SOME QUESTIONS ABOUT THE ALKALI-AGGREGATE REACTION OF HYDRAULIC CONCRETE

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ABSTRACT

In the paper, hydraulic concrete is compared to ordinary concrete. The different behavior in alkali-aggregate reaction caused by the difference between hydraulic concrete and ordinary concrete is analyzed. It is found that hydraulic concrete more dangerous than ordinary concrete when alkali-aggregate reaction occurs. Some doubts are raised if some evaluating methods, criteria, etc. obtained on the base of ordinary concrete can be used to hydraulic concrete.

Key words: Hydraulic concrete; Alkali-aggregate reaction; Difference; Behavior.

1 INTRODUCTION

The serious results due to alkali-aggregate reaction have been realized gradually. Alkali-aggregate reaction has been paid attention in many hydropower projects where the alkali reactivity of aggregate must be evaluated, and some measures preventing alkali-aggregate reaction have been adopted. But, hydraulic concrete has itself features, and is different from ordinary concrete in many aspects. It is due to these differences that alkali-aggregate reaction shows different behavior in hydraulic concrete. But this point has not been perceived until now. In the great majority of hydropower projects, to judge alkali-aggregate reaction and select preventing measures are generally according to some results that are based on ordinary concrete. It is very possible to cause some mistaken knowledge and make some wrong decision when the results of ordinary concrete are used to solve the questions of alkali-aggregate reaction of hydraulic concrete. It should be caused enough attention. In this paper, the differences between hydraulic concrete and ordinary concrete, and the influence of these factors on the behavior of alkali-aggregate reaction of concrete are discussed.

2 THE DIFFERENCES BETWEEN HYDRAULIC CONCRETE AND ORDINARY CONCRETE

According to the behaviors of alkali-aggregate reaction of concrete, there are five differences between hydraulic concrete and ordinary:

1. The size of aggregate particles is larger in hydraulic concrete than that in ordinary concrete. In hydraulic concrete, the size of the largest aggregate is generally 150mm, and the ratio of larger aggregate is higher, aggregate of 80mm~150mm is above 30% of the total amount of aggregate. In ordinary concrete, the size of the largest aggregate is not over 40mm generally. The size of the largest aggregate is not even over 20mm in some cementitious products.

2. The strength grade of hydraulic concrete is lower than that of ordinary concrete. Except for some special location, the strength grade of the concrete for hydropower projects is generally lower, especially for gravity dam. For example, in the main project of Three Gorges, the designed strength of the internal concrete, external concrete and that in the belt of fluctuation of water table is only 15 MPa, 20 MPa and 25 MPa at 90 days respectively. The designed strength of ordinary concrete is generally 30MPa~40MPa at 28 days. The high strength concrete over 60 MPa has been used widespreadly. The designed strength of road concrete is generally over 30 MPa.

3. The amount of cementing materials is less in hydraulic concrete than that in ordinary concrete. Considering the hydration heat, except for some special location, the amount of cementing materials in hydraulic concrete is commonly less, is generally not over 200kg/m^3. The amount of cementing materials in ordinary concrete is over 300kg/m^3, is even over 400kg/m^3.

4. Hydraulic concrete is always in wet circumstances. Because of the particularity of hydraulic structure, hydraulic concrete is always in moisture-laden state. Even if the part over the water surface, it is difficult that the internal water diffuses from inside to outside and evaporates because the volume of hydraulic structure is very large. It is very limited that mixed water is consumed by the hydration of the cementing materials. And the water will also diffuse from the lower part to the higher part because

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of capillary effect. The wet or dry state of ordinary concrete is generally controlled by environment because the greater part of structure is over ground surface. In some dry areas, concrete can be in dry state in longer term. Even if in some wet areas, it is difficult that concrete maintains always moisture-laden state.

5. The required life of structure is longer. Hydraulic structure is generally required longer using life because it costs more money and longer time to construct. The requirement of their durability is higher because of the importance of hydraulic structure. The Three Gorges project began to construct in 1993 and would end in 2009. It will take 17 years and over 50 billions Chinese Yuan to construct. Any problems of Three Gorges will be a disaster to the seven provinces and one city located the downstream of Changjiang River. In these aspects, no concrete projects can be compared to hydropower projects. Thus, a long using life is often required for hydropower project, for example, that of Three Gorges project is over hundreds years. But, the using life required for buildings concrete and roadway concrete is generally not over one hundred years. Especially, the using life of roadway concrete is only required to forty years. It is because roadway needs to be rebuild after twenty or thirty years of abrasion, partial impacting and unhomogeneous settlement of foundation even if alkali aggregate reaction doesn't occur.

It may be seen from the five aspects discussed above, there is very great difference between hydraulic concrete and ordinary concrete. This will cause the greater difference in the behavior of alkali aggregate reaction too.

3 INFLUENCE OF THE SIZE OF AGGREGATE PARTICLE ON THE EXPANSION AND CRACK OF ALKALI AGGREGATE REACTION

In the influence of the size of aggregate particle on alkali aggregate reaction, it is generally considered that for silica aggregate, the expansion of mortar bar is the largest when the particle size of aggregate is 0.15mm~0.80mm. When the particle size of aggregate increases, the expansion of mortar bar decreases markedly. Authors discovered that the expansion of mortar bar is restricted by coarse aggregate when it exists in mortar bar. From these results, it looks as if hydraulic concrete is safer than ordinary concrete. But, further research shows that the viewpoint is incorrect.

1. From the particle size of aggregate, although the expansion of mortar bar decreases with the increase of the particle size of aggregate, the influence is obvious only when the particle size of aggregate is less than 2.5mm. It is not obvious when the particle size of aggregate is larger than 2.5mm, and moreover, there is more fine aggregate in hydraulic concrete too. It is still possible that more serious alkali aggregate reaction occurs and larger expansion arises if the fine aggregate is reactive. From this viewpoint, although the largest particle size of the aggregate in hydraulic concrete is many times as that in ordinary concrete, it is not enough to have the sense of security.

2. From the affection of coarse aggregate on the expansion of mortar bar, the coarse aggregate may restrain the expansion of mortar. But, it is true only under certain condition. The condition is that the free expansion of coarse aggregate under the affection of alkali is less than that of mortar. In concrete, there is no alkali aggregate reaction if both of fine and coarse aggregate is unreactive. If fine aggregate is reactive but coarse aggregate is unreactive, it is obviously that the free expansion of coarse aggregate is less than that of mortar. Thus, it is possible that coarse aggregate restrains the expansion of mortar. Because the coarse aggregate is more in hydraulic concrete than in ordinary concrete, the restrained affection is stronger in hydraulic concrete than in ordinary concrete. Thus, it is possible that hydraulic concrete shows less expansion. But, the restrained affection presupposes the unidentity of the deformation between both of phases. The unidentity of the deformation will cause the tensile stress in interface area. If the tensile stress is larger than the tensile limit of the interface, the circumferential crack is formed around coarse aggregate. The large the particle size of coarse aggregate, the longer the circumferential crack is. The existence of these larger defects will influence many properties of concrete. If fine aggregate is unreactive but coarse aggregate is reactive, it is obvious that the free expansion of coarse aggregate is larger than that of mortar. Thus, coarse aggregate cannot restrain the expansion of mortar. Reversely, mortar restrains the expansion of coarse aggregate. In the condition, the more the coarse aggregate, the larger the expansion of concrete is. Because coarse aggregate is more in hydraulic concrete, it is possible that it causes greater harmfulness. If both of fine and coarse aggregate are reactive, the free expansion of mortar is generally larger than that of coarse aggregate at early age. Thus, it is possible that coarse aggregate restrains the expansion of mortar. But, the free expansion of coarse aggregate may be over that of mortar at lately age. Under the condition, coarse aggregate does not restrain the expansion of mortar, but promotes the expansion of mortar. Thus, the affection of coarse aggregate on the expansion caused by alkali aggregate reaction only is delayed affection.

3. From the crack of concrete, the relation between expansion and crack is different for the aggregate with different particle size. Author found that for the aggregate that the particle size is 0.15mm~0.80mm, the crack doesn't be found on the surface of the specimen by microscope when the expansion is 0.175%. When the expansion is 0.274%,

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crack is found on the surface of some specimens. If 5mm~10mm aggregate is used, crack has been found on the surface of all specimens when the expansion isn't larger than 0.04%. This shows that when the particle size of aggregate is larger, it is easier that concrete cracks although its expansion is less. It can be seen from this point that the decrease of the expansion with the particle size of aggregate doesn't mean the increase of safety. Reason is that the expansion stress caused by alkali aggregate reaction can be well-distributed in the specimen when aggregate is smaller, but can be gathered stronger around the aggregate when aggregate is bigger. In hydraulic concrete, aggregate is larger. Once alkali aggregate reaction occurs, the stress concentration will be stronger. Thus, the possibility of crack will be larger too.

It may be seen from above analysis that the particles of aggregate are bigger and the amount of aggregate is more hydraulic concrete. Although the reaction of big aggregate with alkali is slower and big aggregate may restrain the expansion of mortar under certain condition, these don't mean that hydraulic concrete is safer than other concrete. On the contrary, whether the affection of coarse aggregate on the expansion of mortar or the crack of concrete, it is because the aggregate particle is bigger and its amount is more in hydraulic concrete that hydraulic concrete is easier to destroy than ordinary concrete when alkali aggregate reaction occurs.

4 RELATIONSHIP BETWEEN THE STRENGTH OF CONCRETE AND THE DAMAGE CAUSED BY ALKALI AGGREGATE REACTION

Compared to ordinary concrete, the requirement of hydraulic concrete to strength is lower under common condition. Hydraulic concrete is generally in the strength at 90 days age as design standard, but ordinary concrete is generally in the strength at 28 days age as design standard. This shows that there is greater difference in strength between hydraulic concrete and ordinary concrete. The difference in concrete strength reflects the difference of the strength of hardened cement paste in concrete in greater degree. Lower strength of hydraulic concrete shows that the strength of the hardened cement paste in hydraulic concrete is lower. Analyzed by micromechanics, the hardened cement paste is base phase. When aggregate reacts with alkali, the aggregate expands, but the hardened cement paste restrains the expansion of the aggregate. In same time, a tensile stress yields in the hardened cement paste. When the tensile stress is over its tensile strength, crack occurs. Following criterion may be obtained from this:

$$\frac{\varepsilon_p - \varepsilon_m}{1 + \frac{E_p}{E_m}\left(\frac{1}{k^2} - 1\right)} < R_l \qquad (1)$$

Where:

ε_p —— The free expansion of particle phase;
ε_m —— The free expansion of base phase;
E_p —— The elastic modulus of particle phase;
E_m —— The elastic modulus of base phase;
k —— The volume factor of particle phase, $k = V_p^{1/3}$;
V_p —— The volume part of particle phase;
R_l —— The tensile strength of base phase.

It may be seen from equation (1) that the lower the strength of hardened cement paste, the lower the aggregate's expansion that it is able to bear is. This shows that the concrete is ease to crack. The strength of hydraulic concrete is further low to ordinary concrete. It means that its resistance to the expansion caused by alkali aggregate reaction is lower. We must not lower our guard for it.

5 RELATIONSHIP BETWEEN THE AMOUNT OF CEMENTING MATERIALS AND THE DAMAGE CAUSED BY ALKALI AGGREGATE REACTION

Table 1 shows the amount of cementing materials of some dam concrete in China. It may be seen from this table that in China, the lowest amount of cementing materials of dam concrete is 120kg/m^3, the highest amount of cementing materials of dam concrete is only 220kg/m^3, and average is 161kg/m^3. It is only 40%~50% of the amount of ordinary concrete. Of course, the decrease of the amount of cementing materials may reduce the amount of heat evolution and the temperature rise caused by hydration heat. It is advantageous to the temperature and crack control of mass concrete. But, care should be taken to its special behavior when alkali aggregate reaction.

For alkali aggregate reaction, the cementing materials in concrete have two affection. One is to provide alkali for alkali aggregate reaction, and other is to restrain the expansion of aggregate. The alkali provided by cementing materials is the main source of alkali in concrete. According to common requirement, the alkali content of concrete should be controlled under 3.0 kg/m^3. It isn't difficult for hydraulic concrete because its amount of cementing materials is less. For example, if the alkali content of cement is taken as 1.0% Na_2O_{eq}, the amount of cementing materials is taken as 160kg/m^3, mineral admixture is not considered, superplastizer is added in 0.7% of the amount of cementing materials and its alkali content is 10%, the total alkali content of concrete is only 1.712 kg/m^3. If only the alkali content of concrete is considered, hydraulic concrete is easier to control than ordinary concrete. Because of this reason, some people think that to prevent alkali aggregate reaction is a very easy thing for hydraulic concrete. To control the alkali content of concrete to a lower level and avoid alkali aggregate reaction, it is only needed that the alkali content of cement is controlled slightly. Fact isn't so. In Europe, North America, etc., the examples

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that alkali aggregate reaction caused the damage of hydraulic structure is more. Reason is that under the condition of same alkali content of concrete, the concrete with different amount of cementing materials shows different behavior when alkali aggregate reaction occurs. This is ignored always. For alkali aggregate reaction, cementing materials don't only provide alkali, but also may restrain the expansion of alkali aggregate reaction. The less the cementing materials, the weaker the affection is, and the more the expansion of concrete is. Table 2 gives the influence of the amount of cementing materials on the expansion of alkali aggregate reaction. The result supports this viewpoint. The amount of cementing materials of hydraulic concrete is lower than ordinary concrete. Thus, it is certain that the expansion of hydraulic concrete is large than that of ordinary concrete under same condition. In other aspect, because the amount of cementing materials is less in hydraulic concrete, hardened cement paste will bear larger tensile stress when alkali aggregate reaction occurs. Thus, hydraulic concrete is easier to destroy than ordinary concrete if alkali aggregate reaction occurs.

Table 1. The number of cementing materials in some dam in China

Name	Type of dam	The amount of cementing materials (kg/m^3)
Fuziling	Multiple arch dam	120
Meishan	Multiple arch dam	123
Shangyoujiang	Hollow gravity dam	164~190
Huangtankou	Gravity dam	150
Gutian I	Slotted gravity dam	159~177
Sanmenxia	Gravity dam	137.5~142
Xinanjiang	Slotted gravity dam	129~141.8
Zhexi	Massive-head buttress dam	170
Xijin	Slotted gravity dam	133~141
Qingtongxia	Pier-head dam	161
Liujiaxia	Gravity dam	130.7
Chencun	Gravity-arch dam	142.7~149
Danjiangkou	Slotted gravity dam	144
Wujiangdu	Gravity-arch dam	142.9
Fengtan	Hollow gravity dam	156.5
Chitan	Slotted gravity dam	153.8
Daheiding	Gravity dam	180
Panjiakou	Slotted gravity dam	157~169
Dahua	Gravity dam	154~228.5
Jinshuitan	Three-centre arch dam	185
Manwan	Gravity dam	163
Longyangxia	Gravity dam	160
Ankang	Broken line gravity dam	155
Dongxiguan		148
Yudong	Gravity dam	196
Dahekou	Hollow gravity dam	171
Baishiyao		166
Ertan	Arch dam	174
Guxian	Gravity dam	220
Guoduwan	Gravity dam	168
Dongfeng	Arch dam	164
Dongjiang	Arch dam	182
Average		**161**

Table 2. The influence of the amount of cement on concrete expansion

Type of aggregate	The amount of cement (kg/m^3)			
	300	400	500	600
Zeolitizated perlite	0.119	0.104	0.090	0.076
Carbonate	0.148	0.135	0.121	0.108

Note: The alkali content of concrete is 6 kg/m^3.

At present, the limited index of the alkali content of concrete is produced on the base of ordinary concrete experiment. In the method of concrete prism test, the amount of cement is 420 kg/m^3. It is about 2~3 times of the amount of cementing materials in hydraulic concrete. If is it reliable that the result obtained under this condition is used to hydraulic concrete directly? It should be thought seriously.

6 THE INFLUENCE OF MOIST CONDITION ON ALKALI AGGREGATE REACTION

Three prerequisites of alkali aggregate reaction are that there are reactive aggregate, certain quantity of alkali and enough water in concrete. In alkali aggregate reaction, water has three actions: (1) Water

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is the base of alkali ionization. It is well known that alkali is very active. In water, it is very easy to form alkali ion. It is the alkali ion to be easy to react with the reactive components in aggregate and form reaction products. If it is a solid-solid reaction, alkali aggregate reaction should be very difficult. (2) Water is the carrier delivering alkali. Alkali ions are formed after the alkali in hardened cement paste solution in water. The alkali ions can move to the surface of reactive aggregate rapidly in water. and react with it. If there isn't water, it isn't easy that alkali ion arrives the surface of aggregate. (3) Water is the resource of the expansion caused alkali aggregate reaction. For alkali-silica reaction, the reaction product is alkali-silica gel. The alkali-silica gel has very strong water absorption. After water is absorpted, a larger expansion occurs. If there isn't water, dry alkali-silica gel doesn't cause volume expansion. Seen from these viewpoints, water plays an important role in the process of alkali aggregate reaction. It is just this aspect that hydraulic concrete has very "good" condition. Generally, hydraulic structure is in water in long term. Under this environment, it is impossible that the mix water of concrete is evaporated and lost. Of cause, a part of mix water may be consumed because of the hydration of cement. But, it may be replenished continuously by outside water. Thus, hydraulic concrete may lie state of saturated water always. The condition cannot be often arrived for other concrete. Under the condition, once there are reactive aggregate and enough alkali, their potentiality will be given full play to destroy concrete structure. Thus, seen from environmental condition, hydraulic concrete is more dangerous.

7 THE RELATIONSHIP BETWEEN THE REQUIREMENT OF USING LIFE AND ALKALI AGGREGATE REACTION

Because of the huge investments, long construction time and special importance of hydraulic structure, the requirement of using life is longer for hydraulic structure. It is very correct. For heavy hydraulic structure, using life should be over hundreds years. It is the requirement of long using life to give alkali aggregate reaction enough time.

Generally, alkali aggregate reaction is a very slow process. It needs longer time. For some slowly expansive reactive aggregate. it will be longer. In Europe and North America, the damage caused by alkali aggregate reaction occurred after more than ten years, even decades that structure had been built. Val-de-da-Mare dam in Britain was built from June to August 1960. In the winter of 1971, the crack caused by alkali aggregate reaction was found. For the three hydropower station in the southwest of England, the crack caused by alkali aggregate reaction on the concrete foundation was found after more than ten years that the stations had been build. The Buke dam of America was built in 1922. After ten years, serious alkali aggregate reaction occurred. The Beauharnois hydropower station of Canada was built in 1928. In 1940, serious map cracks caused by alkali aggregate reaction was found in dam body, and caused the different degree of the displacement of the dam body. Chambon dam of France was built from 1929 to 1934. Up to 1958, the deformation of dam body occurred. From 1970 to 1972, the average increase of height was 3.5 mm/year. In 1976, the increase of height reached about 140 mm/year. Because the damage caused by alkali aggregate reaction, the dam cannot continue to be used, and will be rebuilt. If the using life of concrete only is required about twenty years, it is possible that some problems are concealed. The requirement may be satisfied only by some measures delayed alkali aggregate reaction. But, this requirement of using life isn't enough for hydropower construction. Thus, clearer understanding to alkali aggregate reaction is necessary in the construction of hydraulic structure. Deeper research should be done.

8 CONCLUDING REMARKS

At above, the difference between hydraulic concrete and ordinary concrete is compared, and the influence of the difference on alkali aggregate reaction is analyzed. It is found by the comparison that there is very large difference between hydraulic concrete and ordinary concrete in the particle size of aggregate, the strength of concrete, the amount of cementing

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materials, the environment condition and the requirement of using life. These differences effect the behavior of alkali aggregate reaction of hydraulic concrete in different mode. Larger particle size of aggregate makes alkali aggregate reaction slow, but it is easier to form stronger stress concentration when alkali aggregate reaction occurs. Lower concrete strength and less amount of cementing materials make hydraulic concrete have weaker ability resisted alkali aggregate reaction. Moist environment creates a good condition for alkali aggregate reaction. The requirement of longer using life provided enough time for alkali aggregate reaction. These show that in alkali aggregate reaction, hydraulic concrete is danger than ordinary concrete. Thus, a prudent policy should be adopted.

Because the differences between hydraulic concrete and ordinary concrete in these aspects and their influence on alkali aggregate reaction aren't played an attention always, some evaluating methods, criteria and controlled index, for example the safe alkali content of concrete, are build on the base of ordinary concrete. If may they be used to hydraulic concrete? How are they used to hydraulic concrete? For these questions, deep research should be do to give a scientific decide.

REFERENCES

[1] Hobbs, D.W. and Gutteridge, W.A., Particle Size of Aggregate and Its Influence upon the Expansion Caused by the Alkali-Silica Reaction. Magazine of Concrete Research, 31, 109, 1979, pp235-242

[2] Tang Mingshu, Han Sufen and Zhen Shihua, A Rapid Method for Identification of Alkali Reactivity of Aggregate. Cement and Concrete Research, Vol. 13, No. 3, 1983, pp417-422

[3] Zhang Chengzhi, Wang Aiqin, Tang Mingshu, Wu Binqing and Zhang Ningsheng, Influence of the Size and the Size Grading of Aggregate on ASR Expansion. Cement and Concrete Research, Vol. 29, 1999, pp1393-1396

[4] Zhang Chengzhi, Evaluation of the Alkali Reactivity of Aggregate and Evaluation of the Effectiveness Inhibiting of Mineral Admixture on Alkali Aggregate Reaction. Ph.D. Thesis, Nanjing University of Chemical Technology, June 1996

[5] Tang Mingshu, Inspection on Highways, Bridges and Dams in Canada. Journal of Nanjing University of Chemical Technology, No. 2, 1987, pp124-128

[6] Marcel Arnould, Alkali-Reaction with Silica Alkaline Aggregates Results of Recent Researches in France. Proceedings of '97 International Three Gorges Project Technical Seminar, Yichang, China, 26~28 November, 1997, pp184-185

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