Research and application of anticorrosive concrete for shafts in thick and deep surface soil

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Abstract. Most frozen shafts of deep surface layer are located at a harsh environment, surrounding soil or groundwater with lots of corrosive ions such as SO₄²⁻ and Cl⁻. This is deadly to the durability of concrete. Thus, concrete for shafts in deep surface soil requires excellent durability. This paper focuses on the development and preparation of anticorrosive concrete in deep surface layer shafts, and presents engineering application. The experimental results show that NC-H admixture is successfully made to prepare the concrete. The durability and impermeability of concrete are good. The Cl⁻ diffusion coefficient of C60 is 38.1×10⁻¹⁴m²/s, while C90 is only 4.5×10⁻¹⁴m²/s. Besides, high freezing and thawing resistance is discovered. The loss of dynamic elastic modulus of C75 is less than 6.38% when the freeze-thaw cycle is 1000 times, It has high anti-sulfate ability and no corrosion to steel bar. This anticorrosive concrete has applied in many large coal mining projects. It is proved that this anticorrosive concrete has been applied to practical engineering application, and it can completely meet the requirements of cast-in-situ reinforced concrete shaft construction with deep surface layer and corrosion resistance.

1. Introduction

As the more accessible portions of coal resources near the surface are gradually depleted in large coal. It is necessary to explore deeper coal seams, at present, most shafts traverse the topsoil layer during the construction process, and some shafts have topsoil layer thickness deeper than 500m [1-3]. In general, freezing method is used in construction of deep surface layer, due to its strong adaptability, high reliability and well completion speed [4]. Reinforced concrete shaft wall structure is commonly applied in freezing method [5, 6].

With increase of shaft depth, the thickness of concrete in shaft wall increases greatly. On the one hand, increased thickness lead to dead weight and high construction cost of concrete. On the other hand, it enlarges the volume of concrete, which easily causes cracks and not conducive to the safety and service life of projects [7]. Considering this, high strength and performance concrete were applied in shafts as it can reduce self-weight of concrete structure and reduce the material. It is an effective approach to solve the problem of freezing shaft wall design and construction in deep topsoil layer. Currently, C30-C40 and other low-grade concrete has been gradually replaced [2, 7, 8].

In recent years, lots of concrete shaft walls have been damaged to varying degrees, which requires a large amount of funds to be spent on maintenance and reinforcement [9-12].

This seriously affects safety of mine production. In addition to the strength of concrete itself, corrosion resistance and durability are significant challenges for concrete structures of concrete shaft walls in deep topsoil [13]. The deep surface soil, naturally, requires that shaft wall should bear various
pressures, including huge ground pressure and vertical additional forces during the use of the shaft. Besides, it should bear the freezing pressure during the construction of the well in freezing method construction [1,6].

Moreover, deep topsoil owns high water content, pressure and water head. Thus, there exist water seepage, water leakage and corrosion of harmful ions (SO$_4^{2-}$, CO$_3^{2-}$, Cl$^-$, Na$^+$, K$^+$ and so on) in underground water. Some projects are located in in saline soil area with sulphate and part of chlorine salt which has a strong corrosion effect on concrete and steel reinforcement. Chlorine salt corrodes steel reinforcement and easily causes cracking of concrete structure, which destroys concrete structures [1,3]. Sulphate exposure is one of the most frequent and detrimental processes for the durability of concrete structures. The sulphate ions found in ground waters may diffuse through concrete pores and react with its components leading to the formation of expansive products which cause an expansion of the concrete leading to a decrease in the durability and more corrosion to reinforced bars [14].

There are many ways to improve the corrosion resistance of concrete. The general technical approaches are not only to improve corrosion resistance of concrete itself, but also to coat the surface of concrete with anti-corrosion coating [15]. However, for rust resistance of steel bars, the rust resistance layer should be painted on the surface of steel bars and the rust inhibitor should be added in concrete. These commonly used approaches for new concrete wellbore project is very difficult and not feasible. Therefore, improving corrosion resistance of concrete is more sensible and meaningful.

In this paper, C60~C90 anticorrosive concrete in deep surface layer shafts are developed and prepared successfully, and the properties are furthermore studied. It has been applied in some big projects, such as Juye coal field, Longgu coal mine and so on.

2. Experimental work

2.1 Materials

Cement include two types of Ordinary Portland cement 42.5 and 52.5, and the reference cement. Mechanical properties are given in Table 1.

| Cement grade | Fluidity(mm) | Flexural strength (MPa) | Compressive strength (MPa) |
|--------------|-------------|-------------------------|---------------------------|
|              |             | 3d | 7d | 28d | 3d | 7d | 28d |
| P.O 42.5     | 180         | 6.0| 7.4| 8.4| 28.3| 38.6| 51.5|
| P.O 52.5     | 185         | 7.0| 8.1|10.5| 32.4| 43.3| 56.7|
| Reference    | 180         | 4.7| 6.2| 8.8| 19.2| 32.3| 48.6|

Table 2. Performance indicators of NC-H admixture.

| Labels | Moisture content, ≤ (%) | Fineness, Over 0.045 mm sieve, ≤ (%) | Fluidity of cement paste≥ (mm) | Compressive strength ratio of mortar | Corrosion of steel reinforcement |
|--------|-------------------------|--------------------------------------|-------------------------------|-------------------------------------|--------------------------------|
| NC-H60 | 3.0                     | 10.0                                 | 230                           | 140                                 | 130 120  none                   |
| NC-H70 | 3.0                     | 10.0                                 | 230                           | 140                                 | 130 120  none                   |
| NC-H80 | 3.0                     | 10.0                                 | 230                           | 150                                 | 140 130  none                   |
| NC-H90 | 3.0                     | 10.0                                 | 230                           | 160                                 | 150 140  none                   |

NC-H admixture developed by our previous researches, with characteristics of reducing water, expanding slightly and improving strength, is used. It mainly consists of mineral admixtures, chemical admixtures, micro expansion components, accelerating component and modifying agents. According to different concrete grades, NC-H is divided into a variety including NC-H60, NC-H70, NC-H80 and
NC-H90. The performance indexes of NC-H are shown in Table 2. For cement paste experiment, the content of NC-H60, NC-H70, NC-H80 and NC-H90 is respectively 10%, 10%, 15% and 15%. For motor, the content is 25%, 30%, 35% and 40%.

Fine aggregate is sand from river with fineness modulus of 2.9. Table 3 shows the basic performance. Coarse aggregate is limestone with grain size of 5–25mm. There are three kinds labeled as G1, G2 and G3. The basic characteristics are displayed in Table 4.

| Table 3. Characteristics of the sand. |
|--------------------------------------|
| Apparent density (kg/m³) | Bulk density (kg/m³) | Porosity (%) | Grading region |
| 2670 | 1440 | 46.1 | II |

| Table 4. Characteristics of course aggregate. |
|-----------------------------------------------|
| Number | Apparent density (kg/m³) | Bulk density (kg/m³) | Needle flake content (%) | Moisture content (%) | Cumulative percentage retained (%) |
|       | 25 | 20 | 16 | 10 | 5 | 2.5 |
| G1 | 2740 | 1380 | 7.4 | 0.80 | 11 | 40 | 86 | 100 |
| G2 | 2740 | 1420 | 4.2 | 0.63 | 5 | 26 | 76 | 100 |
| G3 | 2710 | 1380 | 6.1 | 0.70 | 2 | 16 | 37 | 87 | 99 | 100 |

2.2 Preparation of concrete

Through many previous studies on the influence of NC-H content, water-cement ratio, ratio between mortar and coarse aggregate and sand ratio on the concrete by our team, the mixing ratio of C60~C90 concrete was finally determined as shown in Table 5. P.O 42.5 cement was used for C60, C70 and C75 concrete, whereas, P.O 52.5 was used for C80 and C90 concrete.

| Table 5. Proportions of concrete mixture. |
|----------------------------------------|
| Concrete | Blending materials (kg/m³) | sand ratio (%) | W/B |
| Total | Cement | NC-H | |
| C60 | 520 | 390 | NC-H60 130 | 38 | 0.28 |
| C70 | 570 | 399 | NC-H70 171 | 38 | 0.27 |
| C75 | 580 | 377 | NC-H70 203 | 38 | 0.27 |
| C80 | 580 | 406 | NC-H80 203 | 38 | 0.25 |
| C90 | 580 | 348 | NC-H90 232 | 38 | 0.25 |
3. Results and discussion

3.1 Working behavior of freshed concrete

The slump is the comprehensive performance of cohesion, fluidity and stability of concrete mixture. Generally, the technical performance of concrete mixture is controlled by the size of slump on the construction site. The experimental results are shown in Table 6. The initial slump of concrete is above 200mm, and the slump expansion is above 500mm. At the same time, the slump loss was slow, and the retention value of slump for 30min is around 200mm. This infers that the prepared concrete has a low loss of slump, no bleeding and segregation, which can well meet the needs of the construction technology of concrete on-site mixing, centralized mixing and tandem pouring. The concrete has good working performance.

Table 6. The workability of concrete.

| Slump (mm) | Slump flow (mm) |
|------------|-----------------|
|            | 0min  | 30min |            |          |
| C60        | 225   | 200   |            | 520      |
| C70        | 220   | 200   |            | 515      |
| C75        | 210   | 195   |            | 510      |
| C80        | 220   | 205   |            | 520      |
| C90        | 210   | 190   |            | 505      |

3.2 Compressive strength

It can be seen from Figure 1 that the compressive strength of prepared C60–C90 concrete are all high in various ages. Among them, strength of 1d reaches 38% ~ 51% of the designed strength, and the strength of 3d reaches 76% ~ 86% of the designed strength. After 7 days, the strength reaches more than 100% of the designed strength. The strength of 28d reaches more than 112% of the designed strength. Besides, with the extension of the curing period, the strength at later stage continues to increase. When it reaches 1 year, the strength increased by over 8% compared with the strength at 28d. It is concluded that anticorrosive concrete prepared in the present study has good mechanical properties.

![Figure 1. Compressive strength of anticorrosive concrete.](image-url)
3.3 Dry shrinkage
Due to the characteristics of shaft construction, it is difficult to maintain the concrete. Therefore, the concrete shrinkage value measured after 3d in standard curing condition is quite different from actual situation. Here, the concrete is directly put into the curing room with constant temperature and humidity after 18h of concrete molded. Then the concrete shrinkage value is measured at different times which is shown in Figure 2. As can be seen, overall, dry shrinkage increases faster at the first 28 days and later it develops slower and tends to be stable. The dry shrinkage value of 1year is less than $5 \times 10^{-4}$.

![Figure 2. Shrinking percentage of prepared concrete.](image)

3.4 Anti-permeability
It was well known that the transmission of corrosive ions in concrete seriously affects the durability. The diffusion coefficient of corrosive media in concrete can reflect the permeability of concrete. The Cl$^-$ diffusion coefficient is investigated. It has been reported that the Cl$^-$ diffusion coefficient of concrete with poor quality is in the order of $1000 \times 10^{-14}$m$^2$/s, whereas, in ordinary concrete the Cl$^-$ diffusion coefficient is in the order of $100 \times 10^{-14}$m$^2$/s, and the Cl$^-$ diffusion coefficient of concrete with high impermeability is in the order of $10 \times 10^{-14}$m$^2$/s [16]. The relationship between Cl$^-$ diffusion coefficient and concrete permeability is shown in Table 7.

| Coefficient $10^{14}$m$^2$/s | >1000 | 500~1000 | 100~500 | 50~100 | 10~50 | 5~10 | <5 |
|-----------------------------|-------|----------|---------|--------|-------|------|----|
| concrete permeability       | extremely high | high | medium | low | very low | extremely low | ignored |

In this experiment, Cl$^-$ diffusion coefficient after 28 days was conducted. Figure 3 displays the results. It shows that the chloride diffusion coefficient of C60 concrete at 28d is $38.1 \times 10^{-14}$m$^2$/s, and for C70–C80 concrete it is $(10~20) \times 10^{-14}$m$^2$/s, while that of C90 concrete at 28d is only $4.6 \times 10^{-14}$m$^2$/s. In comparison with Table 7, it can be seen that the permeability of C60–C80 concrete at 28d is in a very low range, and that of C90 HPC at 28d is in an extremely low range. It firmly infers that the concrete has excellent anti-permeability. As the age of concrete rises, the compactness and permeability are both improved.
Figure 3. Chloride diffusion coefficient of prepared concrete.

3.5 Resistance to sulfate attack

Table 8. Results of sulphate attack test.

| Concrete | Strength after 150 cycles | Standard curing strength at the same age | Corrosion resistance coefficient |
|----------|---------------------------|----------------------------------------|---------------------------------|
| C60      | 71.6                      | 71.4                                   | 1.00                            |
| C70      | 81.2                      | 80.3                                   | 1.01                            |
| C75      | 89.0                      | 87.3                                   | 1.02                            |
| C80      | 97.8                      | 94.2                                   | 1.04                            |
| C90      | 106.3                     | 101.1                                  | 1.05                            |

When concrete is in the environment containing SO\(^4^–\), which can react with Ca(OH)\(_2\) of cement to generate CaSO\(_4\) \(\cdot\) 2H\(_2\)O and further ettringite occurs. This can make the solid phase volume in the hardened cement stone increase a lot, resulting in considerable crystallization pressure and leading to the cement stone cracking. The mechanical properties of concrete are reduced and destroyed finally. In general, the concrete first falls off at the edges and corners. As the SO\(^4^–\) corrosion goes deeper, the concrete becomes brittle and loose. The results of C60~C90 concrete after 150 cycles is given in Table 8. It shows that the coefficient of resistance to sulphate attack gradually increases with the concrete grade increasing. All is not less than 1.00, and for C90, it reaches 1.05. So, it can be concluded that prepared anticorrosive concrete has good resistance to sulfate erosion.

3.6 Resistance to freezing and thawing cycle

Frost resistance, as an important indicator of concrete anticorrosion, can indirectly reflect the ability of concrete to resist environmental water intrusion and ice crystal pressure.

Fast freezing method is used to measure the frost resistance of C60~C75 concrete. The results are shown in Table 9. it can be found that the relative dynamic modulus of elasticity loss is less than 4% for C60~C75 concrete with 300 of freeze-thaw cycles. While the cycle times is 1000, the dynamic elastic modulus loss is less than 9% and weight loss is less than 3%.

In view of the small loss of C60~C75 concrete, slow freezing method is used to measure the C80 and C90 concrete, as is shown in Table 10. It can be discovered that, after 350 times of freeze-thaw cycles, the strength loss rate is only 5.3% for C80 concrete, and it is only 2.7% for C90 concrete. By comparing the results of fast freezing-thawing method and slow freezing method, it is found that slow freezing method is more severe. In general, prepared anticorrosive concrete in this work has good anti-
Table 9. Fast freezing-thawing cycle test of C60–C75.

| Concrete | C60   | C70   | C75   |
|----------|-------|-------|-------|
|          | Weight loss (%) | Relative dynamic modulus of elasticity loss (%) | Weight loss (%) | Relative dynamic modulus of elasticity loss (%) | Weight loss (%) | Relative dynamic modulus of elasticity loss (%) |
| 200      | 0.39  | 2.94  | 0.49  | 3.32 | 0.15  | 3.03  |
| 300      | 0.39  | 3.30  | 0.69  | 3.90 | 0.35  | 3.50  |
| 400      | 0.49  | 4.22  | 0.74  | 5.6  | 0.35  | 3.62  |
| 500      | 0.98  | 5.06  | 1.14  | 5.78 | 0.50  | 4.31  |
| 600      | 1.47  | 5.14  | 1.33  | 5.85 | 0.60  | 5.06  |
| 700      | 1.57  | 6.31  | 1.73  | 6.36 | 0.80  | 5.36  |
| 800      | 1.97  | 6.99  | 1.93  | 6.71 | 1.00  | 5.63  |
| 900      | 2.26  | 7.65  | 2.27  | 7.19 | 1.30  | 6.14  |
| 1000     | 2.85  | 8.50  | 2.62  | 7.72 | 1.55  | 6.38  |

Table 10. Slow freezing-thawing cycle test of C80 and C90.

| Concrete | Strength of 28d (MPa) | Freeze-thaw cycles of 350 |
|----------|-----------------------|----------------------------|
|          | Strength after freezing (MPa) | Standard curing strength (MPa) | Loss rate (%) |
| C80      | 94.2                   | 99.9                       | 105.5         | -5.3 |
| C90      | 101.1                  | 109                        | 112           | -2.7 |

freeze and thawing cycling performance. This is mainly attributed to the NC-H admixture, which can improve the grading of pores and make the pore size smaller. The reduced porosity and structure dense are conducive to improve the ability to freeze.

3.7 Corrosion of reinforcement

There are two main reasons for the failure of steel passivation film in concrete: one is the carbonization of concrete; The other is the intrusion of corrosive ions, which diffuse onto the surface of the steel bar to blunt it. Oxygen and water must be involved in the corrosion of steel reinforcement, so the permeability of concrete is very critical to the corrosion of steel reinforcement.

The SCA-01 corrosion tester is used to evaluate whether concrete has corrosive influence on the steel bar, mainly by measuring the anode polarization curve of the steel bar in the hardened mortar and the current-time curve of the anode acceleration test under constant voltage. The anode current decreases with time, indicating that the anode process is inhibited and the steel bar will not be corroded. Figure 4 and Figure 5 gives the two types of curves.

It can be seen from Figure 4 that the potential gradually becomes stable with increase of current. It indicates that passivated film on the surface of steel bar is intact, and the steel bar in the concrete is in passivated state. The anode was then accelerated for 7 days. It is found that the anode current decreases with time (Figure 5). This infers that the anode process is inhibited to some degree, so that the steel bar will not corrode. Besides, it is noticeable that different sizes of current occur in all the concrete, this is due to the different inhabitation.

In a conclusion, prepared anticorrosive concrete of C60–C90 have good performance to inhibit corrosion of reinforcement. This may be attributed to the high impervious performance. Small Cl⁻ diffusion coefficient (Figure 3) can greatly delay the process of decarbonization by Cl⁻ erosion.
4. Application

Anticorrosive concrete for shafts in thick and deep surface soil studied in this paper has been applied in some big coal mine projects. Here only two projects are introduced.

Longgu coal mine, as a national key project, has the highest comprehensive technical difficulty in Asia (Figure 6). The frozen section is designed with internal and external reinforced concrete shaft walls, with support thickness of 1000~2200mm. Concrete strength grade of C30–C70. The concrete in section -378m ~ 615m is C65~C70. The practical application proves anticorrosive concrete developed by our company has good construction performance, low slump loss, and fast developed concrete strength. At the same time, the strength of the later period continues to increase, completely meets the engineering requirements.

Guo Tun coal mine (Figure 7) has the freezing depth of 702m. C60–C75 anticorrosive concrete were adopted. No cracks appeared in the concrete shaft wall, and the quality of the project was very good after the inspection.
Figure 6. Longgu coal mine.

(a)                                                                        (b)

Figure 7. Guo Tun coal mine.

5. Conclusions
From this study, it can be concluded that anticorrosive concrete for shafts in thick and deep surface soil are successfully prepared by use of conventional sand aggregate, ordinary Portland cement of grade 42.5 or 52.5, and especially NC-H compound admixture. The prepared C60~C90 concrete have high and good performance, as is shown in the following.

- high working performance: The slump is above 200mm and have small loss, low viscosity and good construction performance.
- high compressive strength: the strength at 1d reached 35%~60% of the designed strength; the strength at 3d reached 75%~95% of the designed strength; the strength at 7d reached more than 95% of the designed strength. The later strength continues to increase, after 1 year which is increased by more than 10% compared with that at 28d.
- Low dry shrinkage: the dry shrinkage value of 1 year is less than $5 \times 10^{-4}$.
- Good anticorrosion and durability: the permeability of chloride ion is quite low. Cl- diffusion coefficient: C60 is $38.1 \times 10^{-14}m^2/s$, while C90 is only $4.5 \times 10^{-14}m^2/s$; High resistance to sulfate corrosion with corrosion resistance coefficient of over 1.0; The high resistance to freezing and thawing circulation. After 1000 freeze-thaw cycles, the dynamic modulus loss of C60 was less than 8.5%, while that of C75 was less than 6.38%; good resistance to corrosion of reinforcement.
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