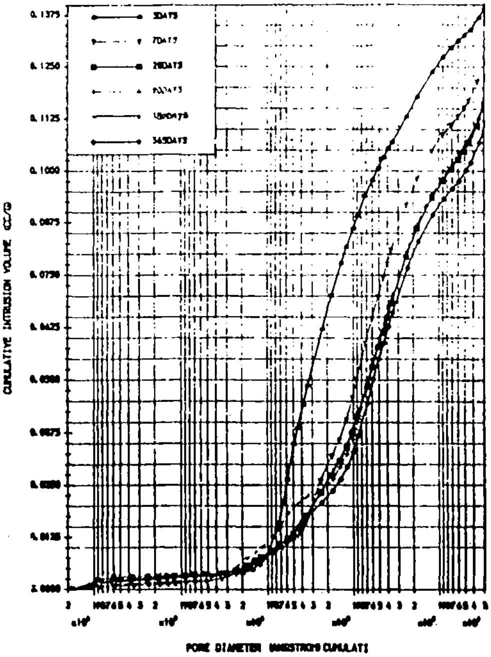

Fig. 3--Cumulative pore size distribution of TR1M mortar at various ages

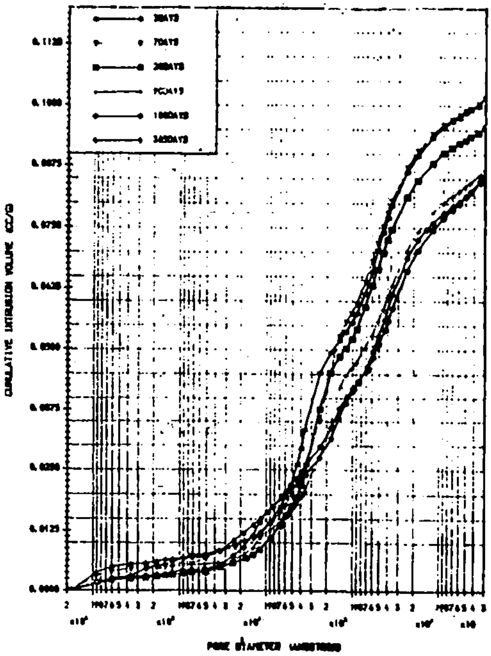

Fig. 4--Cumulative pore size distribution of TR2M mortar at various ages

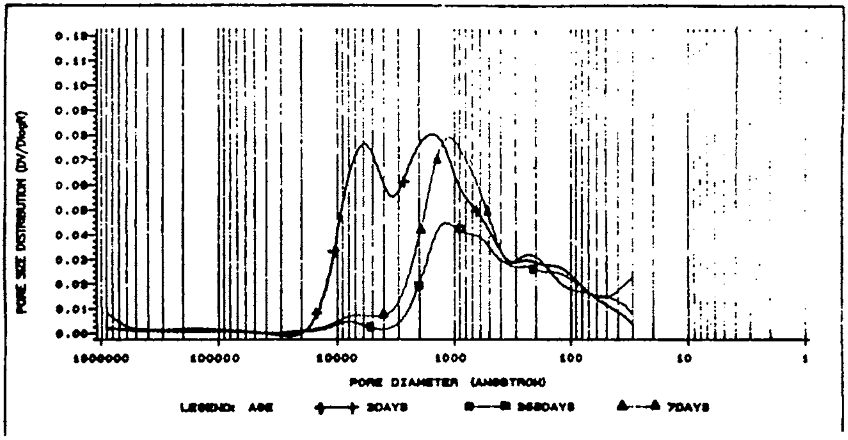

Fig. 5--Derivative pore size distribution for OPC1M mix at 3, 7 and 365 days

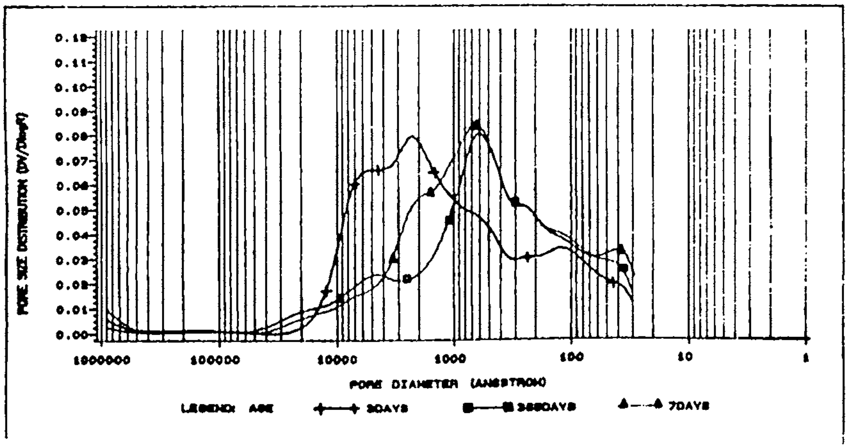

Fig. 6--Derivative pore size distribution for TR1M mix at 3, 7, and 365 days

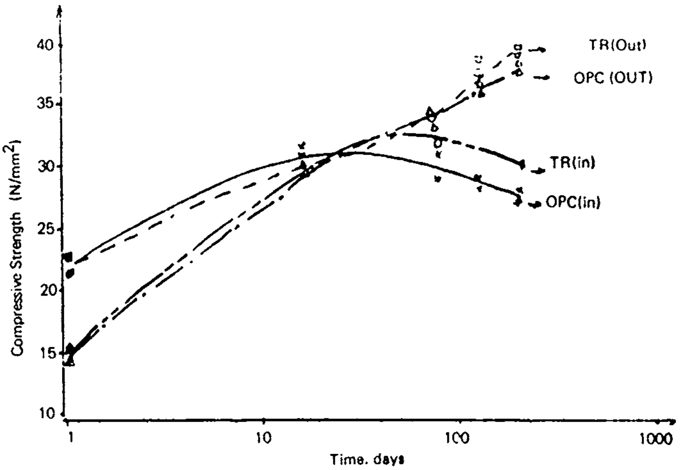

Fig. 7--Compressive strength at various ages for OPC and TR concrete mixes inside and outside sulphate solution

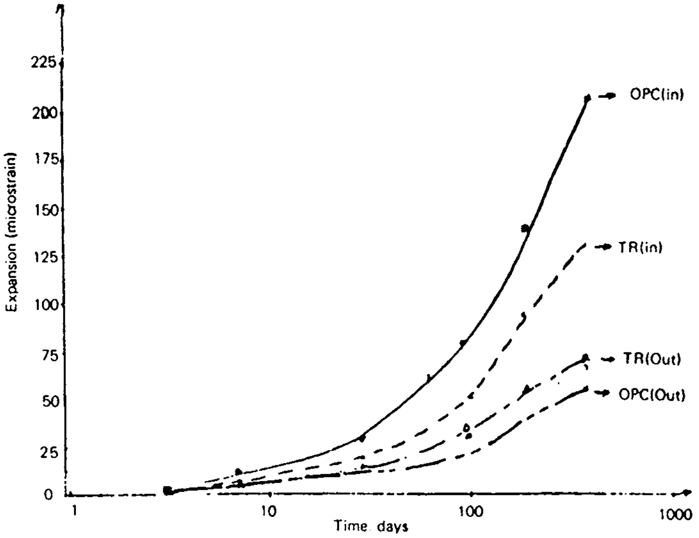

Fig. 8--Expansion at various ages for OPC and TR mortar mixes inside and outside sulphate solution

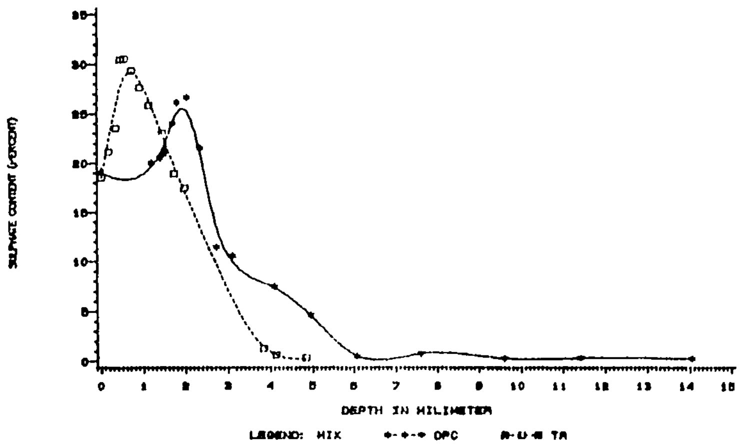

Fig. 9--Sulphate content at different depths

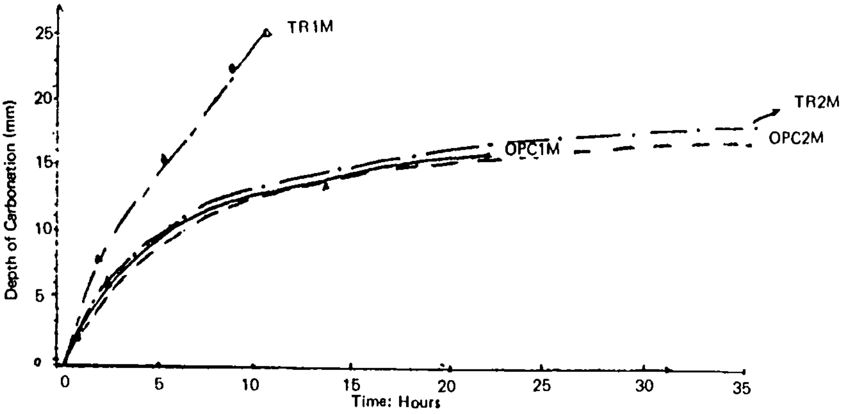

Fig. 10--Depths of carbonation time relation obtained under accelerated conditions 90 percent RH, 90 percent CO_2, 1 At. and 0 days curing for mortar mixes

SP 131-12

Role and Effectiveness of Mineral Admixtures in Relation to Alkali Silica Reaction

by R.N. Swamy

Synopsis: This paper examines critically the role and effectiveness of mineral admixtures in counteracting the effects of ASR. Tests are reported on plain concrete prisms and reinforced concrete slabs incorporating a slowy reactive but moderately expansive reactive aggregate and containing either fly ash, slag or microsilica. It is shown that control of expansive strains and consequent cracking are acceptable and satisfactory solutions in many instances, particularly in unreinforced concrete. However, there are many situations where additional factors such as preserving the strength and stiffness of the damaged structure and control of structural distortions are equally important if the safety, stability and serviceability of ASR-affected structures are to be maintained. Judged on these five significant criteria, data are presented to show that mineral admixtures, when used correctly and at the required level, can control material damage and structural deterioration effectively and substantially, although they may not be able to eliminate all deleterious effects completely and at the same time. Mineral admixtures should not be expected to fulfil such a global and over-protective role, but they have an unequalled, positive and promising function in contributing to the safety, stability and durability of concrete materials and concrete structures affected by ASR.

Keywords: Alkali silica reactions; cracking (fracturing); deformation; durability; fly ash; microsilica; mineral admixtures; plain concrete; reinforced concrete; slags

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INTRODUCTION

It is now universally recognised that of all the possible methods of controlling the deleterious expansion caused by alkali silica reaction (ASR) in hardened concrete, the use of pozzolanic or mineral admixtures can impart the most realistic advantages to the properties of the concrete to enhance its durability characteristics, and hence its resistance to the effects of ASR. Apart from cost benefits, there are sound technical, environmental and energy-related reasons as to why such mineral admixtures could bring considerable practical benefits to concrete construction when they are used as a basic constituent of the concrete matrix (1).

However, in spite of the considerable research carried out on the role of pozzolans and of mineral admixtures in controlling ASR expansion, it is fair to say that there are still several aspects of the mechanism of pozzolanic reactions and their control of ASR expansion that are not yet clearly established (2-7). Published literature shows that there are still a lot of differences of opinion and conflicting results about the role and effectiveness of mineral admixtures in controlling the effects of ASR. There is a strong school of thought that the alkalies in fly ash and slag contribute to the reaction; the effects of silica fume appear to be highly variable, whilst some materials like fly ash, natural pozzolan and slag are sometimes considered to be not only ineffective but even hazardous (8-16). The situation is confusing, to say the least, and designers and users of concrete could be forgiven if they decide to stay clear of materials whose function is reported to be so conflicting and contradictory. To some extent, the real danger has been in considering mineral admixtures as a "universal panacea" and a "global solution" for the problems of ASR.

There are other factors influencing this current feeling of uncertainty on the universality of the effectiveness of mineral admixtures in concrete. The majority of data available to the engineer is based on cement pastes and mortars, and whilst such data contribute immensely to our understanding of the role and effectiveness of mineral admixtures in counteracting the effects of ASR, there are several sound reasons as to why data obtained from such tests cannot readily and unquestioningly be translated to evaluate the behaviour of concrete in all situations. Almost all assessments of the effectiveness of mineral admixtures are based on the ASTM C441 test which has severe limitations not only from test methodology but also from the unreliability of the criteria applied to evaluate expansion limits (17,18). Test results also appear to suggest that the 0.6% limit defined in ASTM C150 for the alkali content of cement and the 1.5% maximum available alkalies for fly ashes in ASTM C618 are inadequate guidelines (19). Further, mortar bar tests (ASTM C227) and data obtained to define pore solution chemistry have also severe limitations and care should be exercised in interpreting these data and in extrapolating them to situations and materials beyond what are strictly only applicable to situations similar to the methodology of the tests.

There are also other engineering aspects to be considered such as the rate at which minearl admixtures are able to control the effects of ASR. The rate of pozzolanicity of fly ash and slag, for example, which is one of the critical factors determining the effectiveness of mineral admixtures, is highly variable, and influenced by many factors. Most fly ashes and slags are also known to retard setting, and have higher rates and volumes of bleed unless the mixes are carefully proportioned. It can readily be seen that it is inevitable that the effectiveness of mineral admixtures cannot but be seen to be highly variable, and very much controlled by the test methodology and test conditions.

Further, there is the more fundamental question which does not seem to have been addressed, namely, what exactly should be the role of the mineral admixture in counteracting the effects of ASR? What do we expect the mineral admixtures to do when incorporated in concrete that is likely to undergo alkali silica rections at some stage in its life? Most published literature, and most planned research seem to assume tacitly that control of expansion and the consequent cracking is the sole function of mineral admixtures, and their effectiveness is judged by their ability to control ASR expansion and/or cracking. This may be so in unreinforced concrete, but what happens to the structure as a whole if there is embedded steel that is inadequately proportioned or badly detailed? Or, what happens when other deteriorating processes are superimposed on alkali silica reactivity? Considering expansion alone, even if it were the sole criterion, the test conditions used by almost all investigators are so highly different from each other, that it seems to be very unfair to mineral admixtures to be judged in this way since many of the results of the tests are not really comparable. The reasons for the prevailing confusion and uncertainty are thus not difficult to see.

The aim of this paper is to examine both the role and effectiveness of mineral admixtures in counteracting the effects of ASR. In order to obtain an overall global picture on the interactive effect of ASR on concrete and steel, tests are reported on (a) plain concrete without and with reactive aggregates, (b) plain concretes containing acceptable proportions of mineral admixtures with the same reactive aggregate, and (c) concrete with reinforcement containing the same proportion of mineral admixtures and the same reactive aggregate. A slowly reactive but moderately expansive aggregate was used to give expansions in excess of 2000 µs. The test conditions were kept the same for all the mineral admixtures. The paper is necessarily confined to engineering properties: the chemical aspects will be reported in due course.

EXPERIMENTAL PROGRAMME

The test programme reported here consisted of three sets of tests. In the first set, two series of tests were carried out on plain concrete as follows:

Series A – Control tests without reactive aggregates

Series B – ASR tests with reactive aggregate

In the second set, three series of tests on plain concrete were carried out as follows:

Series C – ASR tests with 50% fly ash replacement of cement

Series D – ASR tests with 50% slag replacement of cement

Series E – ASR tests with 10% microsilica added.

In the third set, tests were carried out on ¼ scale models of reinforced concrete flat slabs, all made with the same reactive aggregate and containing the same type of quantity of mineral admixtures as in the second set, namely,

Series A1 – Control slabs without reactive aggregates

Series B1 – ASR tests with reactive aggregate

Series C1 – ASR tests with 50% fly ash replacement

Series D1 – ASR tests with 50% slag replacement

Series D1 – ASR tests with 10% microsilica added.

Concrete Mix Details and Materials

Only one concrete mix 1:2.2:1.8:0.5 (cement:sand:coarse aggregate:water) by wt. was used throughout the tests. A high alkali normal portland cement (ASTM Type 1) with about 1% sodium oxide equivalent was used. The fly ash was a low calcium type F ash while the slag had a similar specific surface (350 m^2/kg) to the cement (380 m^2/kg). The cement, fly ash and slag all complied with the relevant British Standard specifications. The microsilica was added in the form of a slurry (50% water and 50% solids), with appropriate corrections for the water content and sand. The quantity of microsilica added was restricted to 10%, the amount now generally accepted as the maximum allowable in practical applications (20,21). The fine aggregate used in the concrete mixes was a washed and dried natural sand, and the coarse aggregate consisted of a mixture of rounded and crushed gravel with 10 mm maximum size. Both concrete aggregates were considered to be completely unreactive so far as ASR is concerned.

The reactive aggregate used in these tests was a slow but moderately reactive synthetic aggregate, an amorphous fused silica identified by the author's group as a suitable reactive aggregate for laboratory studies (22). The fused silica had a particle size distribution of 150 to 600 μm and contained 99.7% silica with practically no alkali in it. The fused silica was used to replace sand by an amount equal to 15% by weight of the total aggregate.

The concrete mixes with mineral admixtures were proportioned by methods developed by the author's group in which the portland cement is replaced by the mineral admixture, weight for weight, and other constituents are adjusted, including particularly the water content (23). The water-binder ratio was kept constant for all the concrete mixes at 0.5. A sulphonated napthalene formaldehyde condensate superplasticizer was used in all the mixes to enhance the flow characteristics of the mixes. The amount of superplasticizer was varied to suit the type of mineral admixture to give consistent flow properties, and varied from 1.0% to 1.7% by wt. of the total cementitious content. In order to reduce bleeding, a special mixing procedure was used in which the aggregates were premixed with a proportion of mixing water before adding the binder (24). All the concrete mixes showed excellent workability with slumps in excess of 100 to 150 mm; the microsilica concrete had less slump of 60-80 mm.

Test Details

The test specimens consisted of the following: 75x75x300 mm prisms for expansion tests, 100 mm cubes for compression tests, and 100x100x500 mm prisms for pulse velocity measurement, examination of cracking, dynamic modulus and modulus of rupture tests. All these properties were measured on three specimens so that the test data presented here are the average of measurements on all three.

The model slabs were cast in pairs, both identical in all respects. The slabs used in these tests were $\frac{1}{4}$ scale models of a prototype flat plate structure loaded through a stub column; the slabs were specially modelled to simulate cracking, deformation and strength (24). The size of the slabs and details of the reinforcement are shown in Fig. 1. The main reinforcement consisted of black-annealed plain mild steel wire of 3.25 mm diameter, while the column ties were of mild steel of 1.6 mm dia. To heighten the effects of ASR, the slabs were reinforced unsymmetrically - 10 bars in each direction at the bottom with 4 bars in each direction at the top. The slab reinforcement and the column reinforcement were tied together to form a rigid reinforcing cage.

All the specimens were cast in steel moulds, compacted on a vibrating table and kept covered in the laboratory for 24 hours. The specimens were then demoulded and transferred to a fog room with controlled temperature and humidity of 20 ± 1°C and 96 ± 2% RH.

All the test specimens were subjected to a cyclic hot-wet and hot-dry exposure regime. The specimens were initially kept in the fog room for about 6 days when the concrete had achieved about 70% of its 28 day strength. They were then placed in a hot room at 38 ± 2°C and covered with wet hessian. The specimens were kept moist by wetting once a day but not continuously so that in effect the specimens were exposed to cyclic wet-dry regime at 38 ± 2°C. The synthetic reactive aggregate used in all these tests had been chosen such that it was sufficiently slow reacting to enable the concrete to develop its strength at early ages while being cured in the fog room before the expansive strains started to occur so that ASR chemical rections did not interfere with cement hydration as would happen, for example, if opal is used as reactive aggregate. This was achieved: while being in the fog room, the expansive strains varied from zero to 270 microstrains so that it can be safely assumed that cement hydration in the critical early stages was not adversely influenced by ASR chemical reactions.

In addition to being slowly reactive, the reactive aggregate was also chosen to ensure that it was capable of developing sufficiently high expansive strains which would be deleterious to concrete and concrete structures. The tests