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Communication

Effect of ground quartz sand on properties of high-strength concrete in the steam-autoclaved curing

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Abstract

Effects of many factors, such as ground quartz sand (GQS) replacement of cement, SiO_2 content and specific area of GQS, and steam-curing temperature on the mechanical properties of high-strength concrete that was steam-autoclaved, were investigated. The mechanism of GQS replacement of cement was analyzed by XRD. The process adjustment and the cost of raw materials in concrete after GQS replacement of cement were also discussed. © 2001 Elsevier Science Ltd. All rights reserved.

Keywords: Concrete; High strength; Ground quartz sand; Steam curing; Autoclaved curing

Pre-stressed concrete pipe piles with high strength (PHCP) have been widely used for consolidating the soft-soil ground in the east and south of China, such as in Shanghai, Guangdong, Hong Kong, and Macao. The compressive strength of the concrete is always higher than 80 MPa, and its pre-stressing value is about 5 MPa. The diameter of PHCP is 30 to 60 cm and the length is 7 to 12 m [1].

PHCP is produced with the centrifugal process after casting concrete. The curing process of PHCP is generally divided into two steps, i.e., the steam-curing stage and the autoclaved-curing stage. In the steam-curing stage, PHCP can attain strength high enough to sustain the releasing pre-stress after demolding. The steam-curing temperature is usually 60–90°C. The strength of concrete in PHCP can quickly reach the design value in the autoclaved-curing stage in which its saturated vapor pressure is commonly about 1.0 MPa. Moreover, only ordinary Portland cement is usually used for producing PHCP, for which the cement content is higher than 500 kg/m^3 concrete in China.

During steam curing with higher temperature at atmospheric pressure, and especially in the autoclaved-curing process, the rate of cement hydration is more accelerated compared with that at room temperature. Furthermore, the degree of crystallinity and the amount of hydrates, such as lamellar $Ca(OH)_2$ and rectangular-tablet α-C_2SH are enhanced, and their crystal size also becomes larger with the increase in temperature [2]. Obviously, lamellar $Ca(OH)_2$ and rectangular-tablet α-C_2SH crystals are weak parts in the structure of concrete and are harmful for the strength of concrete, especially for high-strength concrete and paste–aggregate interfaces.

Consequently, it is necessary to reduce the amount of $Ca(OH)_2$ and α-C_2SH hydrates in order to improve the microstructure and quality of concrete. In this paper, ground quartz sand (GQS) replacement of cement is considered as an important technical measure to get this goal.

1. Experimental

1.1. Raw materials and mix proportions

The 525# ordinary Portland cement according to the Chinese standard GB 175-85 is used. The aggregate consists of 5–20 mm crushed rock, with the river quartz sand having

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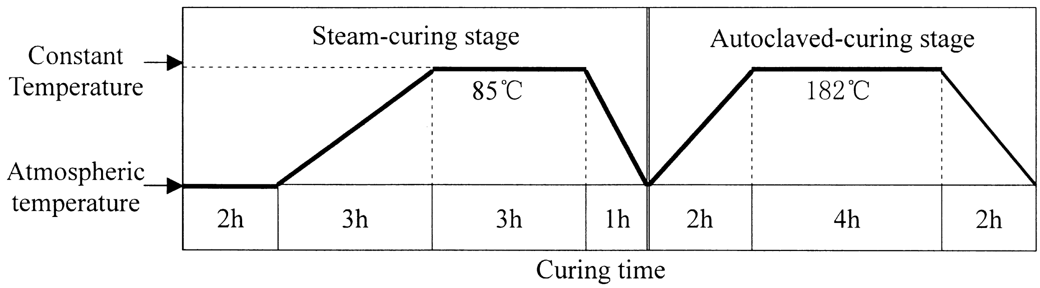

Fig. 1. Conditions in the steam-curing and autoclaved-curing stages.

the fineness modulus of 2.5. Four types of natural quartz sand are used for producing GQS with the Blaine specific area of 283–551 m^2/kg, having SiO_2 content of 99%, 94.5%, 92.1%, and 84.7%, respectively. The GQS with 92.1% SiO_2 is from the same sand as the river sand for preparing concrete. A naphthalene sulfonate superplasticizer, Mighty 100, is used for making the concrete.

The mix proportions of concrete are (cement + GQS)/water/crushed rock/river sand/Mighty = 1:0.282:2.63:1.32:0.005. GQS replacement of cement is 10–40% by weight. The slump of concrete increases with the GQS replacement of cement, i.e., from 10 to 45 mm.

GQS with 92.1% SiO_2 and Blaine specific area of 354 m^2/kg is used and its replacement of cement is 30%, if not otherwise indicated.

1.2. Steam-curing and autoclaved-curing conditions

Cubic specimens of 100 mm were used. After casting, the specimens covered with damp cotton cloth were cured for 1 day in air at 20 ± 5°C and then were demolded. A part of them was stored for 27 days in water at 20 ± 2°C (ordinary curing). Other specimens were stored under the curing conditions in Fig. 1. The constant temperature in the steam-curing stage is about 85°C if no special note. The saturated vapor pressure in the autoclaved stage is about 1.0 MPa (at the constant temperature of about 182°C). Some of the specimens after autoclaving were cured in water for 27 days at 20 ± 2°C.

The compressive strength of concrete was measured after it was cured under the different conditions. The specimens were stored in the steam-curing stage before being entered in the autoclaved-curing stage.

2. Results and discussions

2.1. Amount of GQS replacement of cement

After GQS replacement of cement, results of the compressive strength of concrete cured in the different conditions are shown in Fig. 2. The strength of concrete in steam curing and in ordinary curing for 28 days is reduced with the increase in the amount of GQS replacement of cement. However, the strength of concrete with GQS after autoclaving is higher than that of concrete without GQS when the amount of GQS replacement of cement is 10–40%. Meanwhile, the maximum strength is obtained at a GQS/cement ratio of about 30:70 for the GQS with 92.1% SiO_2 and specific area of 354 m^2/kg. The optimum ratio, of course, depends on the quality and fineness of GQS.

Fig. 2 also shows that the strength retrogression of concrete decreases with the increase in GQS replacement

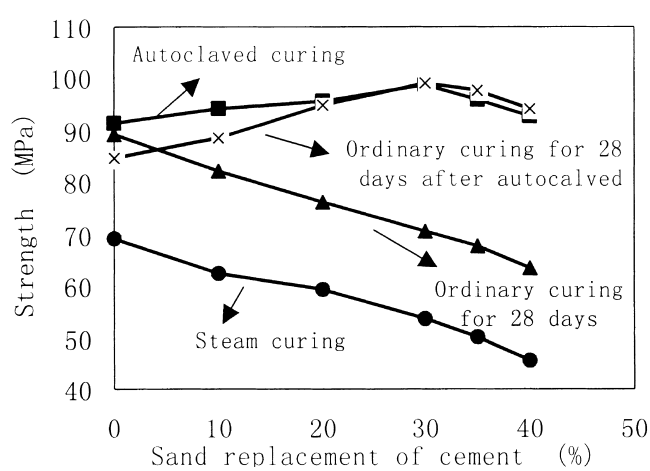

Fig. 2. Effect of GQS replacement of cement on the compressive strength of concrete.

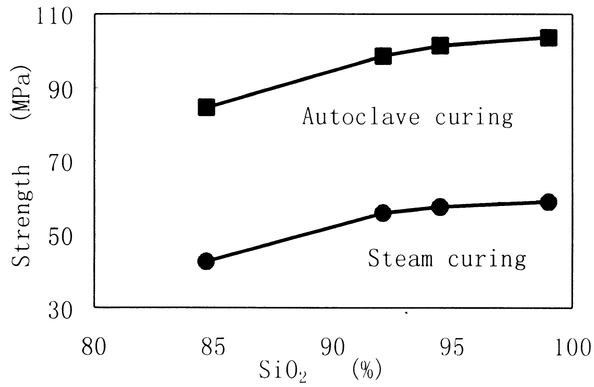

Fig. 3. Effect of SiO_2 content in GQS on the compressive strength of concrete.

of cement when concrete specimens are continually stored in water at 20 ± 2°C for 28 days after autoclaved. The retrogressed strength of concrete without GQS is even lower than that of concrete without GQS in the ordinary curing for 28 days. The strength retrogression of concrete with above 30% GQS does not occur but somewhat increases when concrete is continually stored in water after being autoclaved.

Obviously, at atmospheric pressure, GQS hardly reacts with $Ca(OH)_2$ even though the steam-curing temperature is high enough, about 85°C, and therefore the strength of concrete is significantly reduced when cement is replaced by GQS.

2.2. SiO_2 content in GQS

SiO_2 content is the most important parameter of GQS. The higher the SiO_2 content is, the better is the quality of GQS and the lower is the soil content, and therefore, the higher the strength of concrete with GQS is. From Fig. 3 it is clearly shown that the strength of concrete with GQS, cured in the steam-curing stage or in the autoclaved-curing stage, is enhanced with the increase in the SiO_2 content of GQS. However, the increase in the strength of concrete is not obvious when the SiO_2 content of GQS is higher than about 92.1%. For GQS with 84.7% SiO_2, the compressive strength of concrete with the GQS after autoclaving is only about 82.7 MPa, much lower than that of concrete without GQS, which is about 91.3 MPa. Consequently, it is better for GQS used in PHCP that its SiO_2 content is higher than about 92%.

2.3. Specific surface area of GQS

Effect of specific surface area of GQS on the compressive strength of concrete is shown in Fig. 4. The reactivity of siliceous materials with $Ca(OH)_2$ increases with the increase of its specific surface area. Fig. 4 indicates that the strength of concrete after autoclaving is enhanced when the Blaine specific area of GQS increases, but the increase in the strength is not significant when the specific area is over 354 m^2/kg. Furthermore, the specific area has little influence on the strength of concrete cured in the steam-curing stage, which shows that the reactivity of GQS is still very low even though its specific area is high enough at about 551 m^2/kg.

2.4. Steam-curing temperature

For PHCP without GQS, the steam-curing temperature is usually about 70°C which is high enough to make the strength of the concrete meet the design demand on the releasing pre-stress. The results in Fig. 2 prove that, at atmospheric pressure, SiO_2 in GQS is inactive and cannot react with $Ca(OH)_2$ formed during the hydration of cement, and therefore the strength of concrete significantly decreases with the increase in the amount of GQS replacement of cement. In order to get strength high enough to undergo the releasing pre-stress, the steam-curing temperature has to be higher for PHCP with GQS. Fig. 5 clearly demonstrates that the strength of concrete with GQS obviously increases with the steam-curing temperature, but the increase of the temperature has little influence on the strength of concrete after

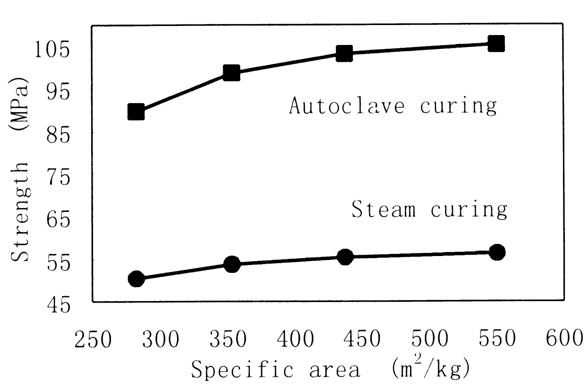

Fig. 4. Effect of specific surface area of GQS on the compressive strength of concrete.

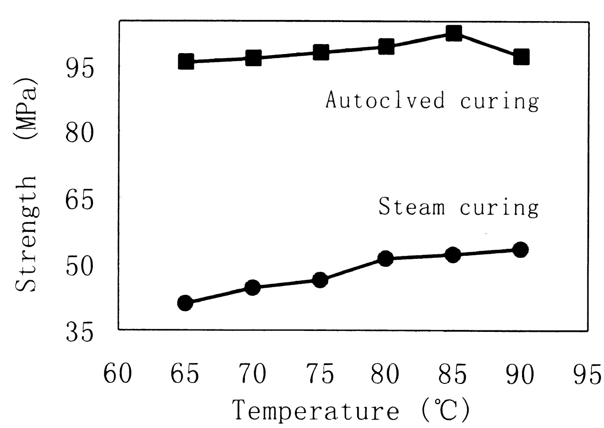

Fig. 5. Effect of the steam-curing temperature on the compressive strength of concrete.

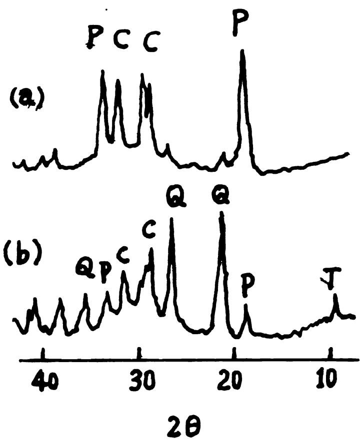

Fig. 6. Analysis results of XRD on the pastes after autoclaving. (a) OPC paste. (b) 70% OPC–30% GQS paste. P, $Ca(OH)_2$; C, C_2SH; Q, SiO_2; T, 9.97 Å tobermorite.

autoclaving. The strength after autoclaving is reduced when the temperature is increased from 85°C to 90°C.

The higher the temperature in the steam-curing stage, the quicker is the hydrate rate of cement and the higher is the strength of concrete after steam curing. However, the increase of the temperature makes capillary pores and hydrates coarser, and enhances the possibility of micro-cracking generated at the paste–aggregate interfaces. Consequently, it is better that the steam-curing temperature is not higher than 85°C.

2.5. Mechanism of GQS replacement of cement

During the autoclave-curing stage under high pressure, inactive SiO_2 in GQS can be activated, and therefore can quickly react with $Ca(OH)_2$ even though it cannot react with $Ca(OH)_2$ at atmospheric pressure. The results of XRD analysis are shown in Fig. 6. For OPC paste, there are a lot of well-crystallized hydrates, such as $Ca(OH)_2$ and C_2SH. However, for 70% OPC–30% GQS paste, a new type of poorly crystallized CSH hydrate with lower C/S ratio, 9.97 Å tobermorite is formed, and the amount of $Ca(OH)_2$ is significantly reduced due to reacting with SiO_2 in GQS. Moreover, the amount and crystalline degree of C_2SH hydrate are reduced, and a lot of residual crystalline quartz still exists. These results clearly show that SiO_2 in GQS can react with $Ca(OH)_2$ to form tobermorite during the autoclave curing with the saturated vapor pressure of about 1.0 MPa.

3. Application of GQS in manufacturing plants

The application results of GQS in a manufacturing plant were measured in Hongji Concrete Pipe Piles (Zhongshan, Guangdong Province).

Based upon the above laboratory results, GQS with 92.1% SiO_2 and specific area of 354 m^2/kg was used in the production of PHCP. The mix proportion of concrete is (70% cement + 30% GQS)/water/rock/sand/Mighty = 1: 0.28:2.54:1.37:0.005. The temperature in the steam-curing stage was changed to 85°C from 70°C, but other curing conditions were not changed. Besides the curing conditions, mixing and centrifugal processes also have a large influence on the strength of concrete with GQS.

3.1. Adjusting the production process

3.1.1. Mixing process

Because the GQS replacement of cement is about 30% and GQS itself does not have a latent hydraulic property, it is very important that GQS is fully mixed with cement, or else it is easy to produce some weak zones in the concrete which would be harmful to the quality of HPC.

For concrete without GQS, it is a common mixing process that all raw materials are added into the mixer and are mixed together for about 1 min. For concrete with GQS, it is better to prolong the mixing time to achieve higher homogeneity of fresh concrete. The new mixing process is that cement and GQS are initially mixed with sand for about 40 s, and then mixed with coarse aggregate and water together for about 50 s. From Table 1 it can be seen that the strength of concrete with GQS is obviously enhanced after using the new mixing process, but this change only has a little influence on that of concrete without GQS.

3.1.2. Centrifugal process

The four-stage centrifugal process is applied for the production of PHCP, i.e. PHCP is centrifugally spun at a rotation speed of 250, 610, 1050, and 1850 rpm in turn. For PHCP without GQS, the common centrifugal time for the four speeds is 2, 3, 6, and 8 min, respectively. Because the densities of GQS and cement are about 2.6 and 3.15, respectively, and the difference between them is obvious, GQS is easily separated from cement paste when the centrifugal process is unreasonable. Consequently, it is necessary to adjust the rotation speed and the time in order to avoid this harmful result.

Table 1
Effect of mixing process on the compressive strength of concrete

	Compressive strength (MPa)			
	Without GQS		With 30% GQS	
Mixing process	After steam curing	After autoclaving	After steam curing	After autoclaving
Common	63.7	93.2	48.6	92.3
New	65.3	94.9	55.4	108.6

Table 2
Effect of the centrifugal process on the compressive strength of concrete

Centrifugal process[a]: $\omega_1+\omega_2+\omega_3+\omega_4$ (rpm); $T_1+T_2+T_3+T_4$ (min)	Compressive strength (MPa)			
	Without GQS		With 30% GQS	
	After steam curing	After autoclaving	After steam curing	After autoclaving
250 + 610 + 1050 + 1850; 2 + 3 + 6 + 8	64.2	95.3	50.7	93.8
250 + 610 + 1050 + 1800; 2 + 2 + 4 + 6	61.3	90.4	52.4	96.8
250 + 610 + 1050 + 1800; 2 + 2.5 + 5 + 6	62.2	92.1	55.3	109.5

[a] T_1, T_2, T_3, and T_4 is the centrifugal time at the rotation speed of ω_1, ω_2, ω_3, and ω_4, respectively.

After steam curing or autoclaving, cubic specimens of 10 cm for measuring strength were cut out from PHCP.

The effects of various centrifugal processes on the strength of concrete are shown in Table 2. It clearly indicates that the technical measures for reducing the highest rotation speed and for shortening the centrifugal time are advantageous for enhancing the strength of concrete with GQS, but these measures reduce the strength of concrete without GQS.

For the old centrifugal process, GQS is accumulated near the inside wall of pipe due to the centrifugal action and the white ground sand can be seen there, and therefore the uniformity of concrete in PHCP with GQS is poor and the strength of concrete decreases. After adjusting the centrifugal process, from the transection of PHCP with GQS it can be seen that the uniformity of concrete is very good.

3.2. Cost of raw materials

The cost of PHCP products is reduced very much while GQS is used to substitute cement. For example, GQS of above 10 000 tons is applied each year in Hongji, and the price of 525# OPC and GQS is about RMB480/ton and RMB120/ton, respectively (US$1 = RMB8.30), so about RMB3.6 millions can be saved for the cost of raw materials every year. According to the mix proportion of concrete used in Hongji, the cost of raw materials in concrete is reduced about 21%.

3.3. Performance of PHCP with GQS

3.3.1. Quality

According to producing records in PHCP plant, the quality of PHCP is improved after adding 30% GQS. From April 1994 to March 1995, the average compressive strength of concrete in PHCP without GQS after autoclaving was about 90.3 MPa and its standard deviation of the strength is 3.73 MPa. From April 1995 to April 1998, the average compressive strength of concrete in PHCP with 30% GQS after autoclaving was about 97.3 MPa and its standard deviation of the strength was 4.5 MPa. Moreover, the appearance quality of PHCP and the compactness of concrete were also enhanced after adding 30% SiO_2.

3.3.2. Piling test in the field

According to the about 5-year piling results in fields, it proved that PHCP with GQS possessed much higher impact resistance than PHCP without GQS when struck by a piling hammer. The intactness of PHCP with 30% GQS almost keeps at 100% even though it is struck with the maximum piling stress allowed by the pile design, but the intactness of PHCP without GQS is always below 75% in this condition. The reason behind this phenomenon may be that the microstructure and paste–aggregate interfaces of PHCP are improved and the amount of microcracking is reduced due to SiO_2 in GQS absorbing and reacting with $Ca(OH)_2$ in PHCP.

4. Conclusions

The effects of 0% to 40% GQS replacement of cement, SiO_2 content, and specific area of GQS on the compressive strength of concrete in the steam curing and autoclaved curing were investigated. After adding GQS, the process adjustments of PHCP and cost effectiveness were discussed. The following conclusions can be drawn:

(1) At atmospheric pressure, the compressive strength of concrete after the steam curing or ordinary curing for 28 days is reduced with the increase in GQS replacement of cement. However, at the saturated vapor pressure of about 1.0 MPa, the compressive strength of concrete with GQS replacement of 10–40% after autoclaving is higher than that of concrete without GQS. Moreover, the strength of concrete without GQS, stored in water for 28 days, after autoclaving retrogresses and is even lower than that of concrete without GQS only in the ordinary curing for 28 days, but the strength of concrete with above 30% GQS does not retrogress but somewhat increases.

(2) In order to get enough high strength to undergo the releasing pre-stress for PHCP with 30% GQS, the temperature in the steam-curing stage needs to be changed to 85°C from 70°C.

(3) In order to meet the demand for the quality of PHCP, the SiO_2 content and specific surface area of GQS need to be larger than 92% and 350 m^2/kg, respectively, when the temperature in the steam-curing stage is about 85°C and the

saturated vapor pressure in the autoclaving stage is about 1.0 MPa.

(4) The technical measures for prolonging the mixing time of concrete, reducing the highest rotation speed, and shortening the centrifugal time are advantageous for enhancing the strength and homogeneity of concrete with GQS.

(5) By XRD analysis, it is clearly proved that the crystalline SiO_2 in GQS can quickly react with $Ca(OH)_2$ released by hydration of cement to form 9.97 Å tobermorite in the autoclaving stage and therefore GQS also possesses effective pozzolanic property in this condition.

(6) By the investigations in laboratory and application of PHCP with GQS in the field, it is effectively confirmed that GQS replacement of cement, not only is feasible in technology, but also significantly reduces the cost of raw materials in concrete.

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