaining ability under different pressure. Results indicated that the minimum water storage of both TJ80-MQ and Formtex® was larger than 0.40 L/m^2.

3.2. Curing water requirement of cement paste and mortar

There is little coarse aggregate in the concrete near the structure surface, so it can be regarded as mortar or paste. It is reasonable to measure the water usage using paste or mortar with the same water-binder ratio.

The samples were prepared in 0.30 m × 0.50 m enamel square plate indoors, and the height was 0.02 m ~ 0.03 m. Total weight and surface area were measured when there was no bleeding. Then injected 10 mm height water and sealed the sample with thin film. Poured out the rest curing water, dried with wet dishcloth and weighed the samples at different ages. The increased specimen quality of unit area, was regarded as maximum water needed for moisture curing. The results were shown in Fig.2.

From Fig.2, the curing water usage was no more than 0.40 kg/m^2 for paste and mortar, and the water retained in TJ80-MQ and Formtex® with 96 kPa lateral pressure is higher than 0.40 kg/m^2.

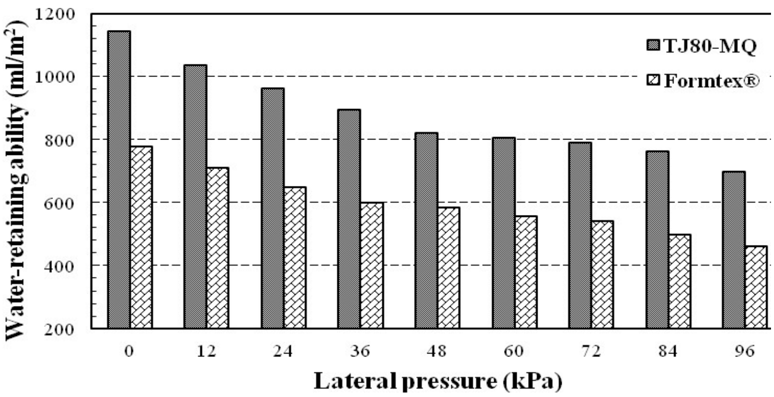

Fig.1 - Water-retaining ability of impounding type CPF under different lateral pressure.

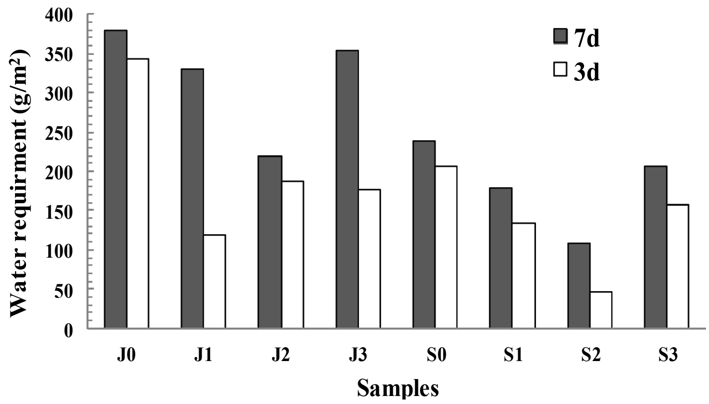

Fig.2 - Maximum curing water requirement of cement paste and mortar.

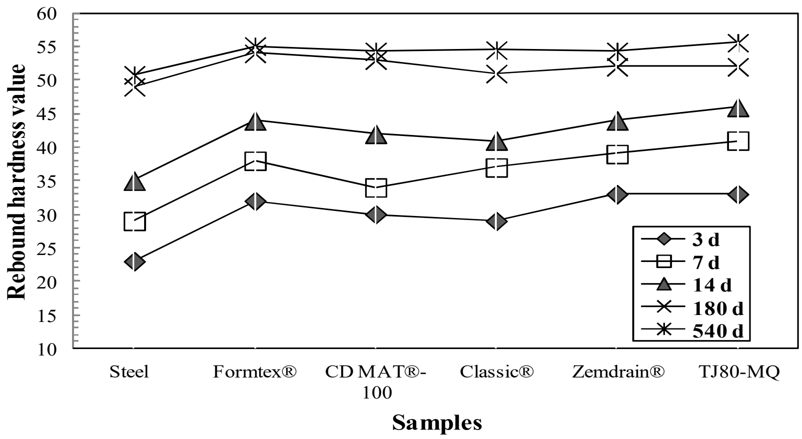

Fig.3 - Rebound hardness at different ages.

It is very crucial to ensure the durability of concrete, especially for marine concrete characterized by a large number of mineral admixture usage and low water-cement ratio, for the early continuous moisture curing is the basic guarantee for the durability of concrete.

The curing water usage of mortar was no more than that of paste with the same water-binder ratio, because of the less binding materials in mortar. The curing water consumption of cement was larger than the samples with mineral admixtures for the hydration speed of mineral admixture was lower than cement. Although the mixing water usage reduced, the amount of water is more abundant relative to the cement because of the admixture would not participation in the early-age hydration. While, the mineral admixtures reacted with some products of cement hydration, water should be added along with the increases of age, the CPF met this requirement perfectly.

3.3. Surface hardness

CPF modification depth of cover concrete is very small, so the improvement could not be characterized by some routine parameters, such as compressive strength, electric flux and diffusion coefficient [6]. While Permit and rebound hammer can be used to test the improvement of CPF on apparent density and uniformity of surface concrete [7]. The preliminary research [14] indicated that CPF can improve the chloride penetration resistance property of surface concrete. The samples were prepared with the size of 1.4 m × 0.25 m × 0.80 m to carry out the rebound hardness test, and the results were shown in Fig.3 and Table 6.

As shown in Fig.3, whether or not having water-retaining ability, the CPF can improve the surface hardness of concrete, especially in the early age. Even though the CD MAT®-100 and Classic® can not provide water curing condition for early-age concrete because of they do not have storage capacity, but they also slightly increase the concrete surface hardness. There is too much free water in concrete with 60% mineral admixture addition at early age, and CPF do drainage some free water. We can take for it that for concrete with a large quantity of mineral admixture it is also effective of taking CPF of no water storage capacity.

Table 7 showed that the increase ratio of rebound hardness decreased with the increase of curing age, the improvement was not remarkably after 180 days curing by less than 10%. The.

Table 7

Rebound hardness increase compared with steel formwork at different ages

Formwork	Rebound hardness increase, %				
	3 days	7 days	14 days	180 days	540 days
Formtex®	39	31	26	10	8
CD MAT®-100	30	17	20	8	7
Classic®	26	28	17	4	7
Zemdrain®	43	34	26	6	7
TJ80-MQ	43	41	31	6	9

Table 8

Influence on carbonation resistance of CPF

Formwork category	Carbonation depth within the formwork corresponding to different ages, $\times10^{-3}$ m		
	28 days	180 days	360 days
Steel formwork	0.2	1.2	2.0
TJ80-MQ	0	0.2	0.4

Table 9

Influence on chloride resistance

Formwork category	Electric flux, C		PERMIT, 10^{-12} m^2/s	
	28 days	180 days	28 days	180 days
Ordinary steel formwork	1780	350	4.427	1.534
TJ80-MQ	1620	280	0.654	0.256

Table 10

MIP analysis of different samples at 3 days age

Sample (W/C=0.45)	Total intruded volume, L/g[4]	Total pore area, m^3/g	Average pore diameter, $\times10^{-9}$m	Median volume pore diameter, $\times10^{-9}$m	Apparent (skeletal) density, g /cm^3	Porosity, %
Steel Formwork	0.0815	4.048	84.7	260.6	2.4276	16.52
CPF	0.0408	1.927	80.6	90.2	2.3427	8.73

difference between concrete hardness improvement at 3 days and 180 days could not be explained by water-cement ratio reducing and water conservation for the CPF usage

3.4. Carbonation resistance property

The carbonation test was carried out by testing more than 20 measure points at different age, CPF delayed the concrete carbonation process obviously as showed in Table 8. The results could be contributed to some water was drained out, and some fine particles of the binding materials brought to the surface, the hydration degree was higher at early ages.

3.5. Chloride penetration resistance

Electric flux method has been widely applied as test method of concrete resistance to chloride penetration, the diameter and height of specimen is 0.05 m. PERMIT tester developed by England Queen's University and electric flux method were used to evaluate the permeability resistance of surface concrete in this research. The results were shown in Table 9.

Electric flux results showed that, the improvement of CPF on surface concrete is not obviously. PERMIT method showed that, the chloride diffusivity of samples using CPF is only 15% of samples using ordinary steel formwork. It comes to the conclusion that CPF can significantly increase the chloride penetration resistance of surface concrete.

3.6. Porosity and pore size distribution

The porosity of samples cured at 3 days age is shown in Table 10. Porosity and average pore diameter of cement paste, and the total intruded volume and apparent porosity, all decreased remarkably. The total porosity of cement with CPF was 8.73%, while the value was 16.52% with steel formwork.

Mean volume pore diameters (MVPD) refers to the minimum diameters of pores when half of the total intrusion has taken place. The MVPD value of sample using CPF was about 90.2 × 10^{-9} m, but the MVPD value of sample using steel formwork was much higher at about 260.6 × 10^{-9} m at 3 days age.

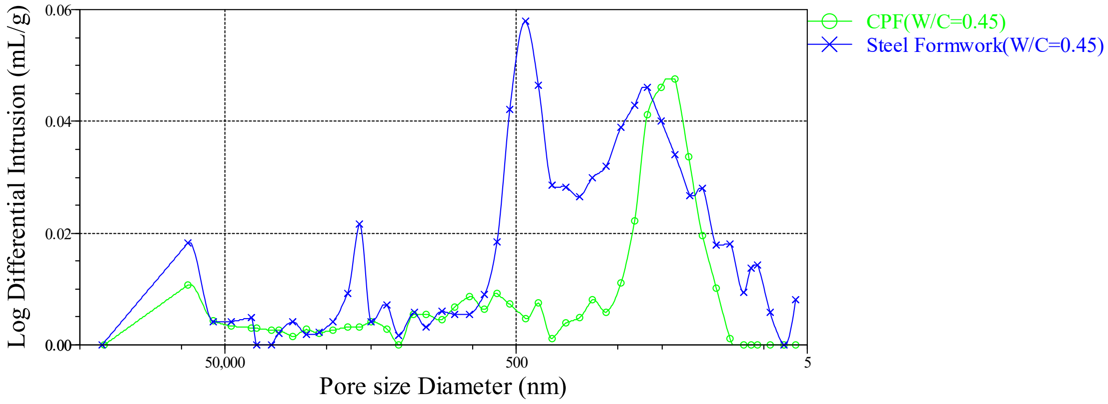

Fig.4 - MIP analysis of pore size distribution: variation of log differential intrusion with pore size diameter after at 3 days.

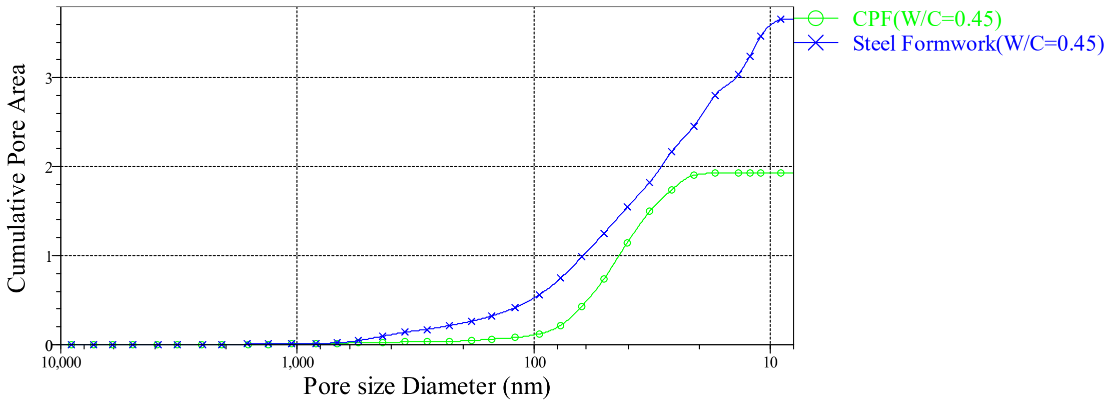

Fig.5 - MIP analysis of pore size distribution: variation of cumulative pore area (103 m^3/kg) with pore size diameter at 3 days.

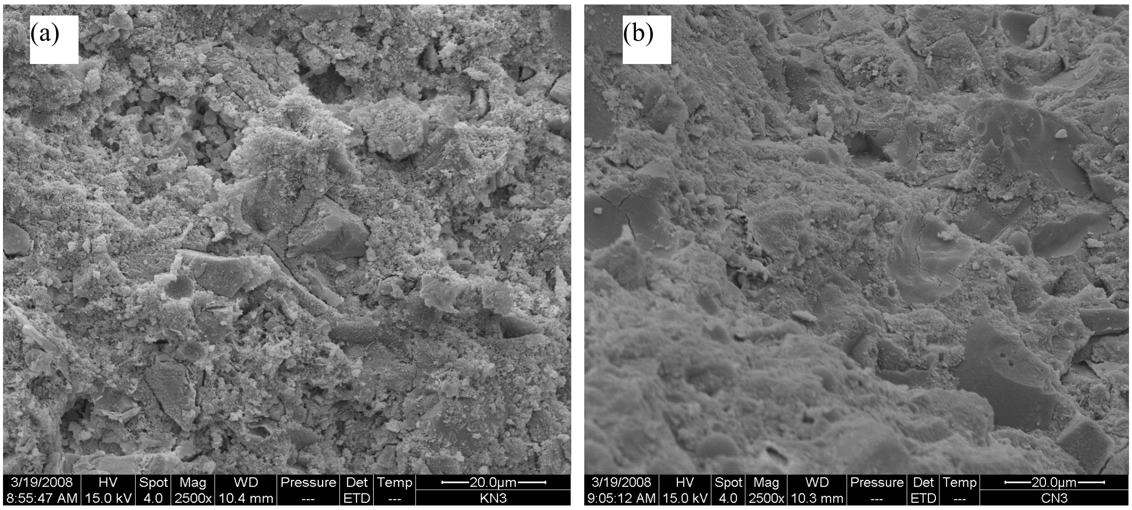

Fig.6 - Typical FE SEM images of samples at 3 days: (a) reference sample; (b) sample using CPF.

The variation of log differential intrusion volume with pore diameter was presented in Fig.4. For sample using steel formwork, log differential intrusion increased with pore diameter decreasing, and reached two maximum value of about 0.06 and 0.05 at the pore size diameter of 0.5 × 10^{-6} m and 0.1 × 10^{-6} m respectively. Thereafter, log differential intrusion decreases with pore diameter decreasing. For sample using CPF, a similar trend can be observed. However, the highest value of 0.045 corresponds to much finer pores, with a diameter of about 0.3 × 10^{-7} m. These phenomena indicated that the presence of CPF reduces pore sizes and fined the pore size distribution.

The variation of cumulative pore area with pore diameter was shown in Fig.5. The cumulative pore area increased with the pore size diameter decreasing for all the samples. The value with CPF was lower than that of using steel formwork. The phenomenon indicates that the presence of CPF reduced cumulative pore area and the composites become compacted.

3.7. Microstructure

Fig.6 shows that compared with the reference sample, the cement hydration products with CPF were intimately mixed and connected to each other. FE SEM analysis shows that the sample using CPF is more compacted than that of steel formwork.

The reduction of porosity in the composites is very important factor to the property's improvement observed. Cement composites are porous materials, in which there exist large numbers of capillary pores and micro voids. The use of CPF reduces the porosity in composites, pores size, and as a result the density is increased as seen in Fig.6.

3.8. Enrichment hypothesis of fine cement particulates on concrete surface

According to the results obtained through indoor and outdoor experiments, in the process of concrete pouring and vibrating, the mixing water of the binding materials flow from the formwork joint and carry a small amount of fine binding materials [15]. When using steel formwork, some free water moves to the formwork surface, which is bound to carry some fine binding material particles (shown in the Fig.7).

Fig.7 - Mixing water of the binding materials flow from the formwork joints.

Thus, the authors put forward the enrichment hypothesis of fine cement particles on concrete surface: after concrete casting, part of the mixing water migrate into the CPF (shown in the Fig.8a). The excess water will be expelled after saturation, the water in the surface concrete structures and CPF reach equilibrium until the concrete concentration increased to begin solidification. When part of the mixing water moving to the controlled permeability formwork, cement fine particles carried by the mixing water gathered on the structure surface (shown in the Fig.8b). The hydration speed of the gathered cement fine particles is quick due to the surface

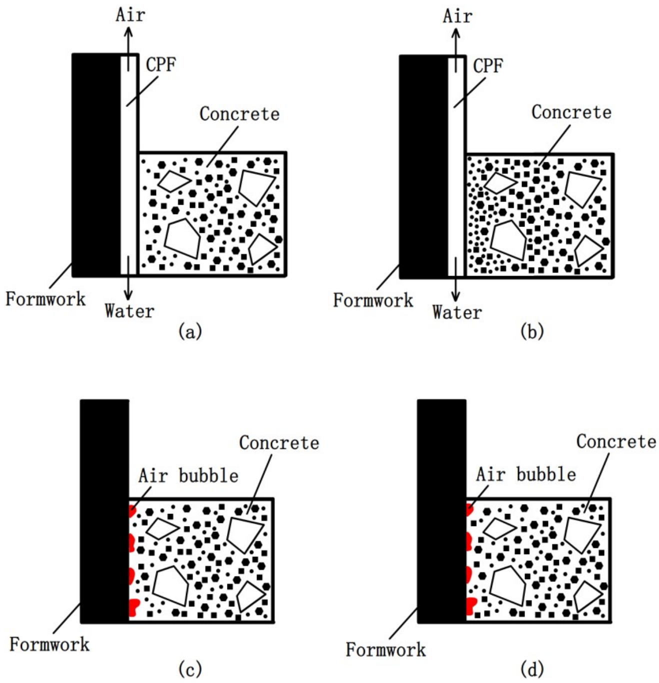

Fig.8 - Mechanism simulation diagram of fine cement particles enrichment hypothesis.

water saturation provided by the abundant water atmosphere and the moisture effect. The mixing water and air bubbles did not rearrange after the end of vibration (shown in the Fig.8c, 8d). The hardness of concrete surface with or without CPF were different largely at the early ages, but nearly the same at 180 days and 540 days, this could be explained from the point of the cement fine particles gathered on the surface by CPF.

4. Conclusions

CPF are widely used in some crucial concrete engineering, for the surface properties of cover concrete can be improved obviously. CPF has superior water draining and retaining ability, and some mixing water remained in it could provide sustained moisture curing for surface concrete. In the process of drainage of water and air out of concrete surface, CPF could impel the finer particles of cementitious materials migrate towards concrete surface, and keep moisture for surface concrete for some days, so it can improve the properties of surface concrete, especially at early age.

It was accepted easily that the excess water and air bubbles at surface of concrete would be discharged by pressure which occurred by weight of concrete itself, compaction, and capillary suction of CPF. The w/c ratio near the surface could be reduced greatly, and the sustained moisture curing function could be continued by water sucked in CPF. While only with this viewpoint, some experimental phenomenon could not be explained clearly. Now, to suggest a conjecture that with discharge of excess water and air bubbles, fine particles of cementitious materials migrate towards surface of formwork to fill the pore space left by water and air at concrete surface, and concrete contacting the CPF might be kept wet with the sustained water. By the moisture curing function, the fine particles could hydrate quickly, the concrete properties at early age would be improved sharply, and its long-term properties would be guaranteed also.

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