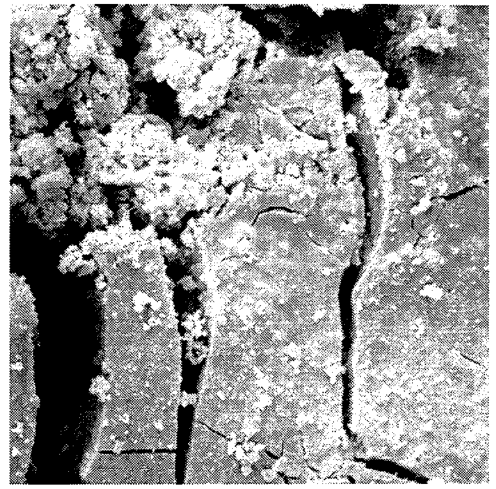

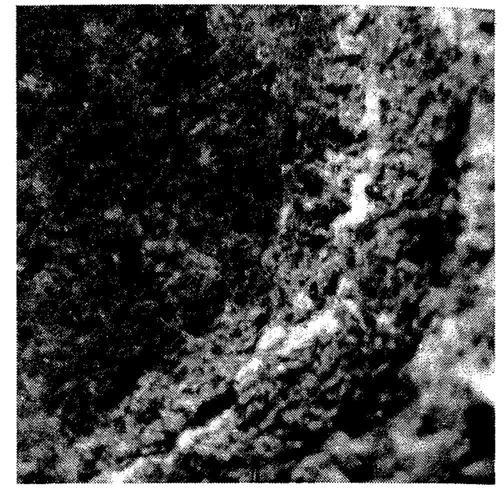

Fig. 10. Jelly deposit of reaction products, fissured by shrinkage (400 X).

Fig. 11. Enlarged view of dark rim on a marly limestone cobble.

5. CONCLUSIONS

Detailed investigations on all concrete samples allowed to conclude that AAR was the most probable cause of the building decay, for the following reasons:

- cracking of concrete structures in humid environment after 8 years since concrete casting;
- deposit of jelly reaction products on crack surfaces, in the concrete mass and in grains of an aggregate defined as "potentially deleterious" by chemical and petrographical analyses;
- finding, inside the concrete mass, altered siliceous grains and aggregate grains showing outer dark rim and inner white zone;

all these, reliable signs of alkali-aggregate reaction /8/.

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INVESTIGATION FOR NATURAL REACTIVE AGGREGATES IN GRAVEL ALLUVIUM OF YANGTZE RIVER BASIN

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ABSTRACT

Multiple purpose projects were constructed and being constructed for the development of water resource of the Yangtze, China. The main hydraulic structures are largely concrete dams. Some of these concrete dams were constructed with natural construction material containing reactive aggregates. For inhibitting the damaging action of the deleterious reaction of reactive aggregates, preliminary investigations were conducted for geographical distribution within the Basin and detailed studies measures taken, were made for mitigating, if necessary. A comprehensive account of above-mentioned studies is given in the paper.

INTRODUCTION

The Yangtze River is the longest river in China and is the third largest of the world. In order to develop its abundant water resources, it is essential to investigate the reactive aggregates in gravel alluvium of the main stem and tributaries of the upper and the middle reaches of the Yangtze River and take samples from the above-mentioned areas for tests. Considerable work has been done and this paper will describe the classification, the distribution and the test result of the reactive aggregates in that area.

DISTRIBUTION OF NATURAL REACTIVE AGGREGATES

In the past thirty years, reactive aggregates have been studied in sand and gravel deposits in the main stem and tributaries of the upper and the middle reaches of the Yangtze River, including Ganjiang of The Poyang Lake Water System, the Dongting Lake Water System, Hanjiang, the Sichuan Water System and the reach of Jinshajiang below Shigu, and samples have been taken from the above-mentioned areas for tests with a view to finding out the reactive aggregates that should be used in concrete. Here are some results of the study.

(1) According to Xu Huarong's classification, the reactive aggregates in sand and gravel deposits fall into two kinds, the kind of alkali-silica reaction such as flint and its varieties (agate and jasper) and the kind of alkali-silicate reaction such as rhyolite, trass, andesite, dacite, breccia. In addition, some siliceous slates are found. Photos show the appearance and microstructure of the reactive aggregates.

(2) The distribution law of the reactive aggregates is quite clear. The natural reactive aggregates in Tuojiang and the main stem and tributaries of the Yangtze River below Tuojiang are mainly composed of flint with the exception that a small amount of agate is found in particular area and a small amount of rhyolite and trass is found in the Gezhouba area just below the outfall of the Three Gorge and a considerable amount of siliceous slate is found in Hangjiang and Yuanjiang area. The proportion of flint amounts to 18%. The reactive aggregates in the main stem and tributaries of The Yangtze River above Tuojiang are

mainly composed of rhyolite and trass, whose proportion amounts to 15%. The proportions of andesite, dacite, breccia and flint (including jasper) in that area are negligible. Obviously, the distribution law is useful in research work and in designing.

INVESTIGATION ON REACTIVE AGGREGATES

As investigation on the reactive aggregates in sand and gravel deposit in the main stem and tributaries of the upper and the middle reaches of the Yangtze River have been carried out for more than twenty years, much experience is gained and data are accumulated. Some of the details will be described as follows.

(1) Classification of reactive aggregates -- Since the problem of alkali-aggregate reaction has arised, emphasis is put on the classification of reactive aggregates. Through the effort of many researchers, great achievement results. Reactive aggregates could be scientifically classified into three kinds, namely, the kind of alkali-silica reaction, the kind of alkali-silicate reaction and the kind of alkali-carbonate reaction. But further study has to be made, so that the classification could be more proper.

It is known that the evaluation of the use of reactive aggregates is formed by means of the length test. As this test needs a long time to give results, it cannot evaluate the use of reactive aggregates in a short time and measures such as the use of low alkali cement have to be taken, hence increasing cost. It is believed that there is a correlation between the classification of reactive aggregates and the safe alkali content of cement, so that the kind of reactive aggregates could be determined in a few days by means of optical identification etc., and then the safe alkali content of cement determined.

In the reactive aggregates found in gravel alluvium of the Yangtze River Basin, those that belong to the kind of alkali-silica reaction have been grouped and those that belong to alkali-silicate reaction are being grouped. Xu Huarong, Senior Engineer of the Institute, has made a study on the former and written an article "Classification of Reactive Aggregates of Alkali-Silica Reaction Class and Safe Alkali Content of Cement". Based on the reactive source, the morphology of reactive aggregate and its formation of rock in nature, the article classificates the reactive aggregates in kind of alkali-silica reaction as follows.

Classification of Reactive Aggregates of Alkali-Silica Reaction Class

- Amorphous silica
  - silica gel
  - silica glass
- cryptocrystalline silica
  - chalcedony type
    - porous flint
    - dense flint
  - tridymite
  - cristobalite
- crystalline silica
  - strained quartz

As for the reaction between the classification of the reactive aggregates in kind of alkali-silica reaction and the safe content of cement, we will describe later.

(2) Mechanism of expansion due to alkali-silica reaction -- study on the mechanism started in late 1960's. In early 1980's, fracture mechanics and catastrophe theory were used to investigate the mechanism of expansion due to alkali-silica reaction. As for the former, Liu Chongxi, Senior Engineer of the Institute, has produced an article "Some problems of alkali-silica reaction in concrete". We now summarize this article as follows.

The products of alkali-silica reaction, viz. alkali-silica complex, are spherical. The size and assembly of spheres are related to the ratio of Na_2O to SiO_2. The size of spheres decreases and the scatter of spheres increases as the ratio increases. For example, when the ratio of Na_2O to SiO_2 is 0.05, the diameter of the sphere is 20,000-36,000Å and most spheres assembly with a small number of scattering single spheres. When the ratio is 0.50, the diameter of sphere is 10-100Å, most spheres scatter as single sphere with a small number of assembling spheres. When the ratio is 1.00, the sphere is very small, indicating that they scatter entirely. The alkali-silica complex would change from white solid to gel state and, finally, become gelatinous solution. Therefore, it is reasonable to conclude:

1. When the products of alkali-silica reaction swell due to water absorption, the system in some degree maintains its elasticity. The porous hardened cement paste at the interfaces of the reaction products will produce screening effect, causing the concrete to expand.

2. When the products become gelatinous, they will be squeezed into the pores of the hardened cement paste under the expansive pressure and combine with the Ca^{++} ions in liquid phase to become lime-alkali-silica complexes. The diameter of the pores of the complexes is 15-30Å, acting as a molecular sieve. It permits the passage of water molecule, but shields the reaction product produced at the ratio of Na_2O to SiO_2 smaller than 0.50. Then osmotic pressure occurs (see figure 1), causing concrete to expand.

From the discussion above, it can be seen that in the region that is close to the interface of unreacted aggregates, the reaction products produce swelling pressure due to water absorption and in the region that is close to the interface of semi-osmotic membrance of the hardened cement paste, the osmotic pressure occurs, causing concrete to expand. It is assumed that the swelling pressure predominates in early age, while the osmotic pressure predominates in later age.

(3) Inhibitory measures

1. Alkali content of cement -- The alkali content of cement has been studied during the classification of reactive aggregates. In his paper mentioned above, Xu Huarong stated that alkali in alkali-aggregate reaction in concrete generally originates from cement and it is incorrect to lay emphasis on the alkali content of cement only. The alkali-aggregate reaction not only depends on the alkali content, but also on the cement content used per unit volume of concrete. In addition, the kind of reactive aggregate and its proportion are also playing an important part in alkali-aggregate reaction. Therefore, all those factors take part in alkali-aggregate reaction and their relation with the expansion of concrete has to be studied further.

It is found that the alkali aggregate reaction with consequent deleterious expansion of concrete depends on alkali quantity with which the unit quantity of reactive aggregate could combine, viz. the ratio of alkali to reactive aggregate. Based on the data obtained from the tests on opal and flint of alkali-silica class found in gravel alluvium of the Yangtze River Basin and other sources of China, it is found that if the ratio of alkali to reactive aggregates is too high or too low, the reactive aggregates will not cause deleterious expansion. According to ASTM standards (1976), cement-aggregate combinations which, when tested by ASTM specification C-227, show expansions greater than 0.1 percent at 6 months usually should be considered capable of harmful reactivity. The mathematical expressions are given as follows.

(1) opal

$$0.075\ (P_sR_s+P_GR_G) \geq P_{sa} \geq 0.500(P_sR_s+P_GR_G) \quad ..... (1)$$

(2) flint

a. porous flint

$$0.025(P_sR_s+P_GR_G) \geq P_{sa} \geq 0.350(P_sR_s+P_GR_G) \quad \ldots\ldots \quad (2)$$

b. dense flint

$$0.018(P_sR_s+P_GR_G) \geq P_{sa} \geq 0.200(P_sR_s + P_GR_G) \quad \ldots\ldots \quad (3)$$

Prior to the derivation of the three expressions, the mathematical expressions of the ratio of safe alkali content and the ratio of alkali to reactive aggregate has to be given.

$$P_{sa} = R_{sa}\ (P_sR_s + P_GR_G) \quad \ldots\ldots \quad (4)$$

$$R = \frac{P_{Al}}{P_sR_s+P_GR_G} \quad \ldots\ldots \quad (5)$$

where P_s or P_G is the percent of reactive aggregate in sand or in gravel respectively, R_s or R_G is the ratio of sand or stone to cement by weight in unit volume of concrete, R is the ratio of alkali to reactive aggregate by weight in unit volume of concrete, R_{sa} is the safe one at which deleterious expansion will not occur, P_{Al} is the alkali content of cement and P_{sa} is the safe ratio at which deleterious expansion will not occur.

2. Inhibitory materials - - In the study of inhibitory materials, emphasis is put on waterquenched slag, fly ash, kaolinite and montmorillonite available in China. Diatomearth and lithium salt are also studied.

Kaolinite and montmorillonite should be calcined before they become hydraulic pozzolan. Differential thermal analysis shows that they possess a remarkable trough which implies dehydroxy reaction.

$$Al_2Si_2O_5(OH)_4 \xrightarrow{600^oC} Al_2Si_4O_4 \quad \ldots\ldots \quad (6)$$

$$Al_2(OH)_2Si_4O_4 \times nH_2O \xrightarrow{600^oC} Al_2Si_4O_4 \quad \ldots\ldots \quad (7)$$

From the equations (6) and (7), it can be seen that after calcining, kaolinite will become metakaolinite and montmorillonite will become metamontmorillonite. They are of quasi-ordered minerals and therefore, possess chemical activity. The absorption test of lime shows that after calcining at 600^oC, the absorption lime values of these two minerals reach the highest values. So, the calcining temperature is taken at 600^oC.
The length test shows that when slag is added to more than 35%, fly ash to more than 25%, and kaolinite, montmorillonite or diatomearth to more than 20% respectively, they will be effective in inhibitting expansion, due to alkali-aggregate reaction. For example, the expansion is 0.297% at the one year when no admixture is added, but will decrease to 0.028%, 0.027%, 0.021% and 0.034% when slag, kaolinite, montmorillonite and diatomearth are added respectively. Fly ash is also effective in inhibitting expansion due to alkali-aggregate reaction when it is added to 25%.

From the test on lithium salt, two different results are obtained. Figure 2 shows LiCl in some degree could inhibit the expansion due to alkali-aggregate reaction at early age when 1% of LiCl is added, but after two months, it promotes the expansion. Figure 3 shows LiF is effective in inhibitting the expansion when 1% LiF is added. The reason why these two lithium salts have different effects is still a question to be solved.

CONCLUSIONS

Investigations of reactive aggregates in gravel alluvium of the Yangtze River Basin have been conducted for thirty years. During that time, many problems concerning the use of reactive aggregates and the alkali-aggregate reaction arised from the hydraulic power projects constructed and being constructed in China and most of the problems have been solved by our Institute. This paper presents part of our research work related to alkali-aggregate reaction and the results of the study lead to the following conclusions:

(1) The reactive aggregates in gravel alluvium of the Yangtze River Basin above Tuojing is mainly composed of rhyolite and trass and below Tuojiang is mainly composed of flint.

(2) In the investigation of reactive aggregates, it is important to relate the classification with the safe alkali content of cement. Based on test results, it only needs a short time to determine the type of reactive aggregates in kind of alkali-silica reaction by means of optical identification etc. without performing the length test, hence the safe alkali content of cement.

(3) In the study of classification of reactive aggregates, mathematical expressions are derived. It is believed that these expressions are new and practicable.

(4) Reaction products of alkali-silica close to the interfaces of unreacted aggregates produce swelling pressure due to water absorption, which prevails at early age, while those close to the interface of semi-membrance of hardened cement paste produce osmotic pressure, which prevails at later age, causing concrete to expand.

(5) Water-queched slag, fly ash, kaolinite and momtmorillonite are effective in inhibitting expansion due to alkali-silica reaction, but kaolinite and montmorillonite should be calcined at 600^oC before they are used.

(6) LiF is effective in inhibitting expansion due to alkali-silica reaction, but LiCl promotes the expansion due to alkali-silica reaction. The mechanism of Lithium salt together with the effect of Lithium salt should be studied further.

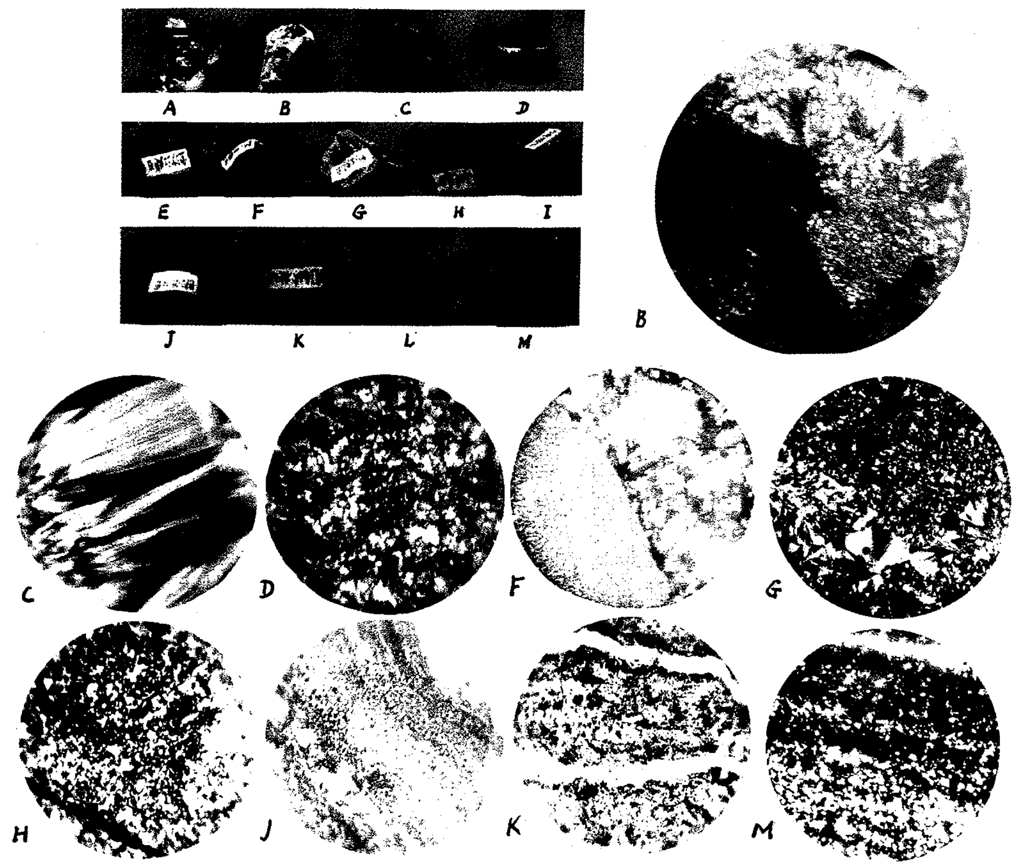

Plate . The appearance and micro-structure of reactive aggregate .

A. Pyrex glass B. Opal C. Agate D. Jasper E. Dense flint
F. Konglomerat G. Porous flint H. Dense flint I. Porous flint J. Rhyolite
K. Tuff L. Andesite M. Siliceous slate

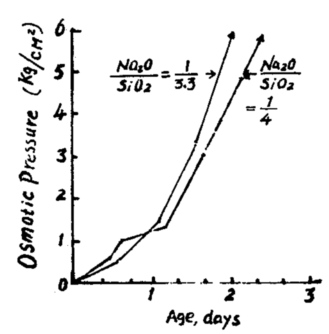

Fig. 1. Osmotic pressure(Alkali -Sillica complex)

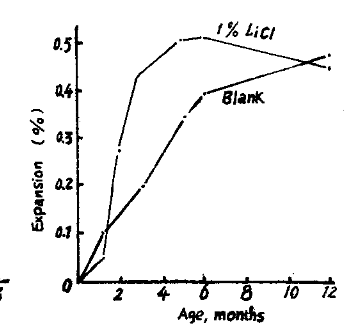

Fig. 2. Effect of 1% LiCl on mortar bar

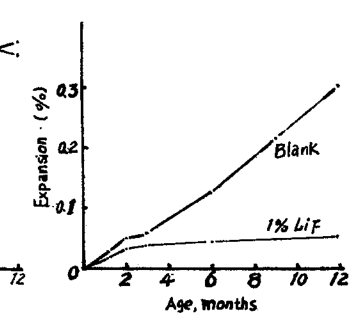

Fig. 3. Effect of 1% LiF on mortar bar

CHAIRMAN'S REPORT, Session 5

Bryant Mather

It was very good to have participation by structural design engineers in the discussion because only they can judge that a structure has been sufficiently damaged to require more than cosmetic maintanance.

Few structures have required demolition and replacement prematurely because of alkali-silica or alkali-carbonate rock reaction. Methods for repair and for reducing the rate of deterioration were described.

We know how to make concrete that will not deteriorate; we are seldom able to obtain the materials, proportions and practices that will guarantee non-deterioration. Research is needed better to judge risk and evaluate materials, proportions and practices so we will have practical, economical means of assuring non-deterioration.

It was good to have a discussion of measures being taken to avoid premature deterioration of concrete to be made for the Faroe Bridge. It appears that the measures being taken are at least as stringent as necessary and that they are being followed.

Concrete need not deteriorate.