Early-age Shrinkage-induced Cracking Prevention of Cast-in-place Concrete of Subway Station under Marine Environmental Conditions

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Abstract. Early-age cracking and leakage phenomena has become a serious problem for cast-in-place concrete of underground station in marine environment, in the present work, an anti-cracking admixture (HME-V) with temperature rise inhibition and micro-expansion properties were adopted to mitigate shrinkage cracking risk. Results indicated that the usage of HME-V exhibits larger expansion behavior not only at temperature rise period but also at temperature fall period, leading to the compensation of real-time shrinkages in concrete. Meanwhile, the early adiabatic temperature rise rate can be significantly reduced with no influence on final value. As a result, the temperature peak value and average cooling rate of the field concrete were decreased by 21.0% and 24.2% respectively. In addition, the usage of HME-V displays considerable impact on early-age compressive strength and but made no difference to the later ones. As no visible cracks and water leakage were observed in the sidewall structure, this work may prove a feasible approach to prevent early-age shrinkage crack of cast-in-place concrete used for underground station.

1. Introduction
Nowadays, the subways play an important role in solving traffic congestion of large cities because of its safety, comfortableness and convenience for people [1]. As the shortage of the land resource in the large cities of China, most subway stations are generally built under the ground by using open-cut method and cast-in-place concrete. Owing to essential influences of structural style, ambient temperature and construction technology etc., the early-age cracking and leakage problems of main structure concrete are prone to be discovered during construction, unavoidably resulting in significant deterioration of durability and the reduction of service life for concrete structure [2-3]. Basically, some relevant engineering practice and survey show that the shrinkage-induced cracks in underground construction account for more than 80% while the rest cracks are mainly caused by load effect [4]. Figure 1 shows the cracking and leakage phenomena of roof and sidewall structure in a subway station after the removal of molds. As is well known, the shrinkage deformation of concrete, deriving from chemical reaction, moisture and temperature exchange, often suffers varying levels of restraints from foundation, adjacent structures and internal reinforcement, sufficient to cause stress generation in concrete [5]. Therefore the cracks emerge inevitably when shrinkage stress develops more than tensile...
strength of concrete at a certain time, specifically which has became considerable as a result of increasing of fineness and hydration heat of modern cement particles[6-10].

![Figure 1. Cracking and leakage phenomena of roof and sidewall concrete in a subway station (a, roof; b, sidewall)](image)

A cast-in-place underground station with a length of 167.2m and width of 19.7m in Qingdao, China, is two-story island-type standard station, belonging to single-column double-span box structure. The environmental class of concrete structure affected by marine environment is level IV-C from geological survey report. In this project, the pouring length is 17.6-25m, and the thickness of main structure containing the roof, sidewall and bottom board, are nearly 0.7-1.2m with C45P10-reinforced concrete higher than C35P8 design of other metro stations in the Chinese interior. As a result, the cracking potential caused by temperature shrink and self-shrinkage, especially for sidewall, may be more prominent due to higher strength and durability.

At present, some necessary anti-cracking measures in dam and bridge project are commonly employed to effectively mitigate shrinkage-cracking risk of concrete, such as low-heat cement instead of Portland cement, the control of concrete molding temperature, the application of cooling pipe system, etc [11-12]. While for subway construction as a large municipal project in China, these approaches almost cannot be achieved by reason of the limitation of objective factors from concrete mixing station and construction units. Furthermore, there is a growing concern that using expansive agents to compensate early-age shrinkage has shown benefits to decreasing cracks of concrete in recent years, for example sulfoaluminate, CaO-type and MgO-type additives are the most commonly used expansive agents. It has been proved that the expansive property of sulfoaluminate relied mightily on the curing condition and it has a limited influence on reduction of shrinkage [13-14]. Moreover, the utilization of CaO often could generate larger volume expansion at the early age but has less expansion at the later age. MgO, however, has delayed expansion characteristic which just makes up for that, and the expansive development of MgO is strongly affected by its reactivity value which is more sensitive to temperature than that of other kinds of expansive agents. Therefore, proper design is needed to match shrinkages of concrete and fully meet anti-cracking requirements in actual structures before MgO is used [15].

In the present work, an anti-cracking admixture (HME-V) prepared by double regulation on hydration rate and volume deformation was adopted to reduce early-age shrinkages cracking of subway station in Qingdao. Firstly, the exhaustive experimental study was carried out to access the effects of HME-V on deformation, thermodynamic, mechanics and durability properties of concrete before it could be applied. Based on this, the temperature and deformation development in sidewall concrete were subsequently monitored to explicate crack-resistance effect in combination with field observation.
2. Experimental

2.1. Raw Materials

The cementitious materials used in the present study comprised of P·O42.5 Portland cement, class II fly ash and S95 slag, which were all manufactured in China. Related physical properties and chemical composition of cementitious materials are shown in Table 1. HME-V is solid power, and its primary components are temperature rise inhibitor [16-17] and slight expansion materials containing CaO and well-designed MgO expansive agents with various reactivity value (80s, 120s and 180s). The basic physical performances of the HME-V were listed in Table 2 according to Chinese National Standard GB/T23439 and GB/T12959. Natural river sand with a fineness modulus of 2.6 and crushed limestone with size distribution ranging from 5mm to 25mm were utilized as fine and coarse aggregates. Additionally for the sake of high workability of concrete, a polycarboxylate superplasticizer is mixed in mixtures in Table 3 to keep similar slump of approximately 200mm.

**Table 1. Physical properties and chemical composition of cementitious materials**

| No. | Specific surface area, m²/kg | Specific gravity, g/cm³ | Chemical Compositions (%) |
|-----|-----------------------------|-------------------------|---------------------------|
|     |                             |                         | CaO | SiO₂ | SO₃ | Al₂O₃ | MgO | Fe₂O₃ | K₂O | Na₂O | TiO₂ |
| Cement | 376                       | 3.04                     | 54.96 | 22.02 | 3.30 | 6.03  | 3.24 | 3.52  | 0.40 | 0.22 | 0.38 |
| Fly ash | 458                      | 2.22                     | 3.17 | 64.50 | 0.41 | 21.60 | 1.13 | 5.02  | 1.24 | 0.48 | 1.03 |
| Slag   | 413                      | 2.84                     | 38.50 | 31.50 | 1.89 | 15.80 | 9.40 | 0.39  | 0.35 | 0.37 | 0.70 |

**Table 2. The basic physical performances of the anti-cracking admixture(HME-V)**

| Item                                      | Test values |
|-------------------------------------------|-------------|
| Restrained expansion deformation/%        | 7d in 20°C water: 0.062 |
|                                           | 21d in 20°C air: 0.007 |
|                                           | Difference between 28d and 3d in 60°C water: 0.024 |
| Compressive strength /MPa                | 7d: 25.8 |
|                                           | 28d: 44.5 |
| Reduction rate of hydration               | 24h: 58 |
| heat after initial setting /%             | 7d: 12 |

2.2. Mixing Proportion

To achieve crack-resistance and durability requirement of C45P10 concrete of Qingdao subway station, Four different mix proportion of concrete(numbered as C1 to C4 as presented in Table 3) were designed by Chinese code JGJ55 for experimental investigation, in which the dosage of HME-V instead of part cementitious materials is 0% and 8%(weight percentage). Therein the C1 and C2 were designated as reference concrete without HME-V, and the C3 and C4 were set as anti-crack concrete with 8% HME-V.

**Table 3. Concrete mix proportion(kg/m³)**

| Mix ID | Cement | Fly ash | Slag | Fine aggregate | Coarse aggregate | Water | HME-V |
|--------|--------|---------|------|----------------|------------------|-------|-------|
| C1     | 315    | 67      | 68   | 788            | 984              | 155   | 0     |
| C2     | 270    | 68      | 112  | 791            | 986              | 150   | 0     |
| C3     | 290    | 62      | 62   | 788            | 984              | 155   | 36    |
| C4     | 270    | 55      | 89   | 791            | 986              | 150   | 36    |

2.3. Experimental Methods

2.3.1. Autogenous deformation under constant and variable temperature

The autogenous deformations of all mixtures in Table 3 under constant and variable temperature were...
evaluated via the laboratory. After mixing, the fresh concrete was cast into one side of sealed PVC pipes with the sizes of Φ100mm×400mm and vibrated to maintain compactness of concrete for about 30-40s. Simultaneously, the setting time of which was determined in accordance with Chinese National standard GB/T50080.

For the constant temperature test, the entire specimens were exposed to a laboratory-controlled environment of 20±0.5°C and 65±2%RH. After casting for 2-3h, the upper surface of each specimen was installed a copper head, and then further sealed with paraffin wax to prevent moisture loss. The autogenous deformation was measured by using a dial gauge with a precision of 1μm at different time periods. It was supposed to be measurements’ zero point, when pouring concrete approached final setting.

For the variable temperature test, an environmental simulation chamber was utilized to set temperature history conforming to simulation result of sidewall concrete, as shown in Figure 2. After casting, strain gauges were positioned in the center of the specimens connecting to data acquisition and wireless transmission system displayed in Figure 3 for deformation measurement, after that, the upper surface of each specimen was covered with plastic film and tin-foil paper to prevent inner moisture from evaporation and then placed in test chamber. In addition, the reference and anti-crack concrete should be adjusted to same setting time by changing the amount of retarder in advance before the trial, and the environmental simulation chamber initiated to run immediately as soon as the concrete reached initial setting.

2.3.2. Hydration heat and adiabatic temperature rise
The hydration heat evolution of cement paste containing 0%, 4%, 6% and 8% of HME-V in accord with weight was measured by TAM-AIR isothermal calorimeter. Prior to the tests, the calorimeter should be adjusted at 30 °C in advance and stabilized for 24h to maintain constant temperature. During the testing, all experiments were conducted with fixed w/b ratio of 0.36, the HME-V was firstly mixed into cement in light of the mix proportion of cement paste showed in Table4. At the same time, the weighed water was added into the mixtures and then stirred them with an electric mixer at the medium speed for 1min, whereafter, the prepared cement paste was weighed into glass ampoule and then put into calorimeter channel to start data collection quickly. The adiabatic temperature rise of concrete was carried out according to Chinese National Standard GB/T50080.

| Mix ID | Cement | HME-V | W  |
|--------|--------|-------|----|
| P1-Ref | 1      | 0     | 0.36 |
| P2-4%  | 0.96   | 0.04  | 0.36 |
| P3-6%  | 0.94   | 0.06  | 0.36 |
| P4-8%  | 0.92   | 0.08  | 0.36 |
2.3.3. Compressive strength and Endurance performance

The compressive strength and endurance performance tests of concrete fulfilled the requirement of Chinese National Standard GB/T50081 and GB/T50082 respectively.

3. Results and Discussion

3.1. Autogenous Volume Deformation of Concrete under the Conditions of Constant and Variable Temperature

Figure 4 illustrates autogenous deformation evolutions for concrete specimens with and without HME-V at a constant temperature. It could be seen that, for reference concrete of C1 and C2, the specimens was in a state of autogenous shrinkage all the time during testing, which generated more shrinkage with the replacement of cement by slag, this tendency is in agreement with previous studies [18]. While for anti-crack concrete of C3 and C4, the specimens generated slightly expansion at early age, and the maximum expansion values were 152.8με and 132.7με respectively, then the deformation began to decrease slowly, for the concrete mixture of C4, the shrinkage trend was obviously smaller than that of the C3, which still have 115.2με expansion deformation after compensating shrinkage at 120d. From the perspective of improving crack-resistance of concrete, the concrete mixture with lower shrinkage performance was preferred.

![Figure 4. Autogenous volume deformation of concrete at a constant temperature.](image)

Considering the temperature field of concrete in actual structure exchanges because of hydration heat and external environment, the autogenous deformations of all mixtures shown in Table 3 at a variable temperature were further investigated. Results of Autogenous deformations of concrete at a variable temperature are presented in Figure 5. It could be observed that, at temperature rise stage, the reference concrete of C1 and C2 generated 174.8με and 182.5με expansion due to thermal expansion, however, the anti-crack concrete of C3 and C4 generated considerable expansion of 550.8με and 538.4με mainly owing to thermal expansion and hydration reactivity of HME-V. At temperature drop stage, C1 and C2 exhibited 350.2με and 329.3με shrinkage due to thermal and autogenous shrinkage, while the anti-crack concrete of A3 and A4 only exhibited 264.9με and 239.8με shrinkage owing to shrinkage-compensating of HME-V. Given the above, C3 and C4 generated 285.9με and 298.52με expansion at temperature rise stage, and still continuously generated 85.1με and 89.8με expansion shown in Figure 5(b) at temperature drop stage comparing to reference concrete of C1 and C2, which can be contributed to effectively improve crack resistance of concrete.
3.2. Hydration Heat and Adiabatic Temperature Rise

Figure 6 shows the hydration heat curves of reference cement paste and the pastes containing different dosage of HME-V. It is obvious that HME-V exerted greatly influence on hydration rate and cumulative heat of cement paste in the acceleration period. Along with the addition of HME-V dosage increasing from 4% of mass fraction to 8%, the hydration peak decreased from 2.68 mW/g to 0.95 mW/g, furthermore, the occurrence time of that was delayed accordingly. As the reduction of hydration rate, the cumulative heat at early age time dramatically was changed. By contrast with reference cement paste, the cumulative heat of cement paste including HME-V content 4% 6% and 8% were remarkably decreased by up to 24.9%, 50.5% and 79.5% at 1 day, respectively, while the reduction of which were 0.65%, 2.8% and 2.9% at 7 days, indicating that little difference in term of total heat later. It can be attributed to the reason that the temperature rise inhibitor inside HME-V has enormous impact on formation and growth of main hydration product C-H-S.

Figure 7 displays the adiabatic temperature rise behavior of all mixtures shown in Table3, and it is found that a similar trend of all curves could be observed, which all were basically divided into three phases of induction period, rapid temperature rise and stable period in the whole process. Comparing temperature rise development of reference concrete of C1 and C2, the replacement of partial cement by fly ash and slag was responsible for decreasing adiabatic temperature rise value to some extent at early age due to lower hydration activity, while the reduction effectiveness of which was not apparent. On this base, by using HME-V instead of a portion of cementitious material, the early-age rate of adiabatic temperature rise could be significantly reduced and then catch up with the reference at later
age, which were in agreement with hydration heat results, meanwhile, the temperature rise value at 7 days was lower than 47°C. As a consequence, the temperature peak value of concrete with HME-V under heat dissipation condition in actual structure was effectively decreased, which could be conducive to mitigate thermal shrinkage.

![Figure 7. Adiabatic temperature rise results of concrete](image)

3.3. Compressive Strength and Endurance Performance

The mechanical properties of concrete are key control points for quality management of construction projects. Figure 8 depicts compressive strength development of concrete shown in Table 3 at 3, 7, 28 and 56 days in standard curing condition of 20±0.5°C and 98±2%RH. Unsurprisingly, the C3 and C4 with addition of HME-V mainly had such an obvious influence on early-age compressive strength of concrete due to the regulation of early hydration heat, but made no difference to the later ones. More specifically, the reduction rate of compressive strengths of the C3 at 3, 7, 28 days was about 17.7%, 8.0% and 3.4%, respectively, which of the C4 was decreased by about 17.3%, 7.7% and 3.4% accordingly. Nevertheless, the 56-day compressive strengths of concrete surpassed the reference, which all fulfilled the requirement of the strength design sufficiently.

![Figure 8. Compressive strength of concrete in standard curing condition](image)

The durability performance results of concrete shown in Table 3 were displayed in Table 5. It indicated that, the seepage resistance of each concrete was more than P10. Meanwhile, the diffusion coefficient of chloride ion and electric flux at 56 days were less than 7.0×10⁻¹² m² /s and 1200 C respectively. Moreover, the 28-day depth of carbonation was lower than 5mm. These results suggest that all performances satisfied the design demands. For reference concrete of C1 and C2, by mixing the appropriate proportion of fly ash and slag, the anti-permeability of concrete could slightly improved, it is generally agreed that the results of hydration products and unhydrated particle of mineral blend filling in pore and densifying microstructure. And on this basis the further enhancement of durability performance was achieved because of the use of HME-V replacing...
cementitious materials.

| Items | Seepage resistance | The diffusion coefficient of chloride ion (56d) / (m²·s⁻¹) | Electric flux (56d) / (C) | Depth of carbonation (28d) / (mm) |
|-------|--------------------|------------------------------------------------------------|---------------------------|----------------------------------|
| C1    | >P10               | 2.86×10⁻¹²                                                | 944                       | 2.6                              |
| C2    | >P10               | 2.75×10⁻¹²                                                | 687                       | 2.5                              |
| C3    | >P10               | 2.79×10⁻¹²                                                | 755                       | 2.5                              |
| C4    | >P10               | 2.68×10⁻¹²                                                | 621                       | 2.4                              |

4. Engineering Application and Effect Analysis

On the base of the researches above, the anti-crack concrete of C4 was decided to be utilized in reinforced concrete sidewall of an underground station in Qingdao. Similarly, the reference concrete of C1 was further studied as a field contrast experiment. The dimensions of actual sidewall structure were approximate 18.0m long, 0.7m thick and 4.5m high, which were built on the foundation of floor concrete. In order to characterize the effect of the crack control by the measures, two strain gauge were pre-embedded along the direction of thickness and length in the middle and bottom center of sidewall, and one thermometer was positioned in the point 50mm away from the surface, to monitor temperature and deformation process of sidewall concrete after casting. Measuring points were assigned as shown in Figure 9. In the whole casting time, the slump of fresh concrete was nearly 200mm, and the thickness of filling layer was regulated by about 300~500mm. At the same time, the insertion depth of vibrating rod should be controlled to penetrate the next concrete layer to ensure uniformity and density of concrete. After casting, the mold removal time was governed by 3 days, and then the heat and moisture insulation measure was applied in time at least 7 days on the surface of sidewall.

![Figure 9](image_url)  
**Figure 9.** Plan view of strain gauge and thermometer embedded in the reinforced concrete sidewall

4.1. Temperature Histories of Field Sidewall Concrete

Figure 10 gives the monitoring results of temperature histories of sidewall concrete. It could be seen that, the molding temperature of the C1 and C4 were 35.7°C and 30.2°C, considering the main effect of ambient temperature and casting time. The maximum temperature rise value were 42.1°C and 30.5°C respectively, which emerged at nearly 0.71 day and 1.04 day, that is, after deducting temperature rise caused by the molding temperature difference, the maximum temperature rise was decreased by about 8.85°C, and the occurrence time of temperature peak was delayed by 46.5% in contrast to the reference concrete of C1. After the temperature peak of concrete ending, the temperature value started to drop. In the first 6 days, the average cooling rate of temperature in the center of the sidewall for the C1 was 7.26°C/d, while which was only 5.5°C/d for the C4. By comparison, the average cooling rate of temperature was reduced by 24.2%. Thus, it is concluded that the anti-crack concrete tends to be better regulation on actual temperature field of concrete.
4.2. Deformation Histories of Field Sidewall Concrete

Figure 11 plots the deformation monitoring results of sidewall concrete. It could be observed that, the deformation values of thickness direction for sidewall concrete in same condition showed much larger than that of length direction, which depended strongly on difference of restrained extent. For the temperature rise stage, the expansion values of the C1 and C4 along thickness direction were nearly the same because of the distinction on maximum temperature rise of sidewall concrete, but the average expansion deformation of which were 11.5με/°Cand 15.7με/°C respectively, indicating that the anti-crack concrete of C4 generated more expansion to compensate shrinkage at temperature rise stage. For the temperature fall stage, as a whole, the shrinkage trend of the C4 showed obviously lower than that of the C1, and the total shrinkage deformation of the C1 and C4 along thickness direction almost were 514.5με and 730.3με, which mainly arise from the combination result of the reduction of temperature rise value and the continuous shrinkage-compensating of HME-V at temperature fall stage. Furthermore, the deformation development process of the C1 and C4 along length direction basically appeared to be similar with the ones of thickness direction, however, there was big abrupt change occurring at an age of around 2.5 days after casting for reference concrete. Simultaneously, the vertical and visible cracks were observed on the bottom surface of sidewall and the leakage phenomena occurred after backfilling. In contrast, no abrupt change was monitored for anti-crack concrete, and the statistic results shown that no penetrating cracks were found.

5. Conclusions

To mitigate early-age concrete shrinkage-cracking of underground station under the marine environment conditions, an anti-cracking admixture (HME-V) prepared by double regulation on hydration rate and volume deformation was used and investigated in this paper, the major conclusion are drawn: Compared with reference concrete, the addition of HME-V exerted larger expansion behavior not only at temperature rise stage but also at temperature fall stage, and such a
volume expansion development could compensate real-time shrinkages of concrete and mitigate the cracking phenomena. Meanwhile, the addition of HME-V obviously decreased main hydration peak and cumulative heat at an early age, but had a negligible effect on gross heating value later, the higher HME-V dosage, the higher hydration peak and cumulative heat was reduced. Consequently, the temperature peak and average cooling rate of the actual sidewall structure was decreased, besides, the addition of HME-V generally had considerable impact on early-age compressive strength but no significant effect on the later ones. The actual engineering application showed that no visible cracks and leakage phenomena were observed in the sidewall by employing anti-crack concrete, but the opposite results happened for the reference concrete.

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