

Experimental Investigation of the Optimal Design of the Ultrahigh Early Strength Concrete

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Abstract. Comparing with the common concrete, the ultrahigh early strength concrete can form in an extremely short time, which can be effectively applied in the field of the fast repair engineering. Based on this point, the design of the optimal mix proportion of ultrahigh early strength concrete was investigated in this study. First, the optimal water-cement ratio was determined through the experiment. Second, the relationship between water reducing agent and concrete strength was investigated, and then the optimal dosage of admixture was determined. The experimental results show that the prepared ultrahigh early strength concrete can obtain the high strength in the early time, which is beneficial for the practical application. Additionally, some other performances are acquired, such as the rapid condensation properties, the permeability resistance and workability etc.

1. Introduction

Concrete, widely used material in civil engineering, has the characteristics of easily accessible raw materials and lower cost. Also it has advantages of high compressive strength and good durability. With the increasing traffic pressure in China, it is necessary to improve the services quality of the roads, bridges and tunnels. At present, facing at the issue of quick repair and construction, there is the demand for ultrahigh early strength concrete. The common Portland cement, which forms in a long time, is inapposite to be used in fast construction. Therefore, the ultrahigh early strength concrete has drawn people's attention.

To prepare the ultrahigh early strength concrete, much scientific research has been carried out. Hanehara et al [1-3] thought high performance concrete with high strength, superior fluidity, and self-compactability could be realized mainly because of chemical admixtures. Cerulli [4] found out that a new polycarboxylate superplasticizer allowed the production of cement mixtures characterized by low water-cement ratio and high early age mechanical strength development. Nkinamubanzi [5] pointed out that the naphthalene-based superplasticizers could accelerate the sulfate cement hydration reaction and control the loss of fluidity of the concrete. It was found that the strength of the mortars was increased because of the more complete hydration of the superfine slag section [6]. Gleize [7] stated that the pore structure of mortar with silica fume was found to be finer than of non-silica fume mortar. Khokhar's study [8] showed that using mineral additions in large replacements could lead to good compressive strength even at early age. Korpa [9] found out that the high performance specimens that contained both micro and nanoscale additives were characterised by very tight structure and were made up of finer structures in closer contact. In the case of concretes containing cement with a high specific surface area and a predominant amount of alite, as well as in the case of concretes containing no silica fume or only a small amount of it, compressive strength increased rapidly in the early stage of hardening [10]. The



previous research results show that the performance requirements of the ultrahigh early strength concrete are as follows. (i) The concrete should have fast hardening process and the early strength should be high enough; (ii) The time of condensation should be moderate, that is, the ultrahigh early strength concrete should have longer initial setting time and shorter final setting time, which can be easy to construct while ensuring early strength; (iii) Also, in order to increase the service life and reduce the maintenance cost, the ultrahigh early strength concrete should have good durability. As the ultrahigh early strength concrete is limited by the above several requirements on performance, special cement are used and the admixture such as silicon powder is added when preparing the concrete. Usually it is not ideal to improve the early strength of concrete by some means. Therefore, a variety of factors should be considered to prepare the ultrahigh early strength concrete, which can meet engineering requirements and solve the practical engineering problems.

The remainder of the article is organized into 3 sections. Section 2 covers the raw materials and experiment scheme, and thereafter, the results of the experiment are described in Section 3. Finally, the paper is concluded in Section 4.

2. Materials and methods

2.1. The raw materials

In this experiment, the sulphate aluminate cement, whose strength grade is 42.5MPa, product from China United Cement Lunan Co.,Ltd, and the granite rock with bulk density 1.71g/cm^3 is the coarse aggregate. The fineness modulus of the natural medium sand is 2.83, and the bulk density is 1.83g/cm^3 . The mineral admixtures selected in this experiment is the silicon powder whose fluidity ratio is more than 95%. The water reducing agent with high performance is HTPCA poly carboxylic acid from the China United Cement Lunan Co.,Ltd. Sodium tripolyphosphate is chooses as concrete retarder in this trial.

2.1. Method

Needless to say, reducing the water-cement ratio is an effective way to improve strength. But the concrete would show the poor workability because of the low water-cement ratio. Therefore, it is important to determine the reasonable water-cement ratio. In this experiment, the water-cement ratio is between 0.36 and 0.42. According to the previous research, water reducing agent can effectively improve the strength and the workability of the concrete. The dosage of water reducing agent ranges from 0.6% to 1.5%. Meanwhile, the appropriate retarder can improve the workability of concrete, so the dosage is set from 0.6% to 1.2%.

In order to analyse the influence factors on the compressive strength of ultrahigh early strength concrete, so as to find the best mixture ratio, orthogonal design method is used in this experiment. Three factors are considered in this study, such as water-cement ratio, water reducing agent and retarder. And each factor has 4 levels according to the reasonable range of the initial trial. The early strength of concrete is enhanced by using the fast hardening sulphoaluminate cement. In this trial, the orthogonal table of $L_{16}(4^3)$ was used to evaluate the compressive strength of the concrete in 8-hour, 3-day and 28-day maintenance respectively. The levels of the influence factors in this orthogonal design are shown in Table 1.

Table 1. The levels of the influence factors

Level	Water-cement ratio	Retarder (%)	Water reducing agent (%)
1	0.36	0.6	0.6
2	0.38	0.8	0.9
3	0.40	1.0	1.2
4	0.42	1.2	1.5

3. Results and discussions

3.1. Analysis of the optimal dosage of 8-hour specimens

The strength of concrete was tested and the results are analyzed in this part. The results of the 8-hour compressive strength were shown in Table 2.

Table 2. Analysis of 8-hour compressive strength

Case number	Water-cement ratio	Retarder (%)	Water reducing agent (%)	Compressive strength (MPa)
1	0.36	0.6	0.6	26.5
2	0.36	0.8	0.9	29.8
3	0.36	1.0	1.2	30.9
4	0.36	1.2	1.5	29.3
5	0.38	0.6	0.9	26.0
6	0.38	0.8	0.6	26.5
7	0.38	1.0	1.5	25.7
8	0.38	1.2	1.2	25.4
9	0.40	0.6	1.2	26.1
10	0.40	0.8	1.5	23.0
11	0.40	1.0	0.6	21.1
12	0.40	1.2	0.9	18.3
13	0.42	0.6	1.5	18.0
14	0.42	0.8	1.2	19.7
15	0.42	1.0	0.9	16.3
16	0.42	1.2	0.6	15.6
K_1	116.50	96.69	89.67	/
K_2	103.57	98.98	90.41	/
K_3	88.49	93.88	102.16	/
K_4	69.64	88.63	95.95	/
\bar{K}_1	29.13	24.17	22.42	/
\bar{K}_2	25.89	24.75	22.60	/
\bar{K}_3	22.12	23.47	25.54	/
\bar{K}_4	17.41	22.16	23.99	/
f	11.72	2.59	3.12	/

3.1.1. Range analysis. The change and rule of the strength under different influence factor were given through the range analysis. The results of the range analysis were shown in Table 2 and the specific trend was shown in Figure 1.

Some information could be obtained from the results of the range analysis in Table 2. The optimum test mix ratio of C40 ultrahigh early strength concrete was under the water-cement ratio of 0.36, retarder of 0.8% and water reducing agent of 1.2%. The best sample did not appear in the test. The maximum compressive strength was 30.9MPa after 8 hours, which reached 77.3% of the design strength. This accorded with the requirement of ultrahigh early strength concrete.

The maximum range of strength was 11.72 MPa, which was caused by the water-cement ratio, and the range of strength caused by the water reducing agent was 3.12 MPa. Finally, the minimum range of strength was 2.59 MPa caused by the retarder. This indicated that the main factors affecting the strength of concrete was water-cement ratio and the water reducing agent had bigger impact than retarder. The water-cement ratio, the main influencing factors, made the largest fluctuations. The reducing agent and retarder made smaller fluctuations and they were secondary factors.

3.1.2 Variance analysis. The variance analysis of the compressive strength influenced by different factors were shown in the table below.

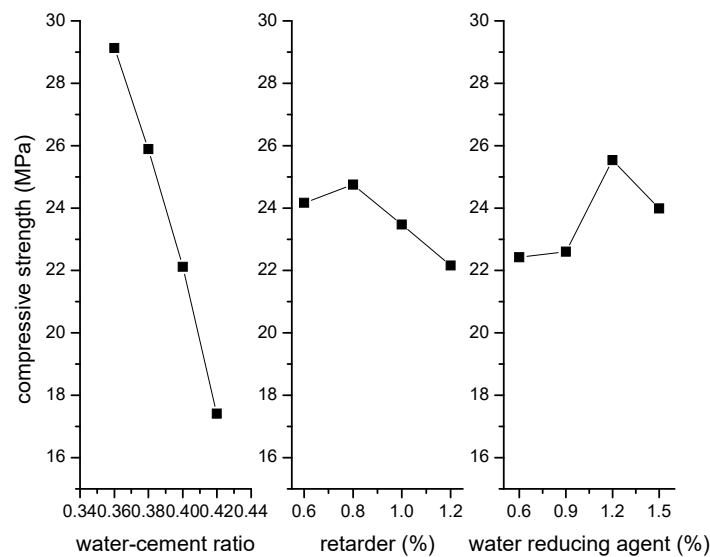


Figure 1. Comparison of 8-hour compressive strength

Table 3. The variance analysis of the 8-hour compressive strength

Sources of variance	Quadratic sum	DOF	Mean square	<i>F</i> value	Significance	<i>F</i> critical value
Water-cement ratio	305.18	3	101.7277	117.2015	highly significant	
Retarder	14.92	3	4.9738	5.730325	significant	$F_{0.01}(3,6)=9.78$
Water reducing agent	25.22	3	8.4074	9.686254	significant	$F_{0.05}(3,6)=4.76$ $F_{0.10}(3,6)=3.29$
Error <i>e</i>	5.20	6	0.8680	/	/	
Total	350.53	15	/	/	/	

It could be seen from Table 3 that according to the mean square of each factor, the influencing factors weakened from water-cement ratio, water reducing agent to retarder after 8-hour maintenance. The effect of water-cement ratio was highly significant and the effect of water reducing agent and retarder was significant, which consisted with the results of range analysis above.

3.1.3 The optimal dosage. From the range analysis and variance analysis, it was concluded that the 8-hours compressive strength was highest when the water-cement ratio was 0.36, the dosage of water reducing agent was 1.2% and the dosage of retarder was 0.8%. The strength of concrete had reached 77% of the design strength after 8-hour maintenance, but the strength of the specimen increased still in high speed, so it was necessary to have further analysis about the 3-day compressive strength of the specimen.

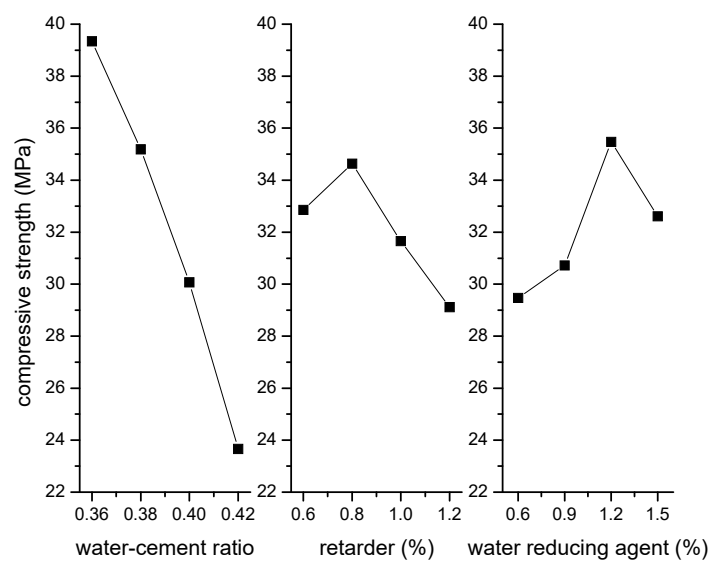
3.2 Analysis of the optimal dosage of 3-day specimens

Using the same method, 3-day compressive strength test results and calculation were shown in Table 4.

3.2.1 Range analysis. The change and rule of the strength under different influence of each factor were given through the range analysis. The results of the range analysis were shown in Table 4 and the specific trend was shown in Figure 2.

Table 4. Analysis of 3-day compressive strength

Case number	Water-cement ratio	Retarder (%)	Water reducing agent (%)	Compressive strength (MPa)
1	0.36	0.6	0.6	35.1
2	0.36	0.8	0.9	41.5
3	0.36	1.0	1.2	42.0
4	0.36	1.2	1.5	38.8
5	0.38	0.6	0.9	35.4
6	0.38	0.8	0.6	36.0
7	0.38	1.0	1.5	34.9
8	0.38	1.2	1.2	34.6
9	0.40	0.6	1.2	36.5
10	0.40	0.8	1.5	32.3
11	0.40	1.0	0.6	27.6
12	0.40	1.2	0.9	23.9
13	0.42	0.6	1.5	24.5
14	0.42	0.8	1.2	28.8
15	0.42	1.0	0.9	22.1
16	0.42	1.2	0.6	19.2
K_1	157.35	131.43	117.88	/
K_2	140.77	138.54	122.89	/
K_3	120.27	126.61	141.86	/
K_4	94.65	116.47	130.42	/
\bar{K}_1	39.34	32.86	29.47	/
\bar{K}_2	35.19	34.64	30.72	/
\bar{K}_3	30.07	31.65	35.47	/
\bar{K}_4	23.66	29.12	32.61	/
f	15.68	5.52	6.00	/

**Figure 2.** Comparison of 3-day compressive strength

Some information could be obtained from the results of the range analysis in Table 4. The optimum test mix ratio of C40 ultrahigh early strength concrete was under the water-cement ratio of 0.36, retarder of 0.8% and water reducing agent of 1.2%. Also the best sample did not appear in the test. The maximum compressive strength was 42.0MPa after 3-day, which reached 105% of the design strength. This was in accordance with the requirement of ultrahigh early strength concrete.

The maximum range of strength was 15.68 MPa, which was caused by the water-cement ratio, and the range of strength caused by the water reducing agent was 6.00 MPa. Finally, the minimum range of strength was 5.52 MPa caused by the retarder. This indicated that the main factors affecting the strength of concrete was water-cement ratio and the water reducing agent had bigger impact than retarder. The water-cement ratio, the main influencing factors, made the largest fluctuations. The fluctuations under the reducing agent and retarder were smaller. They were secondary factors.

3.2.2 Analysis of variance. The variance analysis of the compressive strength influenced by different factors was shown in the table below.

Table 5. The variance analysis of the 3-day compressive strength

Sources of variance	Quadratic sum	DOF	Mean square	F value	Significance	F critical value
Water-cement ratio	549.09	3	183.03	105.99	highly significant	
Retarder	64.34	3	21.45	12.42	highly significant	$F_{0.01}(3,6)=9.78$
Water reducing agent	81.57	3	27.19	15.75	highly significant	$F_{0.05}(3,6)=4.76$ $F_{0.10}(3,6)=3.29$
Error <i>e</i>	10.36	6	1.73	/	/	
Total	705.37	15	/	/	/	

It could be seen from Table 5 that according to the mean square of each factor, the order of influencing the strength of concrete after 3-day maintenance weakened from water-cement ratio, water reducing agent to retarder. The effect of water-cement ratio, water reducing agent and retarder were all highly significant. This was consistent with the results of range analysis above.

3.2.3 The optimal dosage. From the range analysis and variance analysis, it was concluded that the strength was highest when the water-cement ratio was 0.36, the dosage of water reducing agent was 1.2% and the dosage of retarder was 0.8%.

3.3 Analysis of the optimal dosage of 28-day Specimens

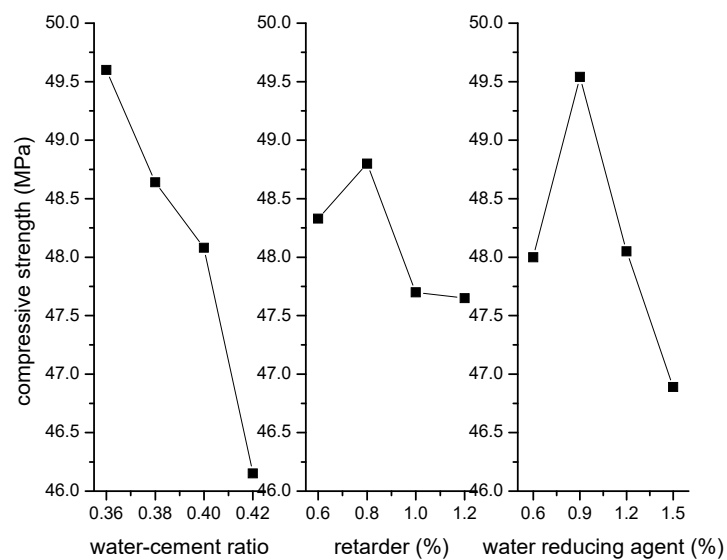
The 28-day compressive strength test results were shown in Table 6.

3.3.1 Range analysis. The change and rule of the strength under different influence of each factor were given through the range analysis. The results of the range analysis were shown in Table 6 and the specific trend was shown in Figure 3.

The optimum test mix ratio of C40 ultrahigh early strength concrete was under the water-cement ratio of 0.36, retarder of 0.8% and water reducing agent of 0.9%. The maximum compressive strength was 52.5MPa after 3-day maintenance, which reached 131% of the design strength. It could guarantee the strength of the concrete. The maximum range of strength was 3.46 MPa, which was caused by the water-cement ratio, and the range of strength caused by the water reducing agent was 2.65 MPa. Finally, the minimum range of strength was 1.14 MPa caused by the retarder. This indicated that the main factors affecting the strength of concrete was water-cement ratio and the water reducing agent had bigger impact than retarder. The water-cement ratio, the main influencing factors, made the largest fluctuations. The fluctuations under the reducing agent and retarder are smaller. They were secondary factors.

Table 6. Analysis of 28-day compressive strength

Case number	Water-cement ratio	Retarder (%)	Water reducing agent (%)	Compressive strength (MPa)
1	0.36	0.6	0.6	50.1
2	0.36	0.8	0.9	52.5
3	0.36	1.0	1.2	48.3
4	0.36	1.2	1.5	47.5
5	0.38	0.6	0.9	49.5
6	0.38	0.8	0.6	48.8
7	0.38	1.0	1.5	47.6
8	0.38	1.2	1.2	48.7
9	0.40	0.6	1.2	48.6
10	0.40	0.8	1.5	47.4
11	0.40	1.0	0.6	47.6
12	0.40	1.2	0.9	48.8
13	0.42	0.6	1.5	45.1
14	0.42	0.8	1.2	46.6
15	0.42	1.0	0.9	47.3
16	0.42	1.2	0.6	45.6
K_1	198.41	193.33	191.98	/
K_2	194.57	195.18	198.16	/
K_3	192.33	190.80	192.20	/
K_4	184.59	190.60	187.56	/
\bar{K}_1	49.60	48.33	48.00	/
\bar{K}_2	48.64	48.80	49.54	/
\bar{K}_3	48.08	47.70	48.05	/
\bar{K}_4	46.15	47.65	46.89	/
f	3.46	1.14	2.65	/

**Figure 3.** Comparison of 28-day compressive strength

3.3.2 Analysis of variance. The variance analysis of the compressive strength influenced by different factors were shown in the table below.

Table 7. The variance analysis of the 28-day compressive strength

Sources of variance	Quadratic sum	DOF	Mean square	F value	Significance	F critical value
Water-cement ratio	25.48	3	8.49	25.29	highly significant	
Retarder	3.59	3	1.20	3.57	normal	$F_{0.01}(3,6)=9.78$
Water reducing agent	14.18	3	4.73	14.08	highly significant	$F_{0.05}(3,6)=4.76$ $F_{0.10}(3,6)=3.29$
Error e	2.01	6	0.34	/	/	
Total	45.26	15	/	/	/	

It could be seen from Table 7 that according to the mean square of each factor, the influencing factors weakened from water-cement ratio, water reducing agent to retarder after 28-day maintenance. The effect of water-cement ratio and water reducing agent were highly significant. The retarder had normal effect on the strength. This was consistent with the results of range analysis above.

3.3.3 The optimal dosage. From the range analysis and variance analysis, it was concluded that the strength was highest when the water-cement ratio was 0.36, the dosage of water reducing agent was 0.9% and the dosage of retarder was 0.8%.

4. Conclusions

In this paper, we proposed a method to prepare the ultrahigh early strength concrete combining with the sulphoaluminate cement, the water reducing agent and the retarder together. Using the orthogonal test methods, the results show that the effect of water-cement ratio on the strength of 8-hour, 3-day and 28-day is very significant. As the value of water-cement ratio decreases, the early strength and later strength of concrete are obviously improved. The optimum water-cement ratio is determined as 0.36 based on the experimental results. Also the water reducing agent affects the 3-day and 28-day compressive strength significantly. The water reducing agent improves the strength of concrete mainly in the later period of time. And the optimum dosage is 1.2%. The effect of water reducing agent on the strength after 3 days is very significant. The retarder improves the strength of concrete mainly in the early period time. And the optimum dosage in this test is 0.8%.

By means of orthogonal test design method, the effect of each factor is mainly obtained by analysing the results of 3-day compressive strength. The 8-hour compressive strength is considered as the supplement. The strength in 28 days is also taken into account. The influence rule of each factor is obtained by the range and variance analysis. We can find out the best mix of the concrete, which can reach the highest strength in 3-day maintenance and that is the best mix of ultrahigh early strength concrete. It is concluded that we can prepare the ultrahigh early strength concrete when the water-cement ratio is 0.36, the dosage of water reducing agent is 1.2% and the dosage of retarder is 0.8%.

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