"A Petrographic Evaluation of Concrete Aggregates with Special Reference to Alkali Aggregate Reactions."

BY

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Thesis Submitted for the Degree of
Doctor of Philosophy of University
of Roorkee.

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1969

CERTIFICATE

This is to certify that the thesis entitled " A Petrographic Evaluation of Concrete Aggregates with Special Reference to Alkali Aggregate Reactions". that is being submitted by Sri B.S.Gogte, M.Sc. for the award of the Ph.D. Degree of the University of Roorkee is a result of bonafide research work carried out by him under my supervision and guidance. The results embodied in this thesis have not been submitted for the award of any other degree or diploma of this University. The candidate has completed the specific period (equivalent to 24 months of full time research).

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ACKNOWLEDGEMENT

I take this opportunity to offer my sincere thanks to the Director, Central Road Research Institute for allowing me all the facilities available in the laboratory during the tenure of my study and for the permission to submit the work in the form of the present thesis.

I am highly thankful to Dr. R.S. Mithal, Head of the Department of Geology and Geophysics, University of Roorkee for his valuable help and guidance throughout this work and for his keen interest in the problem.

I am grateful to Dr. R.K. Ghosh, Head of the Concrete Sub-discipline, Central Road Research Institute for providing all facilities available in the Laboratory and giving some valuable suggestions during the study.

I wish to express my grateful appreciation to Late Shri N.R. Srinivasan, Scientist, Central Road Research Institute for the valuable guidance rendered by him during the initial stages of the work.

It is a pleasure to acknowledge the assistance rendered by Shri M.L. Bhatia, Senior Scientific Assistant, Central Road Research Institute during the mortar-bar expansion studies and chemical test on aggregates.

I am highly thankful to the different State Public Works Departments throughout the country for providing the samples of rock aggregates for the study.

I owe special thanks to Dr. N.G.K. Nair, Lecturer, Department of Geology and Geophysics, University of Roorkee for the very helpful suggestions made during the writing of this thesis.

Thanks are also due to Dr. P. Kumar, Asstt. Professor of Geology, Indian Institute of Technology, Delhi for critically going through the manuscript of the thesis and making helpful suggestions.

I also thank Shri Mehrotra, Scientist, Central Building Research Institute and Shri Jain, Senior Research Scholar, University of Roorkee for their co-operation in taking some of the photo-micrographs.

** B. S. GOGTE **

"A PETROGRAPHIC EVALUATION OF CONCRETE AGGREGATES WITH SPECIAL REFERENCE TO ALKALI AGGREGATE REACTIONS"

ABSTRACT

The history of concrete shows that since its earliest use there have been frequent failures and concrete has not always proven a satisfactory construction material. A survey of failures of concrete structures as made in different countries has shown that chemical reaction between cement alkalies and certain silicious constituents in the aggregate, popularly known as "Alkali-Aggregate Reaction" is one of the major cause for deterioration of concrete structures. The phenomena has been well studied in U.S.A., Denmark and Australia and a good lot of data has been made available regarding the occurrence and nature of reactive aggregates. On the other hand, inspite of major concrete constructions, almost nothing is known of the vulnerability to an attack by cement alkalies of the rocks or their aggregates from different geological formations in India. Further more the problem has not been well-studied from the petrographic point of view even in foreign countries, and only a scanty data is available regarding the petrographic nature of reactive aggregates.

With these objects in view, the present study deals with a detailed investigation and evaluation of

common Indian aggregates, obtained from different stratigraphical horizons, as regards to their susceptibility to alkali aggregate reactions employing the commonly accepted experimental procedures like mortar bar expansion studies, petrographic examination and chemical test. In addition to these, the petrographic examination of thin sections of mortars showing symptoms of alkali aggregate reactions has been made in order to prove more conclusively the identification and association of different reactive constituents in the aggregate with alkali reactions. An attempt is also made during the present studies to assess the effect of alkali aggregate reactions on the tensile strength of mortars.

A correlation between the results obtained with different test procedures used for detecting potential alkali reactivity of aggregates, has been attempted and merits and demerits of these are discussed in light of the petrographic features of the aggregates.

Based on the correlation between petrographic features of the aggregates and their behaviour in mortars, a new scheme for classification of aggregates into six groups has been suggested and the salient petrographic features of the reactive and non-reactive aggregates have been set out.

It is realised that the engineering properties of mortars like expansion and cracking due to alkali aggregate reactions, are intimately related to the petrographic nature of the rock and the type and degree of metamorphic deformation a rock has undergone. Curves showing mortar bar expansions have been plotted for all reactive and a few non-reactive aggregates, under different groups like granitoid rocks, charnockites, basalts, sandstones quartzites and schistose rocks and discussed in order to make a petrographic evaluation of these rocks.

Based on the results obtained during the chemical test, an attempt has been made to classify the aggregates using a standard curve.

Lastly, after a careful processing of the data obtained during the studies, a new concept based on the textural features and percentage of silicious constituents in the aggregate, for evaluating their reactivity with cement alkalies has been introduced, discussed and established.

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CHAPTER - I

INTRODUCTION

Since recent times, the problem of alkali aggregate reactions in cement concrete structures has attracted the attention of chemists, engineers and a few geologists in developed countries, particularly in the U.S.A., Great Britain, Denmark, Australia and others.

In 1940, T.E.Stanton first reported of the phenomena and stated "The chemical reaction between certain silicious constituents in the aggregate with cement alkalies, particularly sodium hydroxide, which are released from the cement during the process of hydration, gives rise to a swelling type of alkali-silica gel complex. The gel imbibes water from the concrete, increases in volume and as it is confined by the cement matrix develops pressures which ultimately result in expansion and cracking of concrete." In later years deterioration of engineering structures like dams and bridges, due to alkali aggregate reactions has been widely reported from many countries, where concrete construction activity is fairly high. Similarly a few instances of this nature due to alkali aggregate reactions have been reported from India also but the problem is not well studied.

Deterioration of concrete, as a result of chemical reaction between the alkalies in cement and mineral constituents in the aggregate, was first observed on a major scale in the Parkar dam on Colorado river. The dam was completed in 1938. After two years it was noted that "...... a few already existing cracks in the concrete mass were enlarging and numerous new cracks were observed to appear suddenly which were seen extending rapidly." (Meissner etal 1941).

From the first critical survey covering the extent and nature of the cracks and a detailed examination of the cores removed from various portions of deteriorated concrete in the dam, Meissner etal.(1941) further observed that "..... many of the air void spaces were completely or partially filled up with a mushy, clear to opaque white gel. It appeared at first that the gel was afflicted with a red zeolitic tuff aggregate and originated by base exchange with the zeolites. Later such gel deposits were also found on the surface of a red non-zeolitic rock." According to them the examination of cores revealed gel deposits associated with andesitic rocks not containing any zeolites but silicious minerals like chalcedony and opal. The concrete for the dam was manufactured with all the care and precautions considered necessary for the production of high quality material. But in spite of all these, the concrete in the Parkar dam was found to be deteriorating due to chemical reaction between high alkali cement and the reactive aggregates.

Similar cracks were also observed in the concrete of the Buck hydroelectric plant built in 1912 (Kammer and Carlson, 1941). In this case the coarse aggregates used were crushed phyllite and gneiss. According to these authors the cracks were first reported in 1922, when the phenomenon of alkali aggregate reaction was not even heard of. Later, after the collapse of the Parkar dam, the structures were examined again in 1941 and a detailed study of the deteriorated concrete revealed that there had been a chemical attack on the phyllite aggregate and a petrographic examination of the aggregate indicated the presence of microcrystalline quartz in the crushed rock.

Previous Literature

In the last 25 years, large scale research has shown that the problem is of extremely complex nature and the intricate reactions have not yet been fully investigated, studied and established.

Tremper (1941) reported deterioration due to alkali aggregate reactions and commented "Five concrete pavements in the vicinity of Spokane exhibited cracking and spalling of concrete." Nicol (1942) observed that a number of concrete pavements in California and Nebraska got unserviceable due to alkali aggregate reactions. Alderman (1944) cited a few examples from South Australia where the deterioration in concrete structures was due to the presence of opal grains in concrete mass. Mather (1951) concluded that the cracks in concrete of Tuscaloosa Lock bridge on the Warrior river in Alabama were due to alkali aggregate reaction. Brown (1955) related the cracking in a few buildings in Los Angeles Island area to alkali aggregate reactions. Idorn (1962) made extensive studies of some of the important bridge structures in Jutland, Denmark and reported severe deterioration due to alkali aggregate reactions. Oleson (1963) attributed surface deteriorations to alkali aggregate reactions in some of the bridge structures in Georgia. Recently in 1966, Ingham reported disintegration of pavement surfaces due to alkali aggregate reaction in South-Western Ontario, Canada.

Of the above authors, Alderman (1944) for the first time expressed that in addition to opal, chalcedony and chert, highly decomposed felspar should also be regarded as a mineral susceptible to alkali aggregate reactions, while Idorn (1962) from Denmark studied the problem specifically from the petrographic point of view and reported the association of flint with alkali aggregate reactions.

The mechanism by which alkali aggregate reaction causes the expansion and cracking of concrete was first reported by Hansen (1944). His hypothesis is based on the reaction of alkali hydroxides in cement with opaline silica in the aggregate. He assumed that the reaction product of alkalies and reactive aggregate exists in the form of an aqueous alkali silicate, the ions of which are incapable of diffusing through the hardened cement paste, which in turn acts as a semi-permeable membrane and confines the reaction product to its site of formation. This results in the development of osmotic pressures of considerable magnitude and thus tending a disruption of the cement paste, which ultimately leads to the development of cracks in the concrete mass. Later this hypothesis of Hansen has been supported by Mc. Connell (1947), Kalousek (1944) and Parsons and Insley (1948). However, Jones (1952) observed that osmosis ".......does play a part", but it functions in exerting pressures only to the reacting particles, which are completely engulfed in a reactive fluid and there is no escpae for the alkali silicate gel into the surrounding open pores of the mortar.

Vivian (1950) believes that opal particles, on reacting with alkalies, absorb water from the surrounding cement and the swelling that ensures in the process of gel formation produces and exerts pressures, which cause expansion and cracking of the concrete. Later, Brown (1955), Pike and Hubbard (1958) and even Idorn (1962) also confirmed this view. Moreover, Powers and Steinour (1955) believe that swelling pressures are adequate to disrupt concrete which could also be produced by gel, if it was of unlimited swelling type. They indicated that under certain conditions, swelling pressures may be similar to Osmotic pressures as discussed by Hansen (1944), while under some other conditions it may act as a directed pressure produced due to swelling of the reactive particles.

A review of the investigations to date indicates that the problem has mostly been studied from the chemical and engineering view points and the very nature of the rock aggregate and their petrographic characters either have not been considered at all or have been attended so far to a limited extent only. Thus, these studies have resulted to a broad conclusion that the rocks containing reactive minerals like opal, chalcedony, chert and volcanic glasses when used with portland or high alkali cement produce alkali aggregate reactions. To explain these ideas and the phenomena of alkali reactions, various theories, particularly the "Osmotic pressure theory", the "gel theory" have been put forward by eminent chemists like Hansen (1944) Vivian (1950) and Powers and Steinours (1955). Though these views are highly conflicting, there is a definite general agreement that the existence of a reactive mineral in the aggregate is one of the prime factors of deterioration in the concrete masses.

As a result of large scale construction in recent times in these countries and the studies on the aggregates, a good amount of data is available on aggregates and their susceptibility to alkali aggregate reactions.

On the other hand, inspite of major constructions, almost nothing is known of the vulnerability to an attack by cement alkalies of the rocks or their aggregates from various geological formations in India. The alkali contents of Indian cements vary widey between 0.40 to 1 percent (Bawa & Jagus-1958). Though the maximum content is comparatively lower than in some other countries, still it has been observed that a few of the recently constructed engineering structures seem to have failed due to alkali aggregate reactions.

Petrography and alkali aggregate reactions

Little work has been done so far on the susceptibility to alkali aggregate reactions of granites and other crystalline rock masses including gneisses, charnockites, quartzites, and even on sandstones, which are considered physically sound and are frequently used for concrete mixtures. As indicated earlier a few research workers in U.S.A. and Australia have mentioned that some granites and quartzites could also be susceptible to alkali aggregate reactions but no satisfactory explanations have been suggested so far. Whatever explanations are available, all attribute the cement alkali aggregate reactions, to the presence of glassy matter and certain unstable forms of silica (.e.g. opal, chalcedony etc.) in the volcanic rocks and the osmotic pressures which are reported to result in the formation of gels. However, Mielenz and Brown (1958) remarked that the petrographic character of a rock could also be a factor for the initiation of alkali aggregate reactions. The study of textures, the mineral constituents of the rocks and the primary or secondary features present in the individual minerals lead to conclude that the supposed less susceptible and innocuous rocks are also liable to deleterious reactions. It is also concluded that a petrographic evaluation can contribute in importat ways towards the proper selection of concrete aggregates in a country like India, where rock aggregates obtained from different stratiagraphical horizons and formations are used in engineering structures with any cement manufactured from limestone of different (stratigraphic horizons). In addition to these two factors the different types of water sometimes with variable compositions and pH. are also used for the erection of the concrete masses, which in turn are also exposed to varied and extreme climatic conditions.

From the present studies it would be seen that the cement alkali aggregate type of reactions could also be due to the minerologic and petrographic features of the rocks in which the commonly accepted susceptible forms of silica are absent. This again leads that petrography can find wider and diversified applications in concrete technology.

Earlier Works and the Problem in India

Auden (1950) while discussing the alkali aggregate reactions in Parkar dam observed ".....So far as is known, no research has been done on this problem in India, doubtless because concretes in important structures have not been subjected to swelling and cracking. Over many parts of the north, east and south India, the aggregates are probably non-reactive, but this supposition may require qualification after research has been done on concretes found on detailed enquiry to be unsound. There is, however, occasion for much research to be done on the basalts of the Deccan traps which contain chalcedonic silica in the form of agates, celadonite, palagonite, glass and zeolites."

Though not so common, small scale failures due to alkali aggregate reaction have been observed in a few concrete structures in South India particularly since the year 1961. In these cases the rocks used as aggregates are the Khondalites, Sillimanite gneiss and quartzites of the Dharwar formations. Of these, the reactions with cement have mainly been noted with the quartzites, which were later found to be highly sheared.

Deterioration of concrete structures of the A.C.C. cement works at Rohri in Pakistan was also reported in 1960 by P.J.Jagus of the Concrete Association of I ndia. In this case the aggregates used are reported to be from a cherty rock.

In light of the above a nd a major number of concrete structures already completed or under construction in the country, a systematic study of the aggregates and a comparison of the important Indian rock formations for aggregate manufacture appear to be of prime importance for future development works.

Aims and Objects

It is with these in view that the present studies have been taken up and the rocks used commonly as aggregates in engineering structures forms the subject matter of this thesis.

In India most of the concrete structures are being built in areas other than volcanic regions. In view of the same a survey of the important quarries and rock formations have been made and is reported in the following pages, along with a discussion on the effects of alkali aggregate reactions observed on these rocks. On the basis of this study (concerning mainly textural and other petrographic features of the aggregates and their mortars) certain new characteristics have been noted and an explanation mainly based on petrographic features of the rock aggregates and the resultant alkali reactions has been attempted. It would, therefore, not be out of place if it is stated at this place itself that the conclusions arrived in this thesis are only based on the petrographic observations.

India is a vast country with a variety of rock types, distinct physiographic features and climates and forms three distinct divisions namely the Peninsular Block, the Indo-gangetic plain and the Extra peninsular Region. Geologically, the peninsula is somewhat a stable land mass or shield structure and is chiefly composed of precambrian formations comprising of various igneous and sedimentry types, which have been intensely deformed and metamorphosed to various degrees. In some places these formations are overlain by younger sediments of Paleozoic and Mesozoic times, coal bearing Gondwanas, extensive sheets of volcanic lavas (Deccan traps) and minor Tertiary sediments particularly along the coasts.

The Indo Gangetic plain, stretching from west to east for nearly 2000 kilometers lies in between the Peninsular shield and the Himalayan chain. It is formed of an enormous pile of pleistocene and sub-recent to recent sediments capped by a thick alluvium.

The extra peninsular region is mainly composed of huge thickness of geosynclinal sediments, of Cambrian to Tertiary periods, which have been intricately folded, faulted and deformed during the Himalayan orogeny.

Thus the Peninsular region of India with abundant hard and durable igneous, sedimentry and metamorphic rocks e.g. granites, gneisses, quartzites, sand stones, charnockites, basalts etc. are the major sources for road and building materials and for concrete aggregates. On the other hand, there is great paucity of hard and suitable rock aggregates in a greater part of the region of the Indo-Gangetic plains and have to depend largely on the boulders and gravel deposits, from the river beds, from the Himalayan region and the other sources of available aggregates.

Mode of Studies

Samples of aggregates used commonly in the country for concrete purposes were either received through P.W.D. or have been collected from several quarries of the different states. Informations regarding their names and exact localities etc. of these quarries have been taken as such, but in a few cases the correct locations of the quarries could not be obtained and hence are not mentioned. About a hundred samples were received from the different organizations and another twenty were collected from important geological formations located near the developing centres.

Of these, seventy samples of the required physical properties have been chosen and subjected to mortar bar expansion tests and the expansions observed for a period of six months. However, comparatively greater emphasis has been laid on the study of rocks like granites, charnockites, and quartzites since these are the most common types used and are considered innocuous so far. Incidentally, almost no information or a very little data is available on the reactivity of these rocks from India.

Of the seventy samples studied for expansion tests, thiry samples are found to be moderately to highly reactive and hence are chosen for a detailed petrographic examination. Of the others, forty samples are comparatively less reactive out of which ten have been examined petrographically in detail.

Though the merits of chemical tests are generally thought to be of much less importance as compared to the mortar bar tests and the petrographic evaluations, still chemical tests ~~and-the~~ pf sixty samples have also been carried out according to A.S.T.M. standards.* Further, megascopic and microscopic etch tests on thirty samples with alkaline solutions have been carried out, but the etch tests do not appear to be of any use unless the aggregates contain opal, chert or chalcedony in abundance.

In addition, petrographic examination of mortars showing symptoms of reactivity and on those with non-reactive characters have been made on the lines of Idorn (1962).

Following Vivian (1950), tensile strengths of mortars of aggregates showing high mortar bar expansions were determined. The tensile strengths have been observed at the age of 28 days and 90 days in each case.

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* A.S.T.M. tests are followed during this study for two reasons:

i) This types of study on alkali aggregate reactions is being attempted for the first time in India and the results need a comparison with the observations made in foreign countries like U.S.A. Australia etc.

ii) There is only little difference in the experimental procedures followed in A.S.T.M. tests and Indian Standards.

Based on the laboratory studies and the observations recorded, an attempt has been made in Chapter V to classify the reactive and non-reactive aggregates from the different geological formations of India. Properties of the aggregates seem to be considerably changed due to the effects of metamorphism. Sometimes even in small areas the properties are variable in a single and more or less continuous area, as the intensity or grade of metamorphism or the local metamorphic history may affect differently the formations in their lateral extensions. This fact indicates that the selection of aggregates is an important factor.

Based on the laboratory studies and the data available in the literature, the following points are discussed under different chapters of this thesis.

Chapter II gives a brief review of the previous studies made on the deterioration of concretes due to alkali aggregate reaction both due to chemical and petrographic behaviour.

The chapter also deals with the factors for cement aggregate reaction as applicable to India regarding the range of alkali content in the Indian cements, proportions of raw materials used in cement manufacture, water for concrete mixtures and Indian climatic conditions as they differ from other countries.

Third chapter summarises the methods generally adopted for detecting potential alkali reactivity of aggregates and those adopted in the present study.

Chapter Fourth details the petography of the rocks observed susceptible to alkali reactions (under this investigation) and the microscopic features and symptoms observed in the affected mortars. Chapter V deals with the mechanical behaviour of mortars and the correlation between mortar bar tests, chemical tests, briquette tests and petrography. A classifications of aggregates based on the texture of reactive constituent has been attempted.

In chapter sixth, the nature of the reactive constituents and their bearing on chemical reactivity with cement alkalies are discussed.

In the end the chapter seventh gives the summary and conclusions on the studies reported in the above chapters.

CHAPTER - II

DELETERIOUS CHEMICAL REACTIONS IN THE CONCRETE

Apart from the nature of aggregates, the factors which are partly considered responsible for harmful alkali aggregate reactions in concrete masses are: i) Alkali content of the cement ii) Water used in construction and iii) Climatic conditions.

Concrete is a product of aggregate, cement and water. It is therefore apparent that the properties of any of the concrete masses will depend on these three essential constituents. Hence in addition to the minerals of the aggregate, there may be certain constituents in the mixing waters also which would react with the cement compounds and thereby affect the qualities of the paste and the durability of engineering structures. Of these constituents, presence of even 0.2% sulphates in the water may cause deterioration of concrete to a considerable extent. Similarly the carbonates, more than 0.5% in the waters may be responsible for a degeneration of the concrete mass by accelerating carbonation of calcium or calcium hydroxide, formed during hydration of the portland cement. The effect of chlorides is similar to sulphates and is particularly harmful in reinforced concretes.

The mechanism of the sulphate reaction has been discussed by Bogue etal (1955), who attributed these effects to two important but general causes: (i) additional products may be formed through a direct chemical combination of the constituents in the cement with ions provided by salt solutions, resulting in a large volume increase and consequent damage to concrete structures, (ii) when portland cement pastes are brought in contact with sulphate bearing waters, the later reacts with the calcium aluminate and/or the calcium hydroxide in the cement paste to form calcium sulfo-aluminate. The later phenomenon is very detrimental for the marine concrete structures.

Aggregates:- There are three possible causes that make coarse or fine aggregates chemically deleterious: it may contain soluble sulphates like gypsum and alunite, which are easily soluble in the mixing water and thus may cause damage due to sulphate reactions. Secondly, pyrite, if present in appreciable quantities in the aggregate, would react with calcium hydroxide of cement and result in the local disintegration and staining of concrete. Thirdly, certain silicious constituents in the coarse and fine aggregates may react with cement alkalies, and give rise to certain swelling type of gels which may be responsible for deterioration and cracking in the concrete masses. The phenomenon is technically termed as "Alkali aggregate reactions" and has been widely reported from many developed countries.

It is common knowledge that with the hydration of the portland cement, its alkali constituents are dissolved slowly and their complete solution is reported to occur within one to three months time, when these alkalies appear as sodium and potassium hydroxide and are then free to attack the active aggregates present in the concrete mixtures. During this process other reactions may also occur, of which the attack by alkalies in cement, on silicious minerals in the aggregate may also be caused. Cryptocrystalline or amorphous silica, such as flint, chert, chalcedony, opal, volcanic glass, palagonite, are the chief minerals which are definitely known as deleterious constituents to chemical reactivity with cement alkalies. Very little is known of the deleterious reactivity of minerals like quartz with alkalies in cement.

One principal damaging aspect of these reactions is the tendancy of the product to swell enormously and cause distress and cracking in the concrete mass. The characteristic features in most of the concrete structures, failing due to alkali aggregate reactions are a random cracking and whitish exudations observed on the surface of the masses. The rate of deterioration may be slow or fast depending on the degree of reaction.

General Theories on Alkali Aggregate Reactions

As noted earlier the phenomenon was first reported by Stanton in the year 1940 and from that time many instances of failure of pavements, buildings, dams and bridge structures have been reported from various parts of U.S.A. To name a few, deterioration of concrete structures in the Parkar dam (1941), Buck hydroelectric project and the failure of concrete pavements in Nebraska are notable. Similar deterioration of concrete in building structures, bridges etc. has also been reported from Denmark, Australia and Canada. As a result of these failures involving several million dollars, attention has been paid both by the chemists and engineers in these countries to this problem and various possible theories mainly based on chemical studies have been advanced.

Since the publication of Stanton's original findings in 1940, a number of similarly affected concrete structures were also studied in detail with regard to the source of aggregates and alkali contents of the cements used. These studies have led to the conclusion that the reactions in most cases have resulted due to the high alkali cements. As a result of these studies, the Bureau of Reclamation U.S.A., in 1940, imposed a general limit of 0.60 percent Na_2O or a total alkali content in cements to 0.50 percent, in areas where reactive aggregates are likely to be used in important concrete structures.

In 1943 studies of Hanna made it clear that a restriction of the alkali content in the cement was not a safe measure of avoiding alkali aggregate reaction, since reactions were observed occurring sometimes even with low alkali cements. However, cases were also cited where deterioration in concrete took place even after the low alkali cements, e.g. in bridge structures at Scandia and Concordia in Kansas State. Similar instances were also reported from Iowa and Missouri in Central United States. Studies by Donald Woolf(1952) also supported these observations.

Kalousek in 1944, based on chemical analyses of gels found in the voids in concretes affected by alkali aggregate reactions, demonstrated that, with an alkali concentration of 0.2 gram of Na_2O per litre the composition of the gel was; $0.003\ Na_2O;\ 2.0\ CaO : 1.0\ SiO_2\ x\ H_2O$. But when the alkali concentration was raised to 20 grams of Na_2O per litre the composition of the gel had a ratio of

$$0.25\ Na_2O : 1.0\ CaO : 1.0\ SiO_2\ x\ H_2O$$

He therefore concluded that higher molar concentration of Na_2O imparts a swelling characteristics to the gel.

Hansen (1944) in his osmotic pressure theory considered that the opaline silica in the reactive aggregate reacts with alkali hydroxides (released during the hydration of cement paste) and forms alkali silicates. Hansen assumed that the reaction product is an aqueous sodium silicate and suggested that the cement paste surrounding the particles of the reactive aggregate acts as a semi-permeable membrane through which diffussion of the alkali solutions and water in the reaction zone takes place with restricted exist of the alkali silicate i.e. the reaction product. From this it is evident that his theory is entirely based on the assumption that the reaction product is an aqueous sodium silicate and since it is confined to its site of formation, it is controlled by the fluid pressures and the effects of osmotic pressure which is sufficient to produce cracking and expansion of the concrete.

Mc Connel supported (1947) the osmosis theory of Hansen through his laboratory experiments on sodium silicate solutions and concluded that the osmotic pressures exerted by the sodium silicate solutions in concrete masses could be as high as 550 lb/sq" which would easily disrupt the concrete. The tenability of this theory was further examined by Parsons and Insley (1948), who carried out tests with opal embedded in a high alkali cement. According to them the mineral opal first swells and liquifies, due to reaction with cement alkalies and the reaction product fills the surrounding pores and forms a semi-permeable membrane of a gel which does not permit further escape of the liquid. The osmotic pressures so developed cause ultimate cracking and distress of concretes and mortars.

Vivian (1950), rejected the Osmotic pressure theory and explained the reactions with his "gel theory" and attributed the expansion of concrete to the direct swelling in the solid reactive particles, during reaction. Through his experimental studies he demonstrated that a solid sodium silicate complex with a tendancy to imbibe water (or cement paste solution) is capable of expansion and an increase in volume by about 130 percent. He further explained that as the reaction product is confined by a comparatively rigid cement paste. The tendancy of the reaction product to swell excessively, ultimately creates internal pressures within the concrete. When these pressures are of sufficient magnitude and exceed the tensile strength of the surrounding cement paste, cracking and expansion of concrete would occur. He also demonstrated that the reaction is accelerated with the rise in temperatures in concretes. The detrimental effects of this reaction in a concrete mass largely depend on a combination of factors such as (i) availability of alkali and solution, (ii) nature, size and distribution of reactive constituents and (iii) the temperature of the concrete. According to Vivian, the penetration of opal bearing rocks by calcium hydroxide in the cement matrix is much less as compared to the sodium or pottassium hydroxides due to its lower solubility in water. He further considered that the reaction of calcium hydroxide with opaline silica, would give rise to calcium silicate, a product, which possesses little power to absorb water and swell. In his opinion the formation of such a reaction product does not seem to cause or increase mortar expansion.

Later in 1952, from a study of the available data, Jones concluded that osmosis does play a part in causing disruption of concretes due to alkali aggregate reaction. However, in his opinion it functions in exerting pressure conditions only in particular cases when the reacting particle is completely enclosed and there is no escape for the alkali silicate gel into the surrounding open pores of the mortar.

Verbeck and Gramlich (1953) emphasized that the reactive silicious aggregates may give rise in concretes either to non-detrimental calcium silicates or to detrimental alkali silicates, depending on the absence or presence, respectively, of certain concentrations of alkali ions in the cement. "In their opinion, all gradations of reaction occur, producing various products and various effects. The alkali silicate may appear as solid, gel or solution but all of these have the common ability to imbibe water, increase in volume and cause expansion. In the case of the solid or gel products, this property is reflected as a swelling tendancy and in the case of the liquid solutions as osmotic pressure tendancy, but fundamentally they are similar."

Power & Steinours (1955) based on the laboratory data of several earlier workers including Kalousek, Hansen, Vivian and others, discussed the problem of alkali aggregate reactions on the principle of chemical reactivity and put forward the idea of "safe and unsafe" alkali aggregate reactions.

"Most reactive rocks are amorphous or contain amorphous constituents. The amorphous constituent may be a condensed gel or it may be vitreous. Both the gel and the vitreous states of silica are characterized by discontinuities in structure. Silicon and oxygen atoms are exposed at all surfaces, and at discontinuities. The exposed atoms do not have their chemical valencies fully satisfied within the solid. This leads to chemical absorption of water and to surface reaction with caustic alkalies by both silica gel and vitreous silica. Caustic alkali when sufficiently concentrated breaks silicon-oxygen linkages and thus extends its range of reaction. The circumstances of the attack may leave the solid still one connected mass, or the action may continue until a sol is produced, or until a solution remains. The ratio of alkali to silica in the product increases as the attack progresses. The product is an alkali silica complex."

On the basis of the direct evidence for both solid swelling pressures, and fluid osmotic pressures, they have also attempted to reconcile the conflicting views of Vivian and Hansen. They further suggest that a solid reaction product may be converted to a liquid reaction product through a continuing reaction with alkalies and by imbibition of water, and both these phenomena are capable of producing pressures. However, they conclude, that the most damaging and distressing reaction products are of the solid state.

Pike etal (1955) observed that the expansive forces responsible for alkali aggregate reaction are initiated by ion exchange between the free water and the sodium in cements, and on the other hand the reactive aggregate. As a result of this the components necessary for the formation of a hydrated sodium silicate complex in greater volume are brought about in the reacting mass. Continued swelling of the reaction product may then be caused by the osmotic action of the cement paste and due to imbibition of water in concretes.

Later in 1958, Pike and Hubbard, using the interferometric techniques concluding that the (i) calcium hydroxide in cement has an inhibiting effect on alkali aggregate reactions (ii) Opal can swell in the absence of any cement membrane due to reaction with sodium hydroxide. (iii) Aggregates are more rapidly attacked in settling cement sludge than in aqueous extracts from the same cement as the pH of the sludge is higher than that of the aqueous extracts.

"Petrographic Studies on Concrete Aggregates"

In 1940 Stanton, while discussing the famous "Bradley pavement failure" reported that the distress in the concrete pavements, north of the town of Bradley in California was due to the chemical interaction between the opaline silica of the fine aggregates and the cement alkalies.

He introduced the term "Pessimum ratio" suggesting thereby that the reaction depends on the ratio of the percentage of alkali in cement to the percentage of opal in the aggregate. If the ratio is more or less than unity expansion will not occur. However, in actual practice many difficulties cropped up and it was almost impossible to apply the technique in natural aggregates as there are many other reactive constituents of different minerological characters or of reactivity.

After the publication of Stanton's original findings a number of similarly affected failure as in Parkar dam, (1941) Buck hydroelectric plant (1941) were investigated and reported by various workers. (Meissner, Tuthill and others). Soon after the collapse of Buck hydroelectric project [illegible] Berkey (1941) for the first time thought of the problem purely from a geological angle. According to him "Concrete is essentially an artificial rock. Both in its outer and in its internal form it resembles a conglomerate." He further noted, "It's final stages of transformation from a physico-chemical system of water, cement and aggregate to a petrographic product of hardened concrete remind one of certain well known end stage changes that commonly take place in the forming of igneous rocks." To the excess alkalies he compared these as similar to the "Surplus mineralizers to minerals in natural rock", and the attack of alkalies on aggregates has been described as "A rover causing progressive disintegration by reacting destructively with the aggregate."

Meissner etal (1941) made a detailed petrographic study of the phyllite aggregates, considered responsible for the failure of Buck hydroelectric project due to alkali aggregate reactions and observed that the phyllite did not contain any opal or gel silica but contained certain amount of microcrystalline quartz. Almost simultaneously in 1941 and later in 1942 Tremper reported severe deterioration in concrete pavements and in some bridges due to alkali aggregate reactions, in the vicinity of Spokane (Washington). A Petrographic examination of the fine aggregates and the rocks revealed of an abundance of chert in fine aggregate and glass in andesites.

Parsons and Insley (1944), on the basis of alkali etch tests with strong sodium hydroxide solutions on different rocks and minerals, observed that only chert, chalcedony, opal and volcanic glass show noticeable reaction.

Laboratory studies conducted by Carlson etal (1944) indicate that many rock types are susceptible to alkali aggregate reaction. Their studies on mortar bar expansion tests revealed of deleterious expansions with certain andesites, phyllite, slate, graywacke, weathered granite and even a fresh granite. However no detailed petrographic analyses of these rocks or the microscopic features have been reported.

Later, Alderman (1946) reported alkali aggregates reactions in a few concrete structures from South Australia, with opaline rocks and remarked that decomposed felspar could also be susceptible to alkali-aggregate reactions.

In the Sierra Nevada region of Southern California many concrete structures were built using granodiorite as an aggregate. In (1946) Chadwick reported certain surface deteriorations in some of these structures. Though for over a period of twenty years efforts were made to determine the cause of this deterioration these did not leading to any clue. However, on the discovery of the phenomenon of alkali-aggregate reaction, these structures were re-examined for evidence of such a reaction and a few probable examples were noticed, though the reactive constituents could not be identified and established.

Deterioration due to alkali-aggregate reaction in some of the railroad structures, built during the period 1901 to 1929 in Indiana, Kentucky, Ohio, and Tenesse states (U.S.A.) have also been reported by Porter and Gillimore (1952). A concrete wall, 30 feet high and several hundred feet long, built in 1901 for protecting the railway embankment from erosion due to water in the stream-bed, showed excessive cracking, spalling and popouts. According to the above authors, the detailed examination indicated conclusively that the deterioration was caused by alkali aggregate reaction due to chalcedony particles in the aggregates chiefly made up of quartzite and chalcedonic limestone. Distinct reaction rims of silica gel were also observed on every particle of chalcedony. Similar incidences of reaction with chalcedonic particles were noted in other structures also, though the deterioration of concrete material varied from slight to moderate and in a few cases the concrete was found in good condition.

[illegible] Jones (1953), has reported a few instances in Great Britain where the failure of concrete structures has been attributed to alkali aggregate reaction. In Great Britain the first structure, in which the failure was later traced to alkali aggregate reaction was the King city bridge built in 1919-20 over the Salin as river. Laber another failure was also observed by him in a bridge on Santa Clara river and the suspected aggregate was found to be a cherty shale.

Alkali aggregate reaction with metamorphic quartzite has been reported by Brown (1955) in a few walls and bridge piers in the Los Angeles Island area U.S.A. In these cases also distinct reaction rims were found developed around the quartzite aggregate. Detailed petrographic examination of the rock by Mielenz (1956-57) indicated that it is made up, mostly, of the coarsely crystalline, highly strained, granulated and fractured quartz. In the absence of opal, chalcedony, glass or fine silicious gels in the rock, the deterioration had been ascribed to the reactions with this predominantly strained quartz in the aggregate.

Swenson (1958) reported deterioration due to alkali aggregate reaction in a major concrete bridge called the "Canadian Bridge" in eastern Canada. In this case, the aggregates used were the phyllite and sandstone. Here also distinct reaction rims were observed with whitish encrustations on the aggregate surface and the alkali-silica gel filled the voids.

Deterioration due to alkali aggregate reaction has been reported by Idorn (1961,62) in a number of bridge, railroad and marine structures in Denmark. Though in some of the coastal areas chemical attack by sea water has also been regarded as cause of deterioration of concrete masses. In these cases, the aggregates associated with the alkali aggregate reaction the chalcedonic flint, which at times contain opaline silica. Based on studies of thin sections, prepared from the deteriorated mortars and aggregates, he has given a useful and quick petrographic method to the study of the problem of alkali aggregate reaction and its mechanism.

Concrete distress attributable to expansive carbonate rocks in the vicinity of Kingston, Ontario, in Canada have been studied by Swenson & Gilliot (1961). They observed that the first sign of the reaction is a rapid expansion of the concrete with attendent cracking. On the basis of laboratory studies, they have shown that the poor performance of certain Kingston concretes could be due to alkali-carbonate reaction particularly where dolomitic limestones are used as aggregate. A petrographic examination of the rocks showed that they were argillaceous dolomitic limestones and did not contain any opal or chert. Almost simultaneously Hadley (1961), observed that although the great majority of dolomitic aggregates give excellent service in concretes, still certain fine grained argillaceous dolomitic aggregates may give rise to deleterious effects though they may not show any appreciable expansions in mortar bar tests or the reactivity with chemical tests. On the basis of these results he has categorized such rocks into two groups, i) Rocks in which the carbonate skeleton has sufficient strength to resist the expansive forces due to dedolomitization. ii) Reactive Rocks or the rocks with appreciable expansion i.e. in which forces are sufficiently strong to overcome the restraint imposed by carbonates of the aggregate. He explained the reaction as

$$Ca\ Mg\ (Co_3)_2 + 2\ MoH = M_2Co_3 + Mg\ (oH)_2 + CaCo_3$$

where M = Na or K.

Since the phenomenon is not explained fully, much remains to be known of the exact mechanism of these expansion in these rocks.

Very recently in 1961-62, feeble alkali aggregate reaction with quartzite has been reported from certain cement factory in South India, where the foundations of some structures built in 1937-39 got deteriorated. These were built with a low alkali cement (0.35%) and the coarse aggregate consisted of rocks like khondalite, sillimanite gneiss and quartzites, occurring close to the works. The deterioration was usually marked with cracks, corrosion of reinforcement and spalling of the concrete mass. The laboratory tests showed that the khondalite and sillimanite gneiss are innocuous while the quartzite showed expansion upto 0.068% in six months' time, indicating deleterious expansions. A petrographic examination of the quartzite pieces from concrete masses with reaction rims showed that it is rich in internally fractured, strongly undulose, strained and sheared quartz, with altered felspar and microcline as minor constituents. The chemical tests also indicated of a high silica release. The chemical analyses of water available in the area showed that it had 0.51% of chloride as Cl_2 and 0.025% of sulphates as So_3, which happens to be within the specified limits.

Failure due to alkali aggregate reaction accompanied by pattern cracking in some of the bridge structures in Georgia and Alabama built in 1947-48 have been reported by Oleson (1963). In this case the aggregate is a granite used with a high alkali cement (Alkali content varying from 0.92 to 1.02%). However, no detailed petrographic studies regarding these are available.

Roper & Erlin (1960,64) have described deterioration in some of the concrete structures in South Africa accompanied by expansion and cracking of concrete. The aggregates used include weathered dolerite and a sandstone. In these cases no indication of alkali reaction accompanied by reaction rims around the aggregate, or infillings of alkali silica gel in voids have been reported, while the deterioration has been attributed to the shrinkage characteristics of the aggregates. The petrographic examination of the sandstone further revealed that the rock used is composed of subangular quartz grains and sericitized felspars set in a matrix of finer materials of biotite, muscovite, chlorite, calcite and zeolite, while the weathered dolerite contained montmorrillonite in considerable quantities.

In 1964, a review of the problem made by the Water Ways Experiment Station, Mississippi, indicated that the petrographic features of the alkali reactive rocks and minerals need a considerable attention and concluded that the constituents of the aggregate as considered to react deleteriously with minor alkalies of the portland cement are,opal, natural glass, tridymite, cristobalite and chalcedony. It has also been remarked that the important common characteristics of all these constituents is the presence of thermodynamically metastable silica.

Ingham & Duni Kowska (1966), reported disintegration of concrete pavements due to alkali aggregate reaction in parts of Southwestern Ontario, Canada, and the disintegration has been attributed to the use of chert. A petrographic examination of the cherts indicated essentially the presence of micro to cryptocrystalli quartz and minor amounts of calcite and dolomite.

Review on raw materials in cement manufacture and their quality.

Deleterious Constituents of Cements: The term "Alkalies" as used in the cement industry refers to the oxides of sodium and potassium which may be derived from the impurities present in the limestones or clays used in the manufacture of cement. As has been noted in earlier pages the presence of these alkalies even in minor quantities is generally considered objectionable due to their tendancy to react with the aggregate and give rise to silica "gels" which may cause deterioration and disruption of the concrete mass.

Though there is no direct evidence available in the literature on the source of alkalies in cement it can safely be assumed that these may be derived from certain mineral constituents used in cement manufacture e.g. the limestones or the shales or the clays. Very recently Martin and Gibson (1966) argued that the most important source of alkalies in cement is the felspar in the limestone, which occurs as an authigenic mineral in some of the limestones. Sericite and illite also occurs as fine detrital grains in the limestones or shales and are considered as source of alkalies. In addition, coal ash which is sometimes used in cement manufacture may also contribute towards alkalies in cement. (A sample of coal ash studied by American Cement Corporation was found to contain 10% alkali. Gibson (1966). Thus it can be seen that the source of alkalies in cement may be from the raw materials or even from the fuels. Moreover, it can be stated here that these additions may be unavoidable even if the raw materials are petrologically examined and selected. Of course such a selection is not easy nor economical in the manufacture of cement. According to Lea (1955) "It is doubtful whether a commercial cement has ever been made that did not contain alkalies". Further it is common knowledge that the low kiln temperatures in the manufacture of cement may also be responsible for a high alkali content in the cement since the felspar or other alkali rich constituent remain unchanged.

The problem of alkali contents in cements is somewhat serious in most of the developed countries. In U.S.A. a number of cement factories were found to produce high alkali cements even upto 1.50%, which caused serious damage to some of the major concrete structures in U.S.A. However, deterioration due to alkali aggregate reaction has also been reported even with low alkali cements. (Hanna, 1943).

Alkali content of Indian cements

A systematic study of alkali contents of Indian cements was first made by Jagus and Bawa (1958). As a result of this study the problem of alkali aggregate reaction gathered momentum in this country. Using the "perkin elmer flame Photometer" (A.S.T.M. Standard 228-49T) analysis was conducted. The analysed 26 cement samples from 26 different cement plants. The data so obtained are very useful and give a general picture about the alkali content of Indian cements.

The following table gives an idea about the variation of alkali content in cements manufactured and used in India.

TABLE I

Alkali content percent (Na_2O equivalent)	No. of cement factories.
1. Below 0.40	8
2. 0.40 to 0.60	7
3. 0.60 to 0.80	5
4. 0.80 to 1.00	6
5. Above 1.00	nil

From the above it is clear that the minimum and maximum total alkali content in Indian cements varies between 0.15 to 0.99%. A comparison of the variations observed in the alkali contents in the Indian cements with those observed in some other countries is presented below:

India	Britain	Australia	U.S.A.	Denmark
0.15to 1.00% (Jagus and Bawa-1958)	0.20 to 1.20% (Jones-1953)	0.40 to 1.26% (Vivian-1950)	0.20 to 1.50% (Lerch-1959)	0.38 to 1.30% (Idorn-1961)

Thus it can be seen that the average alkali content in Indian cements is not as high as those from Britian, U.S.A. Australia and Denmark.

Table (2) gives an idea of the chemical composition of the limestones and clays used in some of the major cement factories in India.

On the basis of the above analyses it is observed that only when the SiO_2(silica) percentage in a limestone is less than 10%,an addition of clay is essential on an average of 0.15 ton of clay in one ton of cement. This may account for a generally lower alkali content in the Indian cements as compared to those U.S.A. where according to Martin and Gibson (1966) the limestones used for cement manufacture are highly argillaceous.

However, it is unfortunate to note that the analysis of the clay or the limestone used in cement manufacture does not report of the alkali content.

Water

It's basic function for concrete is to react with cement to form a binding paste which by penetrating into the aggregate brings them into close adhesion. The amount of water to be added to concrete has to be decided very carefully. The water cement ratio varies with the cement used. Sometimes too little a water results in dry concrete and too much water produces a weak cement paste due to excess of voids in the concrete mass.

TABLE 2

Name of Cement Factory	Raw Materials Used for Cement Manufacture						
	Limestone		Clay			Gypsum	Laterite
	Percent CaO	Percent SiO_2	SiO_2	Al_2O_3	Fe_2O_3		
1) Gwalior Cement Works Banmor, Gwalior	42.6-47.6	10-16	Only limestone is used			-	-
2) Okha Cement Works Dwarka, Kathiawar	51.6	2.8	53.0	12.0	6.6		-
3) Khalari Cement Works, Khalari(Bihar)	43.7	15.0	-	-	-.		SiO_2-5.3 Al_2O_3-39. Fe_2O_3-34.
4) Kistna Cement Works, Mangalgiri, Vijayawada	26.3-48.1	11.32	Only limestone is used.				
5) C.P.Cement Works, Kymore, Julahi,	48.8	7.7	65.0	16.2	6.6		
6) Lakheri cement Works, Lakheri, Rajasthan.	44.3	15.4	Only limestone is used.				
7) Coimbatore Cement Works, Madurai-S.Rly. Madras State.	46.7	12.8	49.3	20.3	11.7		
8) Porbandar Cement Works Porbandar (Kathiawar)	51.9	3.2	41.9	16.9	4.7		
			Sand				
			63.2	16.9	4.7		
9) Shahbad Cement Works, Shahbad,(Mysore State)	47.3	9.9	53.2	22.5	6.9		
10) Bhupendra Cement Works, Surajpur (H.P.)	51.2	6.2	70.4	10.3	4.8		

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* The above information has been made available from the Geological Survey of India, Memoir by R.S.Mehta. (Year 1951. Ref.No.46).

Quality of Water:- The potentially aggressive constituents of water with respect to concrete are the sulphates, chlorides, carbonates, bicarbonates of alkali metals (Na or K) and magnesium. Many workers like Bogue (1955), Lerch (1955), Mather (1957), Tremper (1957), workers from U.S.Bureau of Reclamation (1958), William Kenning (1966) and others agree that any of the above constituents if present in water for concrete purposes, above certain limits is harmful and may cause alkali aggregate reaction in a concrete mass.

According to Bogue and Lerch (1955) the sodium and magnesium sulphates in water react with the cement to give rise to sodium or magnesium silicate hydrates which swell and cause expansion of mortar and concrete.

Mather (1957) observed that the rate of carbonation of cement paste is accelerated due to a high percentage of carbonate and bicarbonates in mixing water.

It has generally been argued by most of the research workers that strongly alkaline sea water may cause alkali aggregate reactions by releasing sodium or pottasium ions. Chlorides in water are known to be harmful as regards their corroding effect on steel in reinforced concretes.

It has generally been observed that the water used for concrete containing more than .05% sulphates or 0.1% chlorides is likely to be harmful, and may cause the reactions as described above.

Climate as a factor for cement aggregate reactions:

It has been observed in the laboratory studies conducted by Stanton (1941) Vivian (1950) and others that high temperature accelerates the alkali aggregate reactions. There is a general agreement among most of the research workers that hot and humid conditions are favourable for the concrete deterioration.

A review of the average mean temperatures and rainfall in India and other countries, like U.S.A., Australia, Denmark and Great Britain show that the mean temperatures recorded in Indiaare about 80°F. On the other hand the mean temperatures in U.S.A., Denmark, etc. are about 55°F to 60°F.

Studies made on temperatures in concrete pavements in different parts of the country by Ghosh and Krishnamachari (1967-68) indicate that the mean surface temperatures in concrete pavements in India varies from about 120° to 130°F. as compared to 70° to 100°F. in U.S.A., Denmark and Great Britain.

This indicates that the studies on mortars for alkali aggregate reactions in India need to be made at 120°F.

CHAPTER III

EXPERIMENTAL TECHNIQUES

A review of the methods used for testing potential alkali reactivity of aggregates:

Since the discovery of the phenomenon of alkali aggregate reaction by Stanton in 1940, many attempts have been made to develop suitable rapid and reliable tests to determine potential alkali reactivity of aggregates used for concrete construction. None of these, can yet be said to be entirely satisfactory and some have shown to be unreliable. The tests generally used can be classified into two types as i)Rapid tests ii) Long duration tests.

Under the first category comes i) The petrographic examination of the aggregate, ii) The chemical test, iii) Etching test. Of these the petrographic examination is generally though to be much superior to the chemical test, as it gives the most direct approach to the determination of reactive constituents in the aggregate. On the other hand chemical test is known to have certain disadvantages, which have been described in the later pages. Etching test is also nearly a rough replica of chemical test and is not a reliable one.

i) Among the long duration tests, mortar bar expansion test is supposed to be the most reliable and is generally employed in all the laboratories for detecting potential alkali reactivity of coarse and fine aggregates.

ii) Vivian (1950), suggested that measurement of tensile strengths of mortars of graded aggregates at different periods of curing may give an idea about the alkali reactivity of an aggregate. It was thought that the reduction in tensile strengths with "age" may indicate a deleteriously reactive aggregate. But this test has not yet been standardized and has not received much attention.

iii) Scholer and Gibson (1948), suggested a test to detect the potential alkali reactivity of aggregates, which includes casting mortars of graded aggregates, subjecting these mortars to heating and cooling cycles, and measuring their linear expansions at the end of one year. But, it was found that there is no consistent relationship between the alkali content of the cement and percentage of expansion and is thus not considered as a reliable test for predicting the alkali reactivity of aggregates.

Thus the most common tests that are generally adopted for detecting the potential alkali reactivity of aggregates are 1) The petrographic examination of aggregates, II) The chemical test, III) Mortar bar expansion test.

All these three tests are described in the following pages and their advantages and disadvantages are discussed. All these three tests are adopted in the present study also. In addition the Tensile briquette tests have also been made to detect the alkali reactivity of aggregates. The deteriorated mortars have also been examined petrographically according to the procedure adopted by Idorn (1962).

Details of Methods followed during the study:

1) Mortar bar test: This includes the measurement of expansions of mortar bars made with cement and graded aggregates, kept under humid conditions at constant temperature in tightly covered containers. This was first proposed by Stanton and is now used extensively by a large number of laboratories.

Measurement of expansions of moist stored mortar bars is supposed to be the most reliable method for determining the potential alkali reactivity of the aggregates with the cement used (Plate 1 Fig.1).

Plate 1:- Photograph showing a length comparator for measuring mortar bar expansions at different periods. The right hand bottom portion of the photograph shows a standard rod, used for correct caliberation of readings.

General Procedure of test: Mortar bar specimens of size 1"x1"x10" are cast using mould of that size, with 1 part of cement and 2.25 parts of graded aggregate, using enough water to give a flow of 100 to 115 percent. Then after 24 hours of humid storage the length of bars are measured and the bars are stored in tightly covered metal containers kept at 100°F or any other temperature decided for the test at 100 percent humidity. In America the practice is 100°F as the temperature. The reaction can be accelerated by storing the bars at elevated temperatures. The condition of specimen storage is important. The specimens are not kept in water but they are kept standing on a wire gauge kept 1" above the water (Plate 2 Fig.1). Most of the laboratories follow this procedure. The lengths of the bars are observed at regular intervals. Expansion of 0.05 percent at the age of six months are considered deleterious.

In the present study, a) The coarse aggregates are crushed and sieved to the following gradation for the preparation of mortars as: follows:

TABLE 3

Passing Sieve No. and size (ASTM)	Retained on Sieve No.	Percent
1. 4(4760 microns)	8	19
2. 8(2380 microns)	16	19
3. 16(1190 microns)	30	19
4. 30(590 microns)	50	19
5. 50(297 microns)	100	19
6. 100(149 microns)	Pan	5

b) An incumbating temperature of 120°F. was maintained instead of 100°F, taking into consideration the temperatures

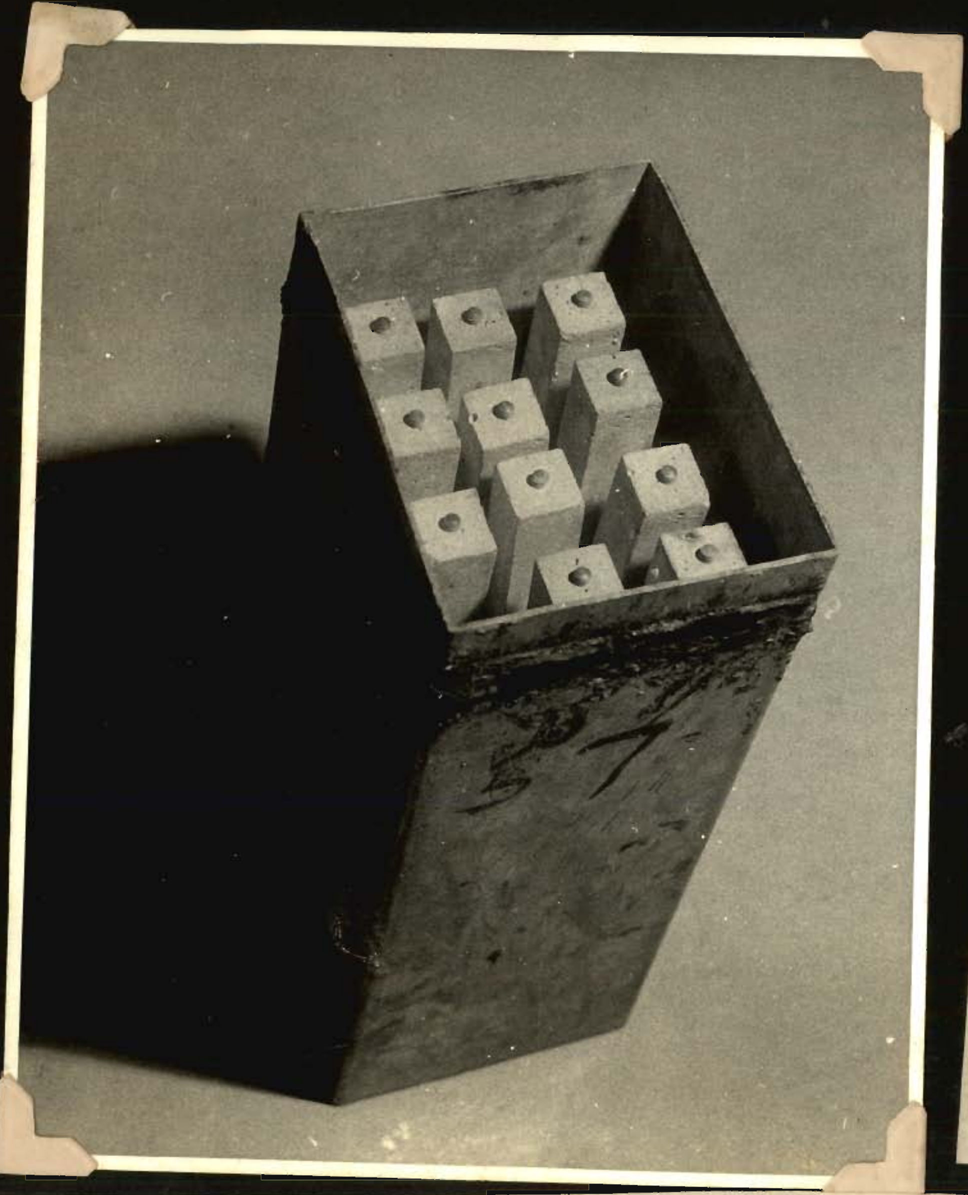

Plate 2: Photograph of a container used for storing mortar bars.
Fig.1 :

Plate 2:
Fig. 2:

Photograph showing effect of six months of humid storage on three mortar bars made with, different aggregates. Mortar bar marked no.1 is made with crushed Delhi quartzite (found innocuous during the studies). Mortar bar marked No.2 is a mortar of highly sheared quartz chlorite schist from Haliyal (Sp.1 Sch.-reactive). Mortar bar No.3 is a mortar made with a basalt with chalcedony from Khamgaon (Sp.5 T-Highly reactive). The surface of the reactive mortar show a number of whitish gel exudations while the less reactive No.1 shows presence of only a few gel exudation.

for which concrete structures are exposed in some parts of the country. The temperatures are tried keeping in view the difference of climate between other countries and India as mentioned in second chapter and also to get results about the chemical reactions at an earlier stage. c) The alkali content of the cement was increased to 1.15% by adding sodium hydroxide to have a constant alkali content in the cement.d)The minimum limit for deleterious reactivity has been fixed as 0.06 percent (6 months) instead of 0.05% as normally adopted. e) The water used for the test is the standard distilled water.

ii) Chemical tests- (ASTM C-289-57T)

25 grams of crushed aggregate sample, passing 50 ASTM mesh and retained on 100 ASTM mesh is immersed in 25 c.c. of one normal NaOH (sodium hydroxide 10% solution) kept in a stainless steel container. The container is kept for 24 hours in an over at temperature 80 ± 1°C. Then the solution is cooled and analysed for dissolved silica and reduction in alkalinity. In general if the ratio of dissolved silica (Sc) and reduction in alkalinity (Rc) expressed as millimoles per litre exceeds unity then the aggregate is taken to be reactive (i.e. if Sc/Rc ~~is~~ $>$ 1 the aggregate is reactive) according to this test. The readings are plotted on a standard graph(Fig.12).

The same procedure has been adopted in the present studies.

iii) Petrographic examination:

This is a very reliable method for identifying the presence of reactive constituents with microscopic examination of thin rock sections. A quantitative estimate of the minerals is also possible (Plate 3 Figs.1 and 2). Alkali reactivity of a sample of concrete aggregate can be determined qualitatively in two general ways by petrographic examination. By petrographic analysis the presence and frequency of potentially deleteriously reactive minerals can be established with any desired accuracy. Similarly, by petrographic examination, the aggregate can be compared in detail with other aggregates for which service records or test data are available. If the necessary background data is available, comparison of the aggregate with others having similar mineral composition material, provided, the petrographic examination and analysis of the aggregates involved, have been made carefully. Textural characteristics of the aggregate and the individual minerals in the aggregate are best studied only through detailed microscopic examination, which also reveals even minute quantity of potentially reactive substances.

The importance of petrographic examination of concrete aggregates has been well stressed by Mielenz (1955), Brown (1955), Mather (1957), Montauni (1966) and others. A review of the literature as made in the second chapter also shows that, petrographic examination of the aggregates has often helped to identify the alkali reactive constituents to explain the failures of concrete in some major concrete structures in U.S.A., Denmark, Australia and Canada. Petrographic identification of harmful constituents in an aggregate, may sometimes be useful for adoping beneficiation procedures which would make acceptable an originally unsuitable aggregate. It is also useful for the selection or rejection of concrete aggregates. But all this requires a close

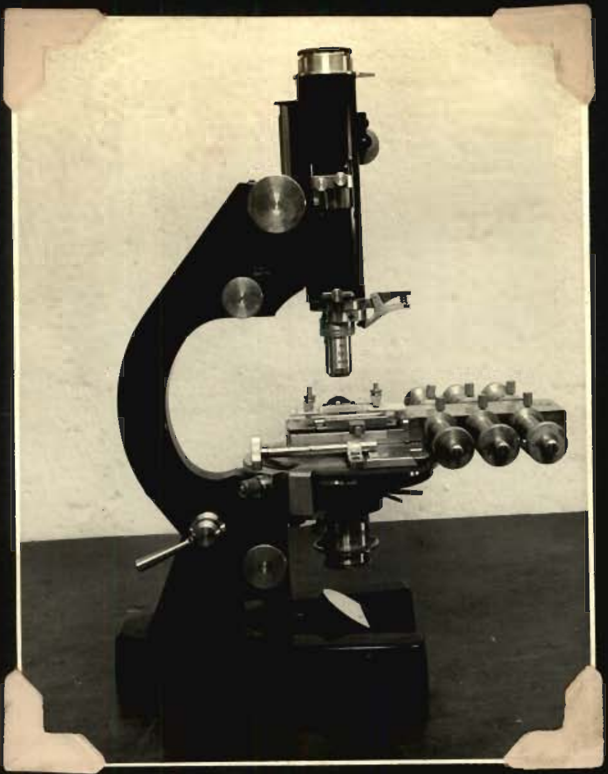

Plate 3: Leitz Research Petrological Microscope with Leitz
Fig. 1: integrating stage, used for model analysis of aggregate

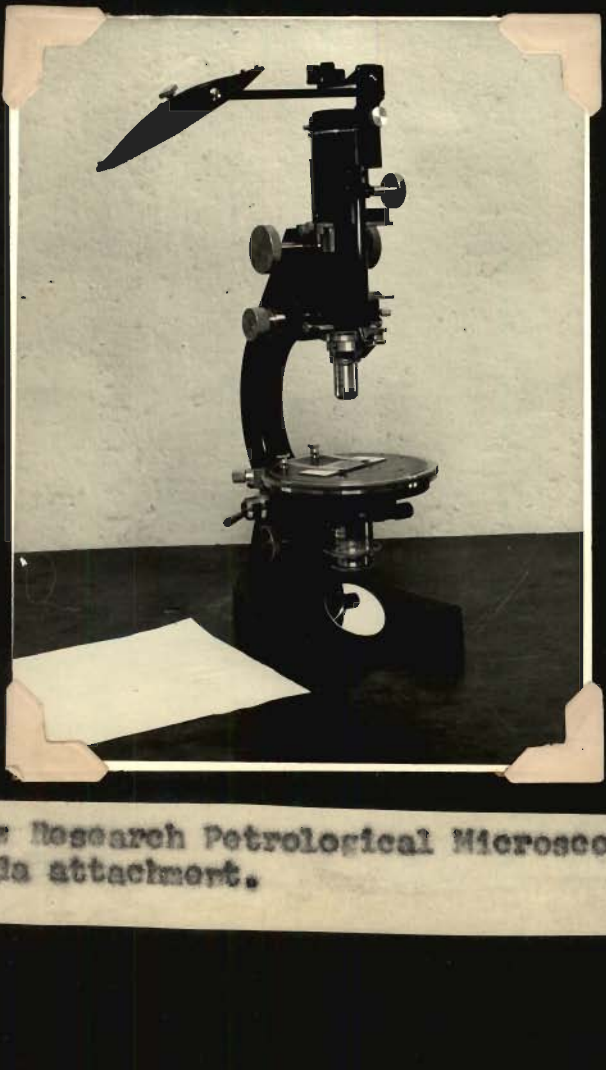

Plate 3: Leitz Research Petrological Microscope with Camera
Fig. 2: Lucida attachment.

co-operation between petrographer, concrete technologist and the engineer. In the present study, not only the general petrographic characters of aggregates given above are paid attention, but special emphasis has been laid on the textural characters of the aggregate and the individual minerals as occuring in the rock specimens. Careful attention has been paid to the strain effects observed in the silica minerals like quartz as well as in felspars and micas. Particular mention is made of the intergrowth structures like perthitic and myrmekitic ones, which are observed in the rock aggregates. Alteration of minerals and their end products have also been given proper attention. Modal composition of the aggregates were determined by the Leitz integrating stage. A quantitative study_of the angle of undulose extinction observed in the quartz grains, (which is directly related to the intensity of strain) has been made, using the procedure described ~~the~~ by Hills and Corvalan (1964).

Method of study followed for calculating the degree of undulatory extinction in quartz grain with reference to 'C' axis. (Hills and Corvalan 1964).

i) The grain is set in a position of highest birefringence.

ii) The microscope stage is then rotated until the first clear evidence of undulatory extinction is obtained. The reading on the microscope stage is recorded. This can be said as reading 'A'.

iii) The stage is further rotated until it passes through complete extinction and further, until the undulatory extinction bands disappear. The reading on the stage is recorded. This can be taken as reading 'B'. Difference of readings between A and B, on the microscope stage gives the angle of undulose extinction of the quartz with reference to 'C' axis.

iv) A number of quartz grains in the rock are thus studied for the angle of undulose extinction and the average recorded.

IV) <u>Petrographic examination of mortars</u>:

A review of experiences of concrete structures, which failed due to alkali aggregate reactions as made in the previous chapter indicates that the phenomena associated with these reactions can be studied satisfactorily by making a detailed petrographic examination of deteriorated concretes and mortars. But no systematic methods for such a study were known till Idorn from Denmark (1960-62), forwarded a sound and systematic method for petrographic examination of concretes and mortars, affected due to alkali aggregate reactions. He supplemented his observations by making an intensive study of concrete structures, which had actually failed due to alkali reactions.

The method mostly insists on symptoms observed due to alkali aggregate reactions, such as a) Pop outs on surface of mortars b) reaction rims, c) partial dissolution of the minerals associated with the reaction d) association of gel.filled voids e) internal fracturing of mineral grains.

The observations included are:-

a) Examination of un-prepared (Broken) faces of pieces of mortar.

b) Examination of polished faces.

c) Examination of thin sections prepared of slices cut out at selected positions according to previous examination.

For observations of polished faces and broken pieces of mortar or concrete, a hand lens and a biocular microscope are used and for thin section observations, a petrographic microscope is used.

The technique employed by Idorn (1961) for making thin sections of mortar or concrete is by immersing the slica of mortar or concrete in araldite, allow it to harden and then make a thin section.

The method involves generally the evidences of chemical reaction in the deteriorated concretes or mortars, and the exact identification of the reactive constituent. The following observations are to be made, which indicate alkali aggregate reactions.

1) Occurrence of pop outs on the surface of concretes and mortars and reaction rims around the aggregate particles and at the contact surfaces between cement and aggregate. It is emphasized that these rims show a dark appearance in reflected light while in transmitted light under the microscope, show a comparitively high transparency. The occurrence of such reaction rims is a very clear indication of alkali aggregate reaction. The reaction rims consist of the resultant gel product which appears as a granular, low birefringent material.

II) The reacted particles or fragments may show fractures filled up with the gel product.

III) The cement matrix surrounding the reacted particles is highly isotropic in nature, and generally shows isotropic character in most of the portion of concrete and is sometimes highly carbonated.

IV) Microfractures, emanating either from the boundary of the reacted particles or from the interior of the reacted particles or fragments, and extending into the surrounding cement matrix are observed in the heavily deteriorated mortars and concretes.

V) The aggregate itself shows corroded margins, indicating partial dissolution due to chemical reaction with the surrounding cement matrix and at times exhibits pigmented appearance.

VI) The voids in the cement matrix are generally filled or lined up with the gel.

In the present study the petrographic examination of deteriorated mortars is conducted on similar lines as Idorn (1960,62). The deteriorated portions of mortars were taken from selected portions of mortar bars used for expansion tests.

The thin sections were prepared by impregnating mortars with Canada Balsam instead of araldite as used by Idorn (1960,62). The following method is followed for preparing thin sections of affected mortars.

Sections were cut 1"x 1" around the reaction spots observed in affected mortars. The area showing the reaction spots is carefully noted. The pieces were ground on the other side of the reaction spots to have a thickness of about 4 mm. The portions of the reaction spot are well preserved. The thick sections are then boiled in Canada balsam for one hour till they are well impregnated by Canada balsam and then cooled to room temperature for 24 hours. The sections were then slightly ground with carborundum powder till the layer of boiled Canada balsam on the side of the reaction spot is removed. The section is mounted on the microslide with Canada balsam and the other side is ground in the usual way a microsection is made till the section has got a thickness of 0.03 mm.

Thus a microscopic petrographic examination of minerals associated with the reaction (i.e. reaction products) is made possible. This technique has proved very useful to know the textural characteristics of minerals actually observed associated with the reaction.

V) Tensile briquette strength test:- Briquettes were cast using crushed aggregate of the same gradation as used in mortar bars using the same cement employed for mortar bar test. The conditions of storage are similar to mortar bars (120°F and moist storage).

Tensile strengths were studied at 28 days and 90 days using the standard apparatus as employed in engineering laboratories (Plate IV Fig.1).

Merits and demerits of some of the Methods

I) Mortar bar test:- Though it is a reliable and well recognized method and is usually employed for delecting the potentially alkali reactive aggregates still it has got certain drawbacks as follows:-

a) It requires several months, or atleast six months to obtain conclusive results. However, the reaction can be accelerated using higher storage temperature. But temperatures above 130°F give unreliable results.

b) The method has not been found useful to detect alkali carbonate reactions by some research workers (Swenson, Hadley- 1961).

II) Chemical Tests: a) It is a very quick test and gives results within a week but it has been observed by Meielenz and others (1958) that some innocuous materials give high Sc/Rc values than Reactive materials. b) It has been noted by previous workers that there is many times no correlation between this test and the mortar bar test or even petrography.

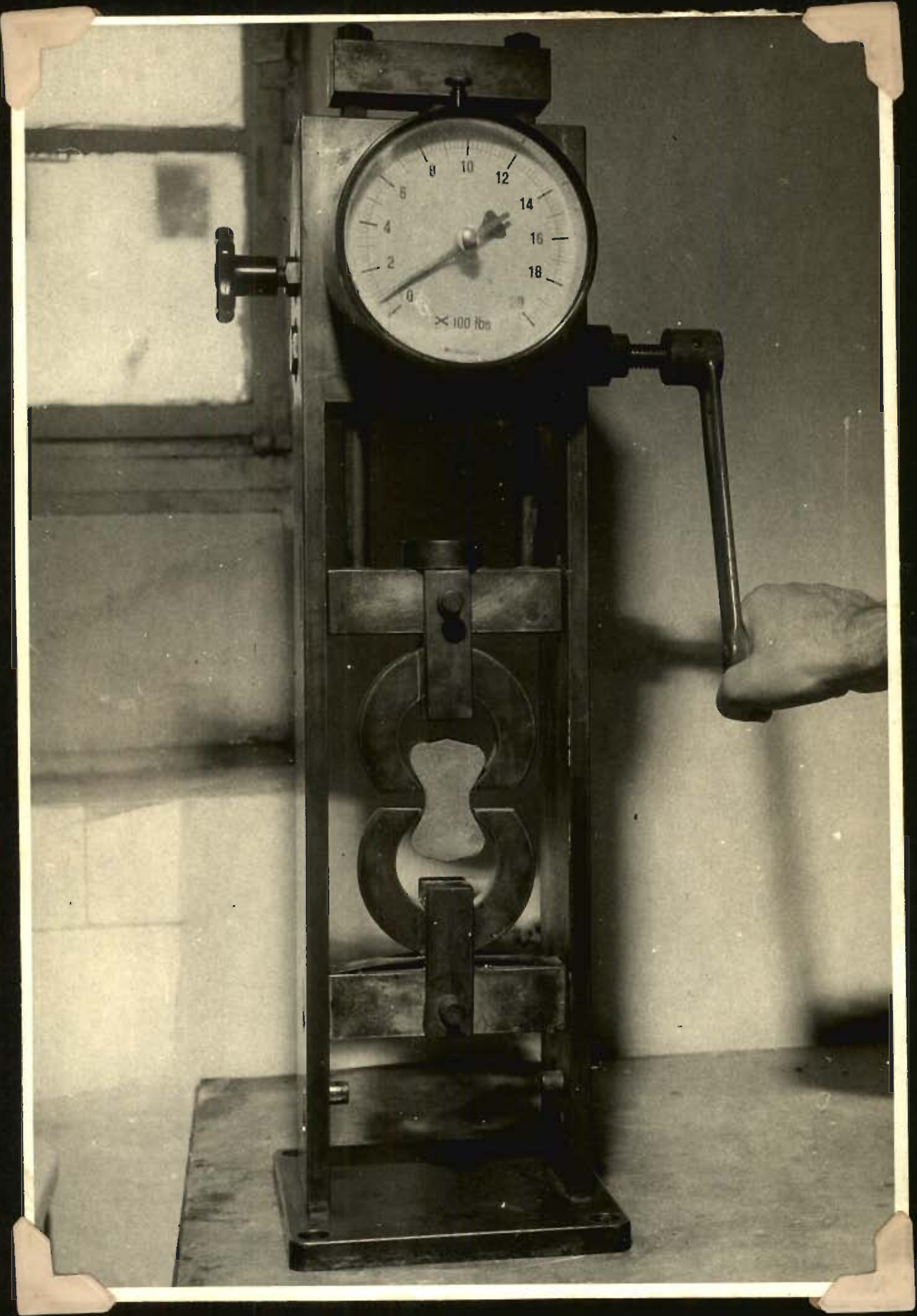

Plate 4: Photograph of tensile briquette strength apparatus. Showing the briquette of mortar held between two jaws of the machine and subjected to tension and the load at failure, which directly gives the tensile strength of the specimen in P.S.I.(per square inch).

III) Petrographic examination: It is supposed to be a very reliable method and it has got the advantage that it can give quicker results than any other method. Fairly good correlation has been observed between the results obtained by this method and mortar bar tests by most of the research workers. In case of known reactive minerals it has got an advantage that it can detect even minute quantities of reactive material and large quantities of reactive material also. But at the same time, the alkali content of the cement is equally an important factor which affects the reaction, and this can be known only after actually casting the mortar bars and conducting the mortar bar test. Thus petrographic examination should always be supported by other methods like mortar bar expansions.

CHAPTER IV

PETROGRAPHY OF COMMON INDIAN AGGREGATES AND THEIR MORTARS

In any country, aggregates for concrete constructions cover almost any rock type-Igneous, sedimentry and metamorphic, since the choice of an aggregate is limited by the rocks present in the region. The selection of an aggregate, therefore involves selection of a material of highest quality against economic considerations. At the same time, to make a general survey and to make a statement on their suitability for concrete purposes would be considered unwise, particularly due to the wide manner in which the rock formations differ, inspite of their being in the close neighbourhood of each other.

This can be achieved through a petrographic examination of the important and common rock types in the country along with their behaviour in mortars or in the concrete masses. The importance of petrography in relation to the problem of alkali aggregate reactions is well known and need not be stressed further. A review of literature clearly indicates that the petrographic microscope serves as a useful tool for studying the evidences of chemical reactions in mortars or concrete.

With this in view, an attempt has been made to collect a hundred samples of common rock aggregates used for concrete constructions in India through the State Public Works Departments and another twenty through field visits. Of these, about seventy samples, as were found suitable for concrete purposes through physical tests, (Appendix) have been further studied for alkali reactivity. For purposes of description, the samples so studied have been classified into six popularly known groups. It is interesting to note that the rocks (Table 4) used for aggregates belong almost to all the important stratiagraphical horizones of the Daccan Shield mass.

TABLE 4

Rock Type	Stratiagraphical horizon
Group I- Granites, granodiorites, gneisses, syenites	Archean and Precambrian unclassified crystallines.
Group II- Charnockites (Acid, Intermediate and Basic)	Archean and unclassified crystallines of Dharwar group
Group III- Quartzites	Dharwar and Cuddapah Formations
Group IV- Phyllites and Schists	Dharwar Formations
Group V - Sandstones	Lower and Upper Vindhyans, Cuddapah. Siwalik Formations, Tertiary formations.
Group VI- Basalts	Cretaceous to Eocene

(Two samples of limestones from Upper Vindhyan horizones have also been tested but these were found to be innocuous).

In the following pages, the petrographic characteristics of the above aggregates are given with special reference to their properties as may be responsible for the alkali aggregate reactions. This is followed by the petrographic examination of mortars made with these aggregates. The observations on the microscopic phenomena in the mortars conclusively prove that the alkali aggregate reactions, with the different aggregates, can be determined through a petrographic microscope. The texture of the reactive constituents as occur in these mortars are given particular attention. It should be mentioned here that the average minerological composition of the reacted fragments in the reactive mortars, should not be mistaken for the original composition of the aggregate, as the mortar slices have been prepared with great care and special attention. (Chapter III Experimental Techniques).

At the end the microscopic observations in the mortars, which are related to the deterioration are discussed briefly for each type of rocks.*

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* (The thin section No's. indicate the rock group and the number of the sample such as I CH = sample No.1 of charnockite group. 1 CHM = sample of mortar of the charnockite sample No.1. 'M' at the end indicates mortar of that particular sample GR= Granitoid rock; SS=Sandstone, T=Basalt or Trap rock; Ph=Phyllite; SCh=Schist, Q= Quartzite).

PETROGRAPHY OF THE AGGREGATES STUDIED

CHARNOCKITES

Charnockites are found to be very hard and durable and may be classified, as one of the best variety of rocks, for use as an aggregate for concrete. But some of the charnockites have been found to show deleterious expansions with high alkali cements in the present studies.

Most of the charnockites studied, belong to the Acid group of rocks containing a high proportion of quartz and felspars. On the basis of the preponderance of plagioclase and potash felspars, the Acid charnockites are classified into two varieties, as mentioned by Tilley (1936), Pitchmuthu (1953) and Subramaniam (1959). The acid charnockites with more plagioclase than the potash felspars are classed "enderbites", and those with predominant potash felspar as "bikermites". Since, the chemical analysis of these rocks is considered to serve no useful purpose on the problem of alkali aggregate reactions, no chemical analysis of the charnockites was carried out.

Important Petrographic Features of Charnockites Studied

The specimens of charnokites studied and reported herein, are even grained, massive, and are characterized by the occurrance of bluish grey quartz, and greenish blue felspars. Only a few specimens show the presence of reddish brown garnet, but the darker colour of the rocks definitely indicates the presence of larger amounts of mafic minerals. Most of the charnockites are fairly dense, and the specific gravity varies between 2.70 and 3.10. The highest specific gravity is indicated by the basic charnockite from Daltonganj.

Microscopic features:- The charnockites studied are generally free from alteration, and most of the mafic minerals as well as the felspars are characterized by a fresh appearance. The rocks show marked textural variations from equigranular to granoblastic, and porphyroblastic or xenomorphic types. Rocks from Madras, Acharapakkam, Dumka, (thin section 2 CH, 6 CH, 12 CH.) are even grained and equigranular, while rocks from Thirukali Kundram, Coonoor, Tholuder, and Daltonganj are varying from granulitic to granoblastic. (Thin section 3 CH, 4 CH, 11 CH.). The porphyroblastic variety from Adony area (thin section 10 CH) also display a xenomorphic texture. In some of the rocks, quartz gives a strong undulose extinction and peripheral granulation, and often corrodes the plagioclase. The plagioclase generally exhibits a patchy secondary twinning and is sometimes antiperthitic. The potash felspar is primarily microperthitic in most of the charnockites. Myrmekitic growths are also observed in a few rocks and occur along the contacts of quartz and the microperthite. Hypersthene generally occurs as subhedral grains and at times shows schillerization. Garnet is generally seen developed near the borders of quartz and rarely the hypersthene. Biotite is usually seen developed along the margins of plagioclase or sometimes garnet. Some of biotite occurs as bended plates in the interstitial spaces between quartz and the plagioclase. Magnetite and apatite occur as irregularly distributed grains throughout the rock. Magnetite also occurs as fine disseminations in quartz and felspars. Zircon and rutile occur as major inclusions in quartz and rarely plagioclase. Zircon usually occurs as minute rounded inclusions, while inclusions of rutile are generally needle shaped.

The minerals making the rocks include:

I) Quartz, Potash Felspar (Microcline Perthite, Microperthite) Plagioclase and Orthopyroxenes (generally Hypersthene) as essential constituents while the

II) Varietal include: Garnet, Clinopyroxenes (Diopside and augite) and Biotite.

Magnetite, Zircon, Rutile, and Apatite occur in minor quantities.

The microscopic features of individual minerals are described as follows:-

1) Quartz:- It is invariably present in all samples of charnockites but varies from 10 to 44 percent. It occurs generally as subhedral to anhedral grains, sometimes exhibiting substured outlines marked by the occurrence of iron oxide. The grain size generally varies from 0.8 to 2 mm. The most common inclusions are, zircon, needlelike rutile and iron ore. Liquid inclusions are rarely observed. At times, the quartz contains tiny flakes of chlorite as inclusions (thin section 10 CH).

In most of the rocks, the mineral is marked by undulose extinction due to strain effects but exceptions are not rare (thin section No. 11 CH, 12 CH). Strain effects in the quartz grains vary widely, and the angle of undulose extinction on the 'C' axis varies from 10 to 28 degrees. Some of the strained quartz exhibits fracturing and marginal granulation.

rocks as subhedral grains of varying size from 0.4 to 0.8 mm. Augite is characterised by weak pleochroism in green and well developed prismatic cleavages and its extinction angle on the prismatic cleavages varies between 35 to 38 °. Of the two (augite and Diopside) the later occurs in minor quantities, as subhedral grains of short prismatic habit and is characterised by high relief.

3) Biotite:- It occurs generally as small irregular flakes or plates. It is strongly pleochroic in brown with absorption X= pale brown; Y = brown and Z = reddish brown (X >Y and Z). Alteration to chlorite is rarely observed. Biotite generally shows straight extinction, but in charnockites from Tholudur and Adoni (thin section No. 1 CH and 10 CH), it shows wavy extinction due to strain.

Important Features of the Alkali Reactive Charnockites

1) The Garnet granulite (thin Section No. 10 CH) from the Adoni area (plate 5 Fig.1) exhibits a porphyroblastic texture, with garnet porphyroblasts in a groundmass of strained quartz and felspars. The rock contains a high proportion of strongly undulatory, fractured and granulated quartz.(Plate 5 Fig.2). Most of the quartz shows well separated zones of undulatory extinction and the angle of undulose extinction on 'C' axis varies from 20 to 27 degrees. Some of the strained quartz shows fractures in the core with a clear granulated marginal rim. Rarely the fractures are seen filled with recrystallised quartz. The granulated quartz is made up of two or more small individual quartz grains in which each part exhibits an undulose extinction and show intercrystal suturing.

2) Felspars:- The most common variety of felspar observed is oligoclase, which varies in composition from $Ab_{80}\ An_{20}$ to $Ab_{75}\ An_{25}$. Most of the grains are subhedral to anhedral, varying in size from 0.5 to 1 mm., and generally display a poorly developed albite twinning and patchy secondary extinction due to strain. Antiperthitic intergrowths are also observed in a few specimens (thin section No. 1 CH, 2CH).

The potash felspars range from microperthites to microcline perthites and microcline. Inclusions of needle like rutile and zircon are some times observed in the plagioclase as well as the potash felspar. The potash felspars are generally subhedral to anhedral varying in size from 0.6 to 1.5 mm.

3) Orthopyroxenes:- They are fairly common in the rocks studied and belong to the hypersthene variety. Hypersthene in these rocks occurs generally as subhedral grains varying in size from 0.35 to 0.8 mm and is weakly pleochroic in pink, yellow and green. Prismatic cleavage is conspicuous and the mineral mostly shows straight to slightly oblique extinction.

Varietal Minerals:

1) Garnet:- Garnet is commonly observed in most of the charnockites studied, except (thin section No. 4 CH, 11 CH). Polygonal grains of garnet, characterised by pink brown colour, high relief and irregular fractures are fairly common in the charnockites and appear to be of almandine variety. The grain size varies between 0.3 to 0.8 mm.

2)Clinopyroxenes: (Augite and Diopside): Though smaller in proportions, these generally occur in most of the

TABLE 5

MODAL COMPOSITION OF SOME REACTIVE AND INNOCUOUS CHARNOCKITES

Thin section No.	Locality	Rock type	Quartz		Potash Felspar	Plagioclase Felspars	Pyroxenes	Garnet	Any other mafic mineral.
			Strained	Unstrained					
1 CH	Tholudur(S.Arcot Distt) Madras State (H.R.)	Acid charnockite (Enderbite)	38%	2%	5%	30%	10%	10%	Biotite- 5%
2 CH	15 miles North of Madras City (R)	Acid charnockite (Enderbite)	30%	9%	4%	30%	21%	6%	-
3 CH	Coonoor-Madras State (R)	Acid charnockite (Bikermite)	40%	8%	20%	10%	15%	3%	Apatite- 2%
4 CH	Thirukalikundaram Madras State (R)	Intermediate charnockite	35%	5%	25%	20%	10%	-	Biotite- 5%
6 CH	Acharapakkam Madras State (R)	Acid Charnockite (Bikermite)	32%	7%	24%	14%	18%	5%	Negligible quantity of Biotite
8 CH	Nammakal-Madras State (INN)	Intermediate charnockite	2%	38%	15%	26%	14%	-	Biotite-5%
10CH	Adoni- (A.P.) (H.R.)	Garnet Granulite	40%	2%	18%	20%	2 %	12%	Biotite-6%
11CH	Daltonganj-Bihar (INN)	Basic charnockite	12%	-	6%	30%	35%	12%	Biotite-2% Apatite-3%

H.R. = Highly Reactive
R = Reactive
INN = Innocuous

Plate 5: Photomicrograph 80xmagnification showing porphyroblastic
Fig. 1: texture in a garnet granulite from Adoni (Sp.No.10 Ch). Coarse porphyroblast of garnet are seen enclosed in a sheared matrix of quartz. The garnet shows minute inclusions of subangular to subrounded quartz, which has imparted a sieved structure to the garnet.

Plate 5: Photomicrograph 80x mag. of the garnet granulite (Sp.10 CH)
Fig. 2: showing the straineffects in quartz, which forms a predominant constituent of the rock. Undulatory extinction and peripheral granulation is particularly prevalent in the quartz. Right hand corner of the photograph shows intense fracturing in the quartz. The fracture planes are generally seen to be filled up with laths of sericite.

Oligoclase ($Ab_{80}An_{20}$) shows patchy secondary twinning which appears to have been produced due to strain. Frayed outlines are observed in a few grains. Some of the grains are fractured and the fracture planes are filled up with brecciated and crushed quartz.

Garnet:- It occurs generally as polygonal grains varying in size from 0.6 to 2 mm. Inclusions of small grains of rounded quartz are conspicuous which impart a sieved structure to the garnet. Biotite flakes exhibit strain effects with bent cleavages and wavy extinction. Diopside occurs as a minor constituent.

2) Acid charnockite (Enderbite) (thin Section No.1 CH) from the Tholudur area exhibits a granoblastic texture and cataclastic features are observed in most of the quartz and oligoclase. The rock contains about 40 percent strongly undulose, fractured quartz and the angle of undulose extinction on 'C' axis varies from 22 to 27°. Most of the quartz is fractured with the fracture planes running parallel to the undulatory bands. Some of the strained quartz grains are broken along the borders and recrystallised into small but less strained fragments giving rise to a mortar structure (Plate 6 Fig.1).

Antiperthitic intergrowths between oligoclase and microcline is observed to a minor extent. As in the earlier types, biotite flakes show wavy extinction due to strain. Garnet, hypersthene and augite are the other important constituents.

3) Charnockite (Intermediate type)(thin Section No.4 CH) from Thrukalikundram shows an even grained granulitic texture and contains a fairly high proportion of strongly undulatory quartz. The other important minerals constituting the rock are

Plate 6: Photomicrograph 80x mag. of a highly sheared acid
Fig. 1: charnockite from Tholudur (Sp.1 Ch), showing intense fracturing and granulation of the quartz. The photograph also shows microshearing and rounding of crystal borders in some of the quartz. The upper left hand portion of the photograph shows bending of biotite flakes due to strain.

Plate 6: Photomicrograph 80xmag. of a charnockite containing a high
Fig. 2: proportion of coarse grained moderately undulose quartz. The left hand portion of the photograph shows strain effects in oligoclase also, characterised by patchy secondary extinction and bending of twin lamellae.

the oligoclase, microperthite, augite and biotite.

4) Acid charnockite (Enderbite) (thin section 2 CH) from Madras shows an even grained granulitic texture. Cataclastic features are observed only in quartz. Strain shadows are conspicuous in most of the quartz grains but the intensity of strain varies widely. A few grains exhibit strong undulose extinction and fracturing, while some of the grains exhibit weak and broad strain shadows. The angle of undulose extinction varies from 10 to 20 degrees (with reference to 'C' axis).

The other important constituents are the oligoclase, augite, garnet and antiperthite.

5) The acid charnockite (Bikermite) (thin Section No.6 CH) from Acharapakkam is an even grained rock and exhibits strain effects in quartz to a moderate scale. The angle of undulose extinction on 'C' axis varies between 15 to 20° and quartz is generally free from granulation. A few grains of quartz are fractured and the fracture planes are filled with laths of sericite. Microcline perthite forms the major felspar. Other important constituents are hypersthene, augite, and garnet (Plate 6 Fig.2).

6) The acid charnockite (Bikermite) (thin Section No.3 CH) from Coonoor is an even grained granulitic rock and contains a high proportion of strained quartz. Some of the quartz shows well separated zones of undulatory extinction, at time accompanied by fractures running parallel to the undulatory bands. The angle of undulose extinction on 'C' axis varies from 18 to 24 degrees. Some of the quartz shows marginal granulation. Microcline perthite, oligoclase, hypersthene and garnet are the other important constituents of the rock.

Innocuous Charnockites

The charnockite from Dumka (thin Section No.12 CH) is an even grained rock and contains a fairly high proportion of quartz, but the quartz is free from strain effects and exhibits uniform extinction. Other important minerals constituting the rock are oligoclase, hypersthene and augite.

The basic charnockite (thin Section No.11 CH) from Daltonganj is an even grained granulitic rock consisting essentially of hypersthene and calcic plagioclase (Ab_{40} An_{60}) and minor amounts of quartz. The plagioclase is remarkably clear and fresh. Hypersthene is characterised by schillerization and shows straight extinction. A few grains of augite associated with hypersthene are faintly pleochroic in green and show an extinction angle of 38° on prismatic cleavages.

Petrography of mortars:

In the following pages, the features observed in the mortars made up of crushed charnockite aggregates have been described. Most of the mortars, which indicated deleterious expansions in the mortar bar test, show clear symptoms of disruption. However, some of the significant observations are mentioned here.

General Features:

Megascopic characters:- The mortar is made up of gray to greenish gray coloured crushed fragments of charnockite rock embedded in a light gray coloured cement matrix. Whitish exudations are conspicuous on the plain surface of the mortar while the polished sections of mortars exhibit dark coloured rims around some of the fragments. A few of the fragments exhibit slight discolouration around the margins. The mortars also contain few voids filled up with white to light gray coloured material. Some of the aggregate pieces with rims, at times show a whitish scum on the surface.

Microscopic characters: The thin section shows fragments of charnockite rock enclosed in a partially isotropic, carbonated cement matrix. The aggregate cement ratio is roughly 2.25:1. The size of the fragments varies between 0.3 to 0.8 mm. The interstitial space filled with cement matrix rarely exceeds 0.6 mm. Some minerals such as quartz and at time oligoclase or pyroxene, occur as independent grains or fragments (due to crushing of the rock to finer sizes in the preparation of mortars) and sometimes are associated with other mineral grains. Some of the aggregate particles exhibit corroded boundaries and reaction zones. In a few specimens (thin Section No.1 CHM, 4 CHM, 10 CHM) the particles show cracks emanating from the margins into the adjoining cement matrix. The pattern of cracks differs from specimen to specimen. Microcracks in the cement matrix are also observed in a few specimens (thin Section No. 1 CHM, 4 CHM, 10 CHM, 3 CHM).

The original charnockite aggregates, which are generally medium to coarse grained, are crushed to smaller sizes in the fabrication of mortars. The mineral grains of the original charnockite rock therefore form discrete constituents, which has proved very useful in the identification of the alkali reactive constituents and in differentiating the reactive constituents of the rock from the non-reactive or less reactive constituents. The composition of the mortars varies slightly in different specimens but shows a common chronological order. The mineral fragments in the mortars, in the order of their decreasing predominance are: Strained quartz, Oligoclase (sometimes strained), Pyroxenes (Hypersthene, Augite, Diopside), and Garnet. Only a few fragments of the rock containing two to three of these minerals are observed. Biotite generally occurs associated with other minerals. The ratio of total mineral fragments to cement varies from 2.25 to 2.50:1.

1) Strained Quartz:- Individual grains of strained quartz vary in size from 0.3 to 0.5 mm. Most of the strained quartz in the mortars exhibits highly corroded boundaries, and at times is fractured along the boundaries (thin Section No.10 CHM). A few of the grains show slight pigmentation, marked by a faint reddish colour, probably indicating that some portion of the quartz has dissolved (thin Section No. 1 CHM, 10 CHM)(Plate 7 Fig.1). The chemical reaction between strained quartz and the surrounding cement matrix is further indicated by the occurrence of a thin rim of a low birefringent gel along the peripheries of most of the quartz grains. The marginal portion of the quartz is dissolved in a few cases (thin Section Nos. 1 CHM, 2 CHM, 3 CHM, 4 CHM, 10 CHM) and it shows highly irregular outlines which at times are indistinct due to the deposition of a gel like granular product along the peripheries (Plate 7 Fig.2).

At times, the gel has slightly impregnated the quartz grains also along its fractured planes (thin Section No.1 CHM, 10 CHM). The thickness of the gel layer is found to vary along the different grains. Around the coarser grains, the layer is less than 20 microns while the thickness of the gel layer is observed to be of the order of 50 microns when the size of the reactive strained quartz fragments is between 0.2 to 0.3 mm, and thus appears to be a function of grain size (thin Section No.1 CHM) (Plate 8, Fig.1). Some of the fragments of strained quartz exhibit severe dissolution and only relict patches are seen enveloped in a thick mass of gel (thin Section No.1 CHM).

Plate 7: Fig. 1: Photomicrograph 90xmag. of a mortar of charnockite (Sp.10 Chm.) showing reaction of strained quartz with the cement, characterised by zonal discolouring, marginal fracturing and pigmented borders. The lower portion of the photograph shows a grain of augite associated with strained quartz, but which shows distinct outlines and is devoid of reaction rims.

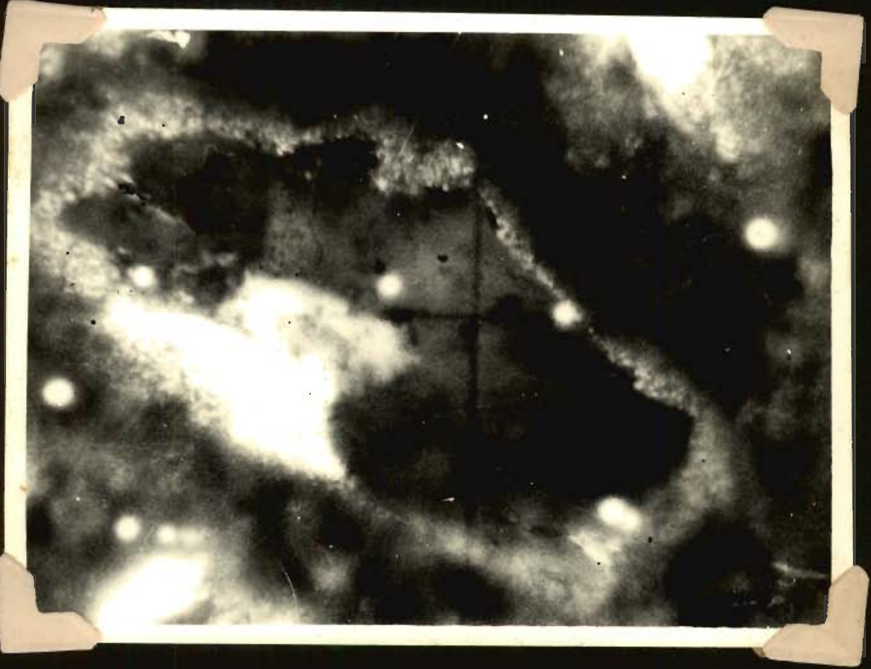


Plate 7: Fig. 2: Photomicrograph 400x Mag. showing reaction of a grain of strained quartz with the surrounding cement matrix. The boundaries of the reactive strained quartz are all corroded and show embayments all along the borders, which are filled with ax microgranular gel material indicating partial dissolution along the margins. The reaction is slightly more along the undulatory bands of quartz grains and the gel has slightly impregnated along the fractures.

Quartz fragments with feeble undulose extinction do not show any clear indication of any chemical attack by the alkalies in the surrounding cement matrix (thin Section No. 12 CHM, 8 CHM).

2) Oligoclase: (Ab_{80} An_{20}) oligoclase grains show distinct outlines and rarely exhibit any indications of chemical reaction with the cement matrix.

3) The mafic constituents of the charnockite rock e.g. the hypersthene, augite, garnet and diopside also do not exhibit any symptoms of chemical reaction when in contact with cement.

Microfractures in the mortars:- In a few specimens (thin Section No. 1 CHM, 4 CHM, 10 CHM) the mortars exhibit a few distinct cracks emanating from the margins of the reacted fragments of strained quartz. The pattern of cracks vary only slightly and can be classified into two types as follows:-

a) Link Cracks b) Chain Cracks.

a) Link Cracks: These cracks are observed to emerge from the margins (thin Section No. 1 CHM, 4 CHM, 10 CHM) of different reacted fragments of strained quartz. They are seen extending through the surrounding cement matrix and joining another reacted grain of strained quartz. The cracks are generally observed partially to totally filled up with the gel (thin Section No. 1 CHM, 4 CHM, 10 CHM), but empty cracks may also be present (thin Section 4 CHM) (Plate 8 Fig.2). The length of the cracks varies from 0.3 to 0.5 mm.

b) Chain Cracks: When a number of link cracks joint together they give a chain like pattern of cracks. Thin section (1 CHM) shows about eight reacted grains of strained quartz inter-connected in a chain like pattern. The cracks

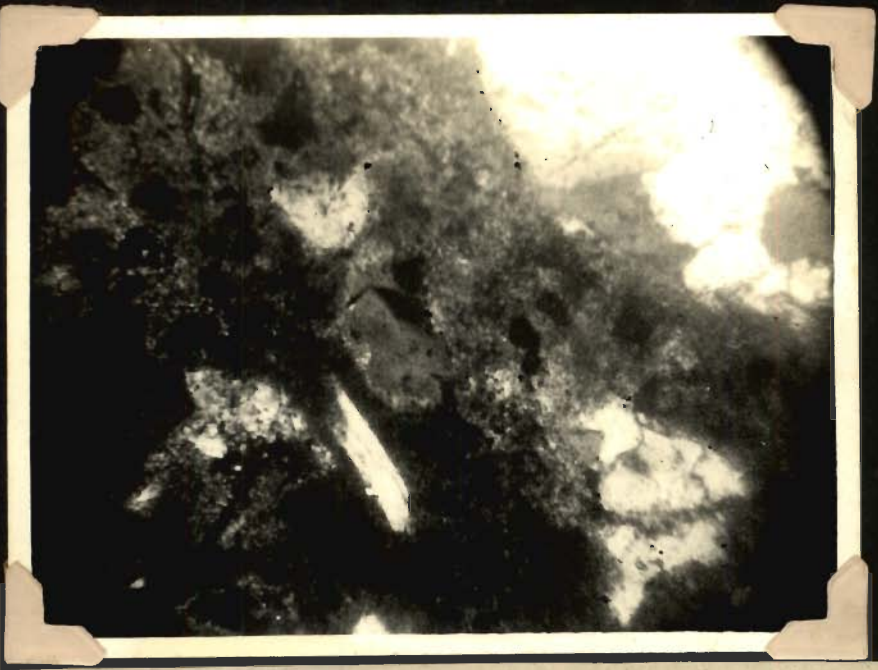


Plate 8: Photomicrograph 120x Mag. of a mortar of reactive charnockite (Sp.No. 2CH). showing deposition of a microgranular
Fig. 1: gel material along the peripheries of particles of strained quartz. The gel has thoroughly impregnated the surrounding cement matrix. The right hand corner of the photograph shows that the gel layer is comparatively thinner in case of coarser particles of reactive quartz.

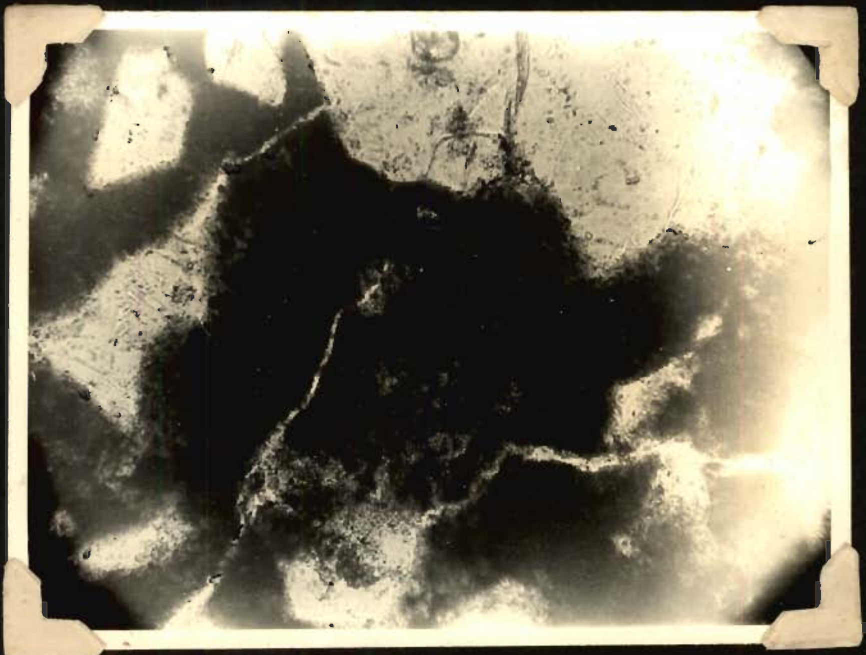


Plate 8: Photomicrograph 120xMag. (without Nicols) of a mortar o
Fig. 2: reactive charnockite (Sp.4 Ch) showing cracks emanating from the edges or margins of reactive strained quartz ar joining another fragment of reacted quarts.(Link cracks) Rim corrosion is conspicuously observed in all the reacted quartz fragments. The cracks are lined with gel material.

are generally seen starting from the margins of one particle, passing along the periphery of another particle, and then joining the third reacted particle at the margins and as on. These cracks are partly to wholly filled up with the gel. Thin sections (3 CHM, 2 CHM, 8 CHM) do not show microfracturing of the mortar.

Nature of the cement matrix:- The cement matrix is severely carbonated and microcrystalline grains of carbonate substance are frequently observed in the matrix. These are characterized by high birefringence. Sometimes the cement matrix adjacent to the reacted fragments of quartz in the mortar appears dark and opaque, probably due to the impregnation of the cement matrix by the gel. A few indistinct microcracks are observed in the cement matrix also (thin Section No.3 CHM) but these do not indicate any notable features. The cement matrix also contains a few voids varying in diameter from 0.1 to 0.2 mm, filled up with the gel (Plate 9).

Important observations:- The megascopic as well as the microscopic observations of the specimens of mortars studied are remarkable in certain respects. i) The mortar is made up of high alkali cement and crushed charnockite rock aggregate with a fair amount of strongly undulatory fractured and granulated quartz. ii) Though, Oligoclase, pyroxene, potash felspar and garnet are also present, but of all these minerals only strained quartz show chemical reaction with cement resulting in the formation of a gel; which is not only filling in the cracks or voids but sometimes seem to be penetrating and embaying the quartz grains. iii)Gel filled cracks emanating from the margins of reacted fragments of strained quartz are very often inter-connected (thin Section 1 CHM, 4 CHM, 10 CHM), indicating that the reaction has resulted in the disruption of mortar which also appears to be a combined effect of

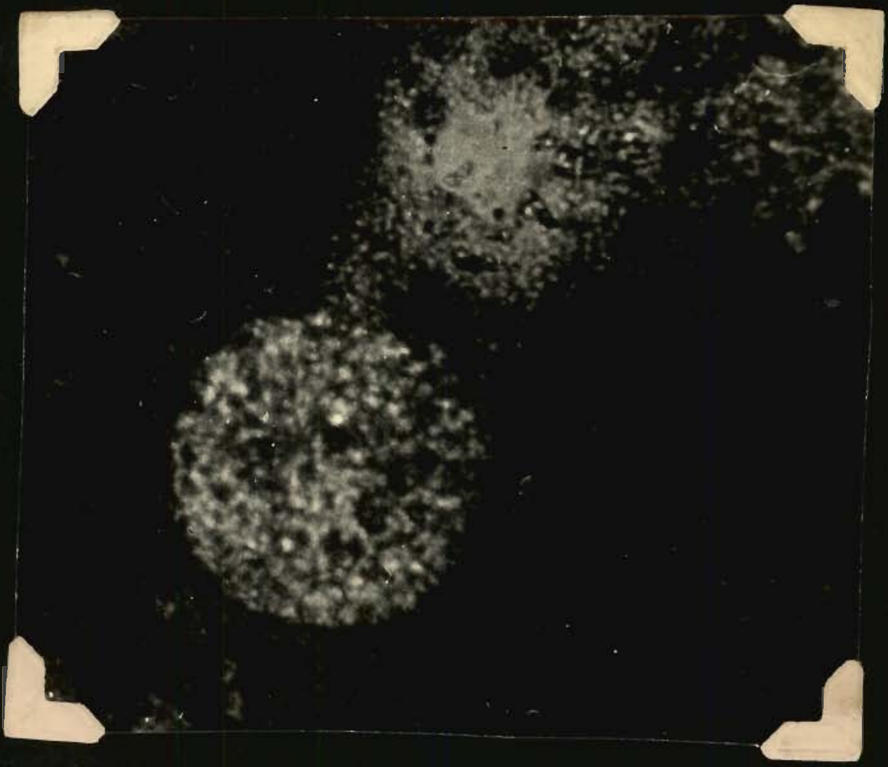


Plate 9: Photomicrograph 400xMag. of a mortar of a highly reactive charnockite (Sp.No. 1 Ch) showing a circular void filled up with alkali silica gel. Right hand top corner of the photograph shows the gel surrounding a quartz grain. The gel is microgranular in texture and is making embayments on the peripheral margins of the reacted quartz grain. The top right hand portion of the photograph shows a gel filled crack which is seen interconnecting the reacted fragment and the circular void as mentioned above, and the gel appears to have flowed through this crack to fill up the void.

the reaction of a number of strained quartz particles with the cement alkalies.

GRANITOID ROCKS

Granites, Granodiorites, Granitic Gneisses and Syenite

To make a study of the granitoid rocks from all over India will be an uphill task and is beyond the scope of the problem. But at the same time it may be added that the important features observed in the reactive granitoid rocks do not vary much, as the alkali aggregate reactions occur mostly with the silica minerals and there is no reference in the literature where the reaction has taken place with felsic, mafic or any other such constituents nor it has been observed in this study.

Like the charnockites these rocks are grouped together for the study, due mainly to the general and common petrographic features and only slight variation in textural and minerological properties. Most of the rocks studied under this group from the peninsular India belong to the Archean group of rocks. It has been observed, that, being hard, compact and massive rocks, having good resistance to attrition, abrasion, they are widely used as concrete aggregate in Andhra Pradesh, Mysore, Madras, Kerala and to a certain extent in Bihar, Orissa, M.P., U.P., Rajasthan and Gujarat.

In the following pages the petrographic features of aggregates are described in general and since the studies mainly concern with cement aggregate reaction, only the important features of reactive aggregates are brought out.

The granites and granodiorites studied are found to be generally hard, pink to grey coloured, medium to coarse grained massive rocks. They are characterised in the hand specimen by the occurrence of medium to coarse grained light grey to greyish white, quartz, flesh red to dark grey coloured felspar and dark brown coloured biotite. Most of the granitic rocks studied grade from granodiorite through adamellite to granite according to Johansen's classification.

The specific gravity of the rocks studied varies from 2160 to 2.74.

Important Petrographic Features of the Granitoid Rocks Studied

Microscopic features:

Texture: Most of the granite specimens from Cudur, Hyderabad, Mellore, Jangaon, Sullurpetta etc. exhibit an equigranular hypidiomorphic fabric, with subhedral quartz and felspar which in turn is scattered with small flakes and plates of biotite and very irregular grains of magnetite. A few of the granites (thin Section No. 9 GR, 11 GR) from Bangarpet, Tumkur show a slightly foliated texture due to sub-parrallel biotite flakes. The potash felspar in most of the granites is microcline microperthite with veins and blebs of albitic plagioclase exsolved in subhedral microcline. Myrmekite is occasionally developed along the quartz plagioclase contact. Cataclastic effects are predominantly observed in some of the granites and granodiorites (thin Section No. 2 GR, 3 GR, 8 GR, 9 GR, 14 GR, 15 GR) from West Chittor, Dhone, Kandi, Kazipet, Kawali and Bhongir. Most of the quartz in these rocks exhibits strong undulose extinction and at times corrodes the adjacent plageioclase. Some of the quartz shows fracturing and the fracture planes are at times filled up with laths of sericite. Sometimes the plagioclase also shows bend lamellae with rare sercitization in the core. A few of the granites (thin Section No. 15 GR) show slightly bent plates of biotite, sometimes enclosed between quartz and plagioclase. It may be worth mentioning here that the rocks showing cataclastic effects appeared similar to other granitic rocks in the hand specimen and showed no external indications of deformation, though the major microscopic constituents like quartz and plagioclase exhibit strain effects. Zircon and rutile are observed to occur as minor inclusions in some of the quartz. Zircon generally occurs as subrounded to rounded inclusions while rutile is needle shaped.

Minerology:

As stated earlier the rocks in this group include the granites, granodiorites, granite gneisses, and a syenite. Minerologically these contain :

Essential minerals: Quartz, potash felspars (including orthoclase, microcline, microcline perthite ~~and myrmekite~~), plagioclase (oligoclase, albite).

Varietal minerals:- Biotite, and rarely hornblende or augite.

Minor minerals: Magnetite zircon, rutile (inclusions).

The nomenclature used in these pages of the different rock types is based on the relative proportions of essential minerals and to a lesser extent those of the varietal minerals.

1) Quartz:- It is the common mineral present in all the granites, granitic gneisses and granodiorites studied, and varies from 20 to 45 percent, except in a specimen of syenite (thin Section No. 13 GR) from Kangayam, Madras State, where it is only 10%. Quartz occurs generally as subhedral to anhedral grains, and sometimes exhibits subsutured outlines marked by the occurrence of iron oxide. Generally the grain size varies from 0.6 to 1.5 mm in the medium grained rocks, while in the coarser varieties the size is from 0.8 to 2.5 mm. The nature of inclusions are variable and the common inclusions constitute the ore minerals, sometimes needle like rutile and rarely zircon. Liquid

inclusions are also observed in some quartz in a few granites (thin Section 9 GR, 11 GR). Tiny flakes of chlorite and biotite are also seen to occur as inclusions. (thin Section No. 15 GR, 14 GR). Quartz grains, as seen in thin sections in the rocks studied show a wide variety of textural features but their appearance generally confirms with the overall texture of the rocks in which they occur.

In most of the rocks studied quartz is generally free from fratures and typically shows uniform extinction but sometimes weak and broad strain shadow effects are also seen with a variation of undulose extinction. On 'C' axis betwen 4 to 10 degrees, while quartz from some of the granites and granodiorites is granulated at the margins and (thin Section No. 15 GR, 14 GR, 3 GR) shows fracturing in the core with moderate to strong undulose extinctions. The intensity of strain in quartz of these rocks vary widely and the angle of undulose extinction with reference to the microscopic axis 'C' varies from 15° to 24°. The textural features in quartz as observed in thin sections in these rocks are described in detail in their description in the proceeding pages.

2) Felspars: They form the most predominant constituent and vary between 30 to 60%. The most common variety of potash felspar is microcline which occurs as medium to coarse subhedral grains of 0.6 to 1.6 mm in size, in medium grained varieties, and from 0.8 to 3 mm in the coarse grained varieties. Minor inclusions of rounded quartz, flakes of biotite and finely divided iron oxide are sometimes observed. Most of the microcline exhibits the characteristic griddiron twinning. Perthitic intergrowth between microcline and albite are frequently observed and are of the

exsolution type. Blebs of albite are fairly common in most of the microcline perthites. Someties microcline is kaolinized along the margins and rarely in the core. Orthoclase in subhedral grains is sometimes observed generally associated with the microcline. It shows a characteristic turbid appearances due to alteration and is generally perthitic. Carlsbad twinning is sometimes observed. It's grain size in the rocks studied varies from 0.6 to 1.2 mm.

Plagioclase: Plagioclase builts hypidiomorphic, generally albite twinned crystals, many of which are sericitized and kaolinized (thin Section No. 8 GR, 9 GR) and vary in grain size from 0.6 to 1.5 mm. Sometimes the plagioclase is corroded by microcline, quartz and biotite. The larger grains in most of the rock consist of albite-oligoclase (Ab_{80} An_{20})to (Ab_{90}- An_{10}), while the smaller grains are (Ab_{75} An_{25}) in composition. Most of the plagioclase shows sericitization in the core, but generally the albitic rims are clear. Strain effects characterized by bending of twin lamellae are observed in a few specimens (thin Section 15 GR, 8 GR, 9 GR). Rarely the plagioclase occurs as minor inclusions in the coarse subhedral microcline. Vermicular myrmekitic intergrowth between albite and quartz is observed in a few granites and granodiorites.

Biotite: Biotite forming flakes and tiny plates is a common constituent in most of the rocks. It may be enclosed and/or corroded by plagioclase. Sometimes inclusions of biotite are seen with the felspar or other minerals. The percentage of biotite in the rocks studied varies from 2 to 10%. Most of the biotite is strongly pleochroic in brown to green. Alteration to chlorite is sometimes observed. Strain effects characterised by wavy extinction in the flakes are observed in a few granites with cataclastic features (thin Section No. 15GR).

Augite: Occurs as an accessory mineral only in a few granites (thin Section No. 20 GR, 17 GR) and is generally subhedral. Most of the augite shows well developed prismatic cleavage and is weakly pleochroic in green. The extinction angle on prismatic cleavages is between 35 and 38 degrees.

Hornblends: It occurs as a minor constituent in a granite (thin Section No.21 GR) from Madhya Pradesh and is strongly pleochroic in yellows. Extinction angle on prismatic cleavage is 18 to 20 degrees.

Iron ores: These include the brown to dark red oxides of iron and grains of Magnetite, and are widely distributed in the rocks studied.

Important features of alkali reactive granitoid rocks

The biotite granite (thin Sections No.14 GR) from Chittor area contains a high proportion of quartz, which is characterised by strain effects and often shows well separated zones of undulatory extinction. The angle of undulose extinction with reference to 'C' axis varies from 20 to 24 degrees. Fracturing is conspicuous in most of the grains and the fractures lie parallel to the undulatory bands. These are sometimes filled with laths of sericite. Microcline, occurs as coarse subhedral kaolinised grains, and at times is perthitic. The plagioclase (Ab_{90} An_{10}) is nearly equal in amounts as microcline and occurs as coarse subhedral grains. It is highly sericitzed and sometimes exhibits patchy secondary twinning due to strain. The rock shows development of myrmekite to a minor extent. Biotite laths occur as chief accessories.

Another sample of a highly sheared biotite granite (thin Section No.15 GR) from the Bhongir area also contains strained quartz as the major constituent, which is often highly sutured, the outlines of which are marked by the occurrence of iron oxide. Most of the quartz shows marked undulose extinction with fractures in the core and a clear granulated marginal rim. Oligoclase (Ab_{80} An_{20}) occurs as subhedra grains and shows strain effects. Some of the albite (Ab_{90} An_{10}) is fractured and fracture planes are filled up with laths of sericite. Biotite, occurs as an accessory mineral and is strongly pleochroic in brown and shows wavy extinction. The rock contains microcline perthite as another important constituent, while Biotite, augite and magnetite are the accessory minerals.

Microcline granite (thin Section No. 2GR Plate 10 Fig.1) from Kazipet contains coarse subhedral microcline as the predominant constituent, which is fairly altered and at times perthitic. Cataclastic effects are prominantly observed in subhedral to anhedral quartz, and are marked by strong undulose extinction and fracturing. The fracture planes are generally filled up with laths of sericite.

An alkali granite (thin Section No. 4GR, Plate 10 Fig.2) from the Nellore district contains Microcline perthite as the predominant constituent, while strained quartz constitutes about 25 percent of the rock. Most of the quartz exhibit weak and broad strain shadows while a few grains show strong undulose extinction and fracturing. Vermicular intergrowths between quartz and albite (myrmekite) are also observed. Biotite occurs as an accessory constituent.

A biotite granodiorite (thin Section No. 9 GR) from Kandi (Plate 11 Fig.1) contains a high proportion of coarse quartz, of

TABLE 6

MODAL COMPOSITE OF SOME OF THE REACTIVE AND INNOCUOUS GRANITOID ROCKS

Thin Section No.	Locality	Rock type	Quartz		Potash fels-pars	Plagio-clase fels-pars	Biotite	Other Mafics
			Strained	Unstrained				
2 GR	Kazipet (A.P.) (M.R.)	Microcline Granite	38%	4%	55%	-	3%	-
3 GR	Kawali Talucqua (A.P) (S.R.)	Alkali Granite	25%	5%	60%	-	[illegible]%	-
4 GR	Gudur area (A.P.) (INN)	Biotite Granite	5%	35%	45%	8%	4%	3% Augite
9 GR	Kandi (A.P.) (M.R.)	Biotite Granodiorite	35%	5%	20%	26%	10%	4% Magnetite
13 GR	Kangyam area (Madras) (INN)	Quartz Syenite	-	7%	80%	10%	3%	-
14 GR	W.Chittor area (A.P.) (H.R.)	Biotite Granite	38%	2%	35%	18%	7%	-
15 GR	Bhongir area (A.P.) (H.R.)	Biotite Granite	40%	3%	24%	22%	8%	3% Augite
19 GR	Bhiwari(Haryana) (INN)	Tonalite (Granodiorite)	2%	26%	20%	45%	3%	4% Magnetite
20 GR	Khmmam (A.P.) (INN)	Augite Granite	-	30%	40%	22%	-	8% Augite

H.R. = Highly reactive.
S.R. = Slightly Reactive.
M.R. = Moderately Reactive.
INN = Innocuous

Plate 10: Photomicrograph 80xMag. of a microcline granite from Kazipet
Fig. 1 : showing a hypidiomorphic granular texture. The central portion of the photograph shows coarse grained moderately undulose quartz occurring interstially and has slightly corroded the enclosing microcline.

Plate 10: Photomicrograph 80xMag of an alkali granite from Kavali.
Fig. 2: The granite predominantly contains microcline and parthite. The right hand corner of the photograph shows altered felspar. The left hand corner of the photograph shows the strain effects in quartz marked by undulose extinction.

which some grains are characterized by undulose extinction and fracturing. Most of the quartz exhibits well separated zones of undulatory extinction and shows granulated borders. A few grains exhibit fracturing in the core with a granulated marginal rim. Some of the quartz is entirely free from strain effects and exhibits a normal extinction. Albite ($Ab_{95}\ An_{5}$) forms about 30% of the rock and occurs as coarse subhedral grains and is highly sericitized. A few of the grains show patchy extinction due to bending of the twin lamellae.

Microcline is generally perthitic, occurs as coarse subhedral grains and is slightly altered in the core as well as along the margins. Biotite occurs as flakes varying in length from 1 to 2 mm and is strongly pleochroic in brown and at times is chloritized.

Biotite granodiorite (thin Section No. 8GR) from Dhone also shows similar microscopic features as thin section No.9 GR.

Less Reactive or innocuous aggregates of the granite clan

Biotite granite: From Gudur (thin Section No.4 GR) is a grey coloured holocrystalline granular rock characterised essentially by the presence of microcline and quartz with biotite as a minor constituent. The rock is medium grained with the grain size varying between 0.6 to 0.9 mm. Perthitic intergrowths between microcline and quartz are observed to a minor extent. Most of the quartz in the rock is characterized by uniform extinction, with a few grains exhibiting faint undulose extinction. Another sample ~~of~~ from Nellore also exhibits similar character (as thin Section No. 4 GR).

Augite granite (thin Section No. 20GR) from Khammam, contains microcline as the predominant constituent and contains about 30 percent quartz with normal extinction.

The other important constituent of the rock is albite ($Ab_{90}An_{10}$) which is also free from strain effects. Augite occurring as subhedral prismatic crystals is the only accessory mineral present in the rock. Tonalite (thin Section No. 19 GR) from Bhiwani (Haryana) is a coarse grained, grey coloured porphyritic rock with coarse subhedral grains of oligoclase ($Ab_{80}An_{20}$) and quartz embedded in a medium grained groundmass of quartz sericitized albite ($Ab_{90}An_{10}$). The phenocrysts of oligoclase vary in size from 0.9 to 2 mm., while the phenocrysts of quartz vary in size from 1 to 2.5 mm. The rock contains muscovite in minor quantities, which generally occurs as irregular flakes. All the quartz in the rock both occurring as phenocrysts and in the groundmass shows uniform extinction. The albite grains are also free from strain effects.

Quartz syenite (thin Section No.3 GR) from Kangayam (Madras State) is a coarse grained, pink coloured massive rock and exhibits a holocrystalline granular fabric. Microcline perthite, which occurs as coarse subhedral grains varying in size from 1 to 1.5 mm forms the predominant constituent. Quartz occurs interstitially as subhedral grains varying in size from 0.5 to 1 mm as a subordinate constituent. The rock contains biotite in minor quantities. Quartz which forms about 10 percent of the rock shows weak and broad strain shadows.

Petrography of mortars:

Megascopic features: The mortars are made up of pink to grey coloured crushed fragments of granitic rocks, embedded in a light grey coloured cement matrix. The aggregate cement ratio is roughly 2.25:1 and varies slightly between 2.25 to 2.50:1 and the size of the fragments varies between 0.3 to 0.8 mm. After six months of humid storage of mortars, whitish exudations are conspicuous on the plain surface of some of the mortar while the polished sections of mortar exhibit slightly dark coloured rims around some of the rock fragments, a few of which also exhibit slight discolouration around the margins. Sometimes the mortars are with few voids which are filled with a white to light grey coloured material.

Microscopic features:- In thin sections, the fragments of the rocks are enclosed in a partially isotropic carbonated matrix. Certain mineral constituents such as quartz and at times microcline occur as independent grains or fragments (due to crushing of the rock to finer sizes in the preparation of mortars) and sometimes associated with other mineral grains.

Some of the aggregate particles show corroded boundaries and reaction zones, thus indicating partial dissolution along the boundaries due to chemical reaction with the surrounding cement matrix.

1) Strained Quartz: Sometimes quartz occurs as individual grains and at times is associated with felspar and biotite.

Most of the strained quartz in the mortars exhibits corroded boundaries and at times shows marginal fracturing (thin section No. 14 GRM, 15 GRM). A few grains are slightly pgimented along the borders. The chemical reaction betwen the strained quartz and surrounding cement matrix is further indicated by the deposition of a low birefringent granular reaction product (gel) in the peripheral space between the strained quartz and the cement matrix, creating a sort of reaction rim (thin Section No. 2 GRM, 8 GRM, 9 GRM, 14 GRM, 15 GRM) (Plate 11 Fig.2). The thickness of the rim appears to be a function of particle size and varies from 20 to 40 microns. Some of the Quartz fragments, with a feeble undulose extinction exhibit distinct outlines and do not show boundary layers of the gel material.

Plate 11: Photomicrograph 80x Mag. of mortar of a reactive granite (Sp.14 GRM). The central portion of the photograph very clearly shows rim corrosion and deposition of a microgranular gel product all along the peripheries of a coarse fragment of undulatory quartz. Similar sympotoms arē also seen with other smaller grains of strained quartz in the mortar, indicating reaction with the cement matrix.

2) Felspars, which belong to the microcline, microcline perthite and albite variety are practically unaffected and exhibit clear outlines.

Microfractures are not observed in the mortars studied.

The cement matrix appears to be highly carbonated with patches of isotropic material, particularly around the reacted fragments of strained quartz. A few voids varying in size from 0.1 to 0.2 mm are lined up with the gel material.

Some Important Observations: The microscopic features observed in the deteriorated mortars are remarkable in some respects, and similar to charnockites.

1) Boundary corrosion and partial dissolution of strained quartz and the deposition of microgranular gel product along the embayed borders is observed.

2) Development of gel filled cracks emanating from the margins are rarely observed. With regard to the similarity of observations as compared to the charnockites, the mortars are made up of crushed granitic rocks with quartz of felspar as the predominant constituents. Of all these minerals only strained quartz in the mortars exhibits chemical reaction with the cement (alkalies), a feature analogues to the charnockites. But at the same time it is noticeable that in the granitic rocks the disruption due to alkali aggregate reaction is comparatively less than the charnockites. The charnockites studied, are more deformed than the granitic rocks, and the microscopic features of the mortars also indicate a comparatively intense reaction in quartz of the charnockitic rocks in which the mortar expansions are also higher. Thus it can be repeated that the microscopic features observed in the mortars give a fairly good idea of the degree of reaction and rate of expansion of mortars.

BASALTS

Basalts are commonly used as aggregates for concrete constructions in western and in parts of central India, particularly in Maharashtra, Gujarat and Madhya Pradesh. Most of the basalts are fairly hard and durable and are generally found to be innocuous unless they contain secondary minerals like chalcedony, opal or altered volcanic glass (palagonite). A petrographic examination of these rocks reveal that some samples contain glass in in minor quantity in the groundmass. Since the petrography of the Indian basalts is fairly known, only the specific features of these rocks found reactive with cement alkalies have been brought out in this study.

Important Petrographic features of the basalts studied

The basalts studied are hard, fairly dense, dark greenish grey to black coloured, fine grained massive rocks. The structure varies from porphyritic and vesicular to compact and dense. At times the vesicular cavities are filled with secondary minerals like zeolite (Sp.No. I T, 2 T), quartz or chalcedony (5T, 15 T). Sometimes the rock is traversed by thin veins of light grey coloured chalcedonic silica.

The specific gravity varies from 2.89 to 3.36.

Microscopic features: The texture is commonly prophyritic with phenocrysts of plagioclase ($Ab_{40}An_{65}$) and augite set in an aphinitic groundmass. The matrix is mainly composed of labrodorite ($Ab_{45}An_{55}$), augite, iron ore and sometimes interstitial glass. Occasionally, olivine occurs as phenocrysts (thin Section No.5T). A few of the specimens (thin Section No.12 T, 13 T, 17 T) show an intergranular texture. Plagioclase phenocrysts are twinned on the Albite, Carlsbad and pericline laws and are sometimes zoned. Of these, the plagioclase forming the groundmass is generally twinned on the albite or the carlsbad laws, while the independent phenocrysts are twinned on pericline types. Pyroxene inclusions are at times observed in the plagioclase phenocrysts and sometimes produce the typical ophitic texture with augite constituting about 40 to 45 percent of the rock mass. Augite sometimes occurs as microphenocrysts but is generally confined to the groundmass.

Iron ore occurs as irregular elongated grains, and as inclusions in the pyroxene, plagioclase and in the glass.

Primary glass forming 5 to 15% of the rock, is mainly interstitial. Palagonite is observed (thin section 3 T) as an ateration product of the primary glass and varies in colour from pale to dark brown. Fibrous texture is conspicuous. Chalcedony is seen to occur as a secondary mineral (thin Section No. 5 T, 15T) filling up the vesicular cavities and as veinlets traversing the rock.

Important features observed in the reactive basalts

1) The olivine basalt (thin Section No. 5T) from the Khamgaon area is prophyritic. Olivine occurs as a major phenocryst, as coarse polygonal grains varying in size from 0.5 to 1.5 mm and is characterized by marked alteration to iddingsite, which has given a rimmed and criscrossed appearance to the mineral Labrodorite $(Ab_{40}An_{65})$ occuring as phenocrysts is subhedral to anhedral, exhibits highly corroded outlines marked by the occurrence of iron oxide and varies in grain size from 0.5 to 1 mm. Augite phenocrysts of 0.5 to 0.8 mm size are weakly pleochroic in green and occur as subhedral grains. The groundmass is composed of microlites of labroadorite felspar $(Ab_{50}An_{55})$ and pyroxene and grains of magnetite. Interstitial primary glass is observed in minor quantities. Chalcedony occurs as amygdular fillings (Plate 12 Fig.1) and as veins. It exhibits the typical fibrous extinction and at times contains

TABLE 7

MODAL COMPOSITION OF SOME OF THE REACTIVE AND INNOCUOUS BASALTS

Thin Section No.	Locality	Rock type	Plagioclase felspars	Pyroxenes	Olivine	Other Mafic Constituents	Interstitial glass	Secondary Minerals chalcedony or palagonite
3T	Bhuj area (Gujarat) (M.R.)	Porphyritic Basalt	40%	38%	4%	3%	8%	7% palagonite
5T	Khamgaon area (Maharashtra) (R)	Porphyritic Olivine Basalt	Labradorite 40%	28%	12%	5%	6%	9% Chalcedony
10 T	Naldurg (Maharashtra) (INN)	Basalt.	44%	40%	-	11%	5%	-
15 T	Gondal (Gujarat) (R)	Porphyritic Basalt	43%	42%	-	3%	4%	8% Chalcedony

Plate 12: Photomicrograph 80xMag. of a reactive basalt from Khamgaon
Fig. 1 : (Sp. 5 T) showing a large grain of chalcedony filling up the amgdule in the basalt. Radiating fibrous structure is conspicuously observed in the chalcedony. The right hand corner of the photograph shows minute inclusions of tridymite occurring as clusters in chalcedony, which also contains minute inclusions of pyroxene.

Plate 12: Photomicrograph 80xMag. of a glassy basalt. The central
Fig. 2: portion of the photograph shows palagonite, exhibiting a fibrous structure and occurring interstitially in a subophitic groundmass with augite partly enclosing the plagioclase grains and partly interstitial between them.

inclusions of tridymite which occur as minute polygonal grains, isotropic in nature. Minute inclusions of granular augite and iron ore are also observed.

2) Microscopic features observed in basalt (thin Section No.15T) are similar to (thin Section No.5T) except that the phenocrysts are mostly labrodorites ($Ab_{50}An_{55}$) and augite. Chalcedony is seen generally occurring as veilets and is sometimes associated with traces of opaline silica. Primary glass also occurs interstitially in the groundmass in minor quantities.

3) The basalt from Bhuj (thin Section No.3T) is fairly similar to the above described specimens except that a few microphenocrysts of olivine are observed in the groundmass. The glass occurring in the groundmass is devitrified at places, and patches of light brown coloured, low birefringent, fibrous, vesicular, palagonite glass are conspicuously observed (Plate 12 Fig.2). However, the rock does not contain any chalcedony or opal.

Petrography of mortars

Megascopic characters: The mortars are made up of dark greenish grey coloured fragments of basaltic rock, embedded in a light grey coloured cement matrix. Whitish porcellaneous exudations are conspicuously observed on the surface of the mortar after six months of humid storage. A few of the fragments exhibit dark coloured reaction rims and whitish scum on the surface. The ratio of aggregate to cement is about 2.25:1. The mortars contain a few voids filled up with a light grey coloured material.

Microscopic characters: In thin section the fragments of basalt are found embedded in an isotropic but slightly carbonated cement matrix. The size of the fragments varies from 0.4 to 0.6 mm and the interspaces are filled with cement matrix which rarely exceeds 0.4 mm. Most of the aggregate fragments show slight to moderately corroded boundaries and reaction zones and sometimes are with cracks emanating from the boundaries of the aggregate particles (thin Section No. 5 TM,15 TM,3 TM).

Sometimes these cracks are linked together, while at times these are seen either passing along the peripheries of another fragment or traversing the adjacent aggregate particles.

As the fragments are made of basaltic rock, the minerological composition of the aggregate particles is fairly similar to the parent rock except that the percentage of interstitial glass in the groundmass and the amount of secondary minerals vary. Chalcedony occurs at the margins or edges of the basalt fragments or sometimes as individual grains. The minerals constituting these fragments in the decreasing order are labrodorite, pyroxenes (augite and other clinopyroxenes), magnetite, olivine, interstitial glass and chalcedony. Devitrified palagonite glass is also observed (thin Section No.3TM). Most of the aggregate fragments with interstitial glass show slight fracturing and corroded boundaries indicating chemical attack by the surrounding cement matrix, which may be having alkali in excess (thin Section No. 5 TM,15TM, 3 TM). Some of the basalt fragments indicate preferential dissolution of the interstitial glassy material (thin Section No.3TM).

Chalcedony is sometimes found to occur along the edges or margins of the basalt fragments or as individual grains and is deeply corroded. It is seen partially to totally altered to low birefringent gel, and at times occurs as relict grains enclosed in a mass of gel.

It is observed that though most of the basalt fragments show slight to moderate boundary corrosion, still they do no exhibit distinct gel rims. However, the intense opaque character of the cement matrix around these fragments suggests impregnation of

Augite and labrodorite are rarely seen to occur as individual mineral grains. These show distinct outlines and do not exhibit any gel rim, or boundary corrosion and appear to be absolutely unaffected by the cement alkalies.

Microfractures in the mortars: The mortars exhibit distinct cracks emanating from the margins of the reacted basalt aggregate fragments and heavily reacted particles of chalcedony. The nature of disruption varies slightly in the specimens studied. Usually, the cracks are partly to wholly filled up with the gel product and vary in length from 0.5 to 0.8mm. The nature of the cracks may be as (a) link cracks (b) radial cracks.

a)Link cracks: The cracks are seen emanating from the margins of the coarse reacted fragments of basalt. The cracks are further seen extending through the surrounding cement matrix which is isotropic in nature, and then joining another reacted fragment of basalt. Sometimes the cracks are seen passing along the periphery of a reacted basalt fragment (thin Section No. 5 TM, 15 TM) (Plate 13 Fig.1).

b) Sometimes two or three cracks are seen emanating from the particle or veins of chalcedony and give a radial pattern. Sometimes these emanate from a heavily reacted particle of chalcedony and are seen to extend through the surrounding cement matrix in different directions. The cracks are generally observed to form a link with another reacted fragment of basalt or chalcedony (thin Section No.5 TM) (Camera Lucida Skietch No.2). The cracks probably indicate that the reactive particle has swelled due to the formation of swelling type of gel along the borders.

Nature of Cement Matrix: The cement matrix in general exhibits an isotropic nature and is slightly carbonated at places,

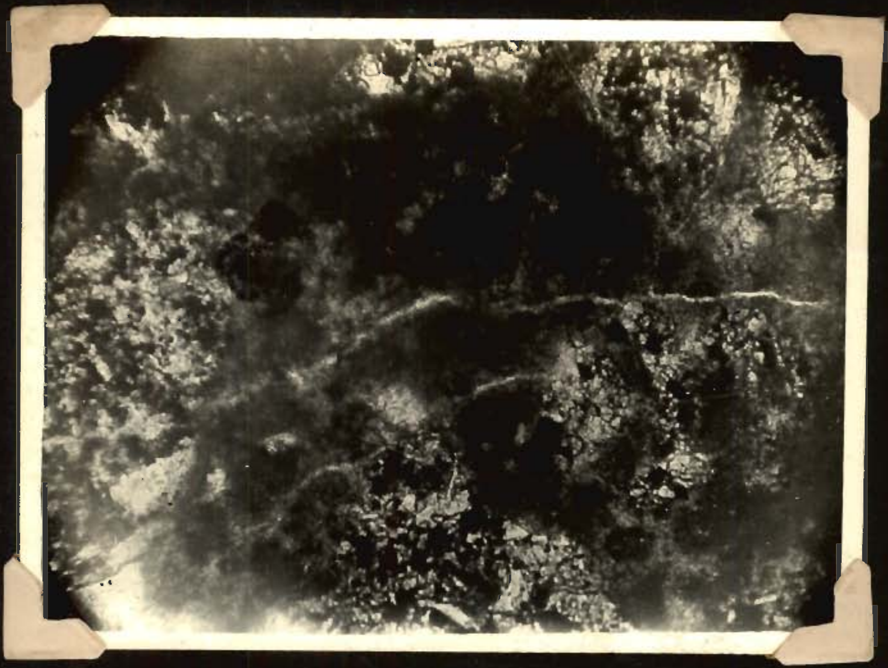


Plate 13: Fig. 1: The photomicrgraph (120xMag.) of a mortar of reactive basalt (Sp. 5 T M) showing two cracks emanating from reacted basalt fragments and running nearly parallel to each other. The cracks are seen passing along the peripheries of adjacent reacted basalt fragments and at times traversing the heavily reacted and weakened basalt fragments. Though no distinct gel rims are observed around these basalt particles, the occurrence of cracks and the intense opaque character of the cement matrix indicates reaction and the consequent swelling of the reacted fragments.

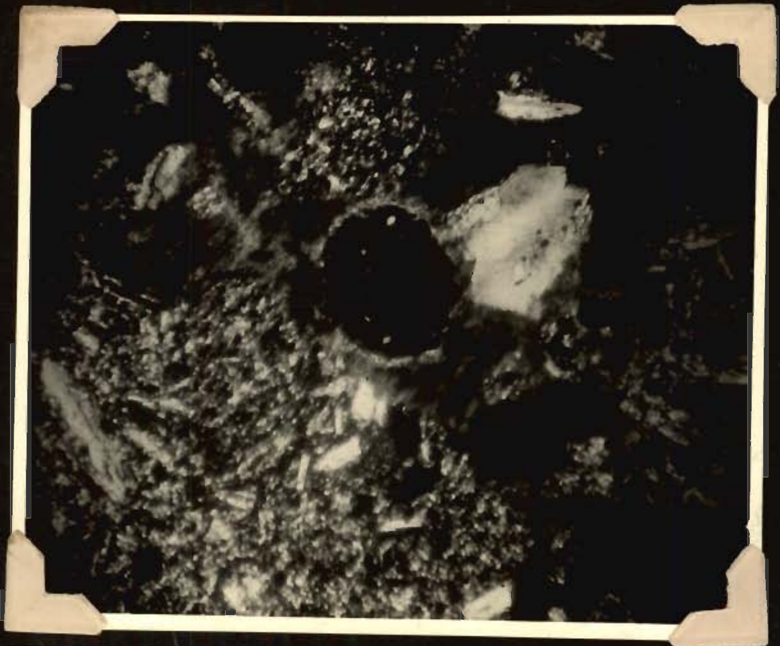


Plate 13: Fig. 2: Photomicrograph (80xMag.) of a mortar of reactive basalt from Bhuj (Sp. 15 TM). The central portion of the photograph shows a circular void in the mortar. Deposition of a microgranular gel material along the boundaries of the void is distinctly observed.

Which is characterised by the highly birefringent carbonate patchy substance. Few voids are observed varying in diameter from 0.2 to 0.4 mm and are usually lined with the gel (Plate 13 Fig.2).

Important observations: The megascopic as well as the microscopic observations in the mortars studied, are striking in some respects. The mortars are made up of high alkali cement and basalt fragments containing interstitial glass and chalcedony as secondary mineral. Most of these basalt fragments exhibit distinct symptoms of reaction with the cement matrix. The occurrence of distinct, long, gel filled cracks, emanating from the margins of the reacted fragments of basalt, indicate disruption of the mortar due to the swelling of the reacted fragments. Especially the occurrence of peripheral cracks along some of the fragments indicates shrinkage of the fragments after the reaction. The occurrence and nature of gel filled cracks emanating from the particles thus throw a good light on the mechanism of reaction. It appears that the disruption of the mortar is a result of swelling of the reacted fragments of basalt. Occurrence of a number of cracks emanating from particles of chalcedony, which is seen altered to a gel product, also indicate the swelling nature of the gel and confirm the observations made by Vivian (1950), Brown (1955) and others, that the disruption of mortar due to alkali aggregate reactions is a sequence of swelling of the reacted fragments. The observations of mortars made during the study are also of similar nature.

SANDSTONES

Sandstone, if hard and durable are also commonly used as building stores as well as concrete aggregates. Such sandstones are found to occur in most of the older geological formations in India and are widely used for concrete constructions. The sandstones studied here belong to the Vindhyans, (upper and lower Vindhyans) Cuddapah, Tertiary and Siwalik formations. In the following pages the sandstone aggregates studied, are described in general and their important features specially regarding the cementing matrix and at times the detrital minerals, of the alkali reactive sandstones have been brought out, as well as those of innocuous characters also have been dealt with.

Important Petrographic features of the Sandstones Studied

The sandstones studied are found to be generally hard, compact, fine to medium grained rocks. The colour of these sandstones varies from pink, grey, dark grey to buff and most of the rocks are characterised in the hand specimen by the predominance of fine to medium grained quartz, sometimes coated with a thin film of iron oxide.

The specific gravity of these sandstones varies from 2.55 to 2.85.

Microscopic features:

Texture: Most of the sandstones exhibit a moderate to excellently sorted, well cemented, granular fabric except (thin Section No.1 SS and 7 SS) which are poorly sorted. The average grain size of quartz in sandstones varies from 0.4 to 1.2 mm.

Minerology: Subangular to subrounded quartz is the predominant constituent and the percentage of quartz varies from 50 to 85%. The cementing matrix is either silicious, clayey or of ferruginous material. The detrital mineral grains observed are the chert, sericite, microcline, tourmaline, chlorite and albite

Important features of the alkali reactive sandstones

(1) Quartzose Sandstone (thin Section No.6 SS) from Chinthala Kurnool formations lower Vindhyan (A.P.) (Plate 14 Fig.1) is a moderately sorted, well cemented rock and contains subangular to subrounded quartz varying in grain size from 0.5 to 1.2 mm as the predominant constituent. Some of the quartz shows a faint undulose extinction. The rock contains about 20 percent chert which also forms the binding matrix. Chert occurs interstitially set in a radiate fashion around the subangular to subrounded quartz grains. Tiny inclusions of flaky chlorite are common in the chert and have imparted a light green colour to the cementing matrix. Chlorite also occurs individual flakes or is associated with the binding matrix. Subhedral to anhedral magnetite is irregularly distributed throughout the rock.

(2) Sandstone (thin Section No.9SS) from Palanpur, Rajasthan (Tertiary formation) (Plate 14 Fig.2) is a moderately sorted, well cemented rock and consists of subangular to subrounded quartz, varying in size from 0.8 to 1 mm., enveloped in a ferruginous clayey matrix composed of highly decomposed and kaolinzed felspar, sericite, chlorite and iron ore. Subrounded to rounded grains of detrital chert (micro to cryptocrystalline quartz) are also observed associated with the cementing matrix and form 8% of the rockmass.

(3) Quartzose Sandstone (thin Section No. 4 SS) from Durg Distt. (M.P.) is an equigranular, moderately sorted, well cemented rock and contains subrounded quartz varying in size from 0.8 to 1.2 mm, cemented by authigenic quartz intergrowths which is characterized by the stippled borders marked by the occurrence of iron oxide around most of the grains.

Some of the individual quartz grains, show a faint undulose

Plate 14: Photomicrograph (120xMag.) of a quartzose sandstone from
Fig. 1: Chinthala (Sp.No. 6 SS) showing subangular to subrounded medium grained quartz firmly cemented by a silicious cherty matrix. Chert is generally seen occurring interstitially between the quartz grains set in a radiate fashion. Right hand corner of the photograph shows slight undulose extinction as observed in a few quartz grains.

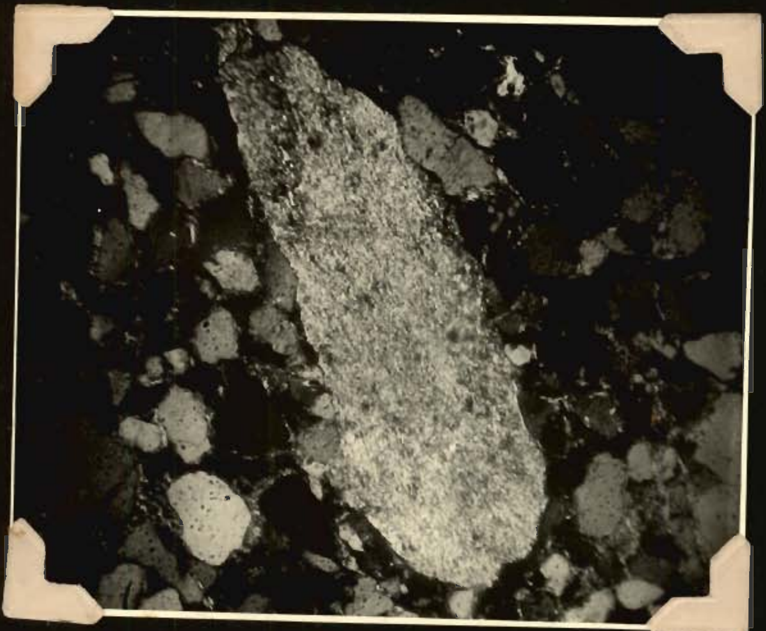


Plate 14: Photomicrograph (80xMag.) of a lithic sandstone from
Fig. 2: Kundaghat (1 SS) showing a poorly sorted fabric. The photograph shows a large phyllite fragment, lenticular in shape and subangular to subrounded medium grained quartz, enclosed in an argillaceous matrix composed of fine shreds of sericite, chlorite and iron ore.

constitutes about 10 of the rock and microcline grains subrounded in shape and 0.2mm in size constituting about 2%, are seen occurring intergstitially, filling up the pore spaces in between some of the quartz grains.

(4) Quartzose Sandstone (thin Section No. 3 SS) from Durg Distt (M.P.) is a moderately sorted, well interlocked rock and contains subangular to subrounded grains of quartz varying in size from 0.8 to 1.5 mm. The grains show well marked boundaries coated with iron oxide. Some of the quartz also show strong undulose extinction. Detrital subrounded chert grains of varying size from 0.8 to 1 mm constitute about 15% of the rock. Chlorite and sericitized albite are also seen occurring as deterital constituents.

(5) Lithic Sandstone (thin Section No. 1 SS Plate 15 Fig.1) from Kundaghat (H.P.) belonging to Siwalik series is a poorly sorted but fairly well cemented rock. Subangular to subrounded grains of quartz constitute only 50% of the rock, while the fragments of sericite phyllite constitute 20% and detrital chert constitutes 10% of the rock. These, along with minor tourmaline are embedded in a ferruginous clayey matrix, which is made up of fine shreds of sericite, chlorite and kaolinitic clay. Quartz grains vary in size from 0.2 to 0.6 mm and some of these exhibit faint undulose extinction. Lenticular fragments of sericite phyllite varying in length from 0.4 to 0.6mm exhibit slight foliation and consist of fine shreds of sericite and a few tiny flakes of kaolinite and chlorite admixed with fine quartz. Detrital chert is highly ferruginous in nature and occurs as subrounded grains varying in size from 0.4 to 0.6 mm. The detrital tourmaline is strongly pleochroic in brown and varies in size from 0.2 to 0.3 mm.

6) Siwalik Sandstone (thin Section No. 7SS) from Kalka (H.P.) is a highly argillaceous, poorly sorted sandstone and consists of subangular to rounded quartz grains, varying in size from 0.2 to 0.5 mm, embedded in a highly argillaceous matrix consisting predominantly of fine shreds of sericite, kaolinite and irregular grains of magnetite.

Innocuous Sandstones

Sandstones (thin Section No.2 SS) from Kota belonging to upper Vindhyan series) is a moderately sorted rock and consists of subangular to subrounded grains of quartz varying in size from 0.4 to 0.6 mm coated with iron oxide at the margins, which also forms the binding matrix.

Petrography of mortars: The sandstones studied vary fairly widely in their petrographic characters. Hence the mortars containing the crushed fragments of these sandstone, which exhibit significant symptoms of reaction, are described separately and categorised as:-

1) Mortars made up of crushed fragments of quartzose sandstones (thin Section No. 3 SSM, 6 SSM, 4 SSM).

2) Mortars made up of crushed fragments of lithic sandstones (thin Section 1 SSM, 9 SSM).

Group 1 (thin Section No. 3 SSM, 6 SSM, 4 SSM)

Megascopic characters: The mortar is made up of light grey to dark grey coloured fragments of sandstones enclosed in a light grey coloured cement matrix. The aggregate: cement ratio is 2.25:1. The polished surfaces of the mortar show whitish exudations, while the broken pieces as well as the polished sections show dark coloured reaction rims (Plate No.15 Fig.2) around some of the aggregate particles. The mortar also contains a few voids filled up with white coloured material.

Microscopic characters: The thin section of the mortar shows fragments of disaggregated sandstone (thin Section No. 3SSM, 6 SSM) enclosed in an isotropic but slightly carbonated cement matrix. The size of the fragments varies from 0.2 to 0.5 mm. The interstitial space filled with cement matrix is less than 0.6 mm. in width. Most of the quartz particles of the sandstones appear to have been disaggregated due to (a) crushing of the rock into finer sizes, while preparing the specimens for the mortars (b) The crushed fragments are further disintegrated due to the partial to total dissolution of the binding silicious matrix (which is often cherty), due to chemical reaction probably with cement alkalies.

The mortars also exhibit distinct cracks emanating from some of the deeply corroded fragments (thin section No. 6 SSM). The average minerological composition of the aggregate particles in the order of decreasing predominances is as follows: coarse quartz, chert, chlorite. The percentage of quartz in the mortars studied varies from 70 to 90%. Some of the quartz exhibits feeble undulose extinction. Chert constitutes about 5 to 10% of the mortars. Chlorite forms about 1 to 2% and occurs as tiny flakes.

The coarse quartz fragments in the mortar vary in size from 0.2 to 0.5 mm. Chert has been heavily reacted and dissolved to give rise to a low birefringent gel. A few grains also show narrow gel rims,(thin Section No. 3 SSM, 6 SSM), and most of the aggregate particles of chert occur as relict grains enclosed in a mass of gel which is well dispersed in the surrounding cement matrix. At times a complete alteration of chert particles to a low birefringent gel product is conspicuously observed.

Microfractures in the mortar: The mortar shows a few distinct cracks emerging from the deeply corroded particles of

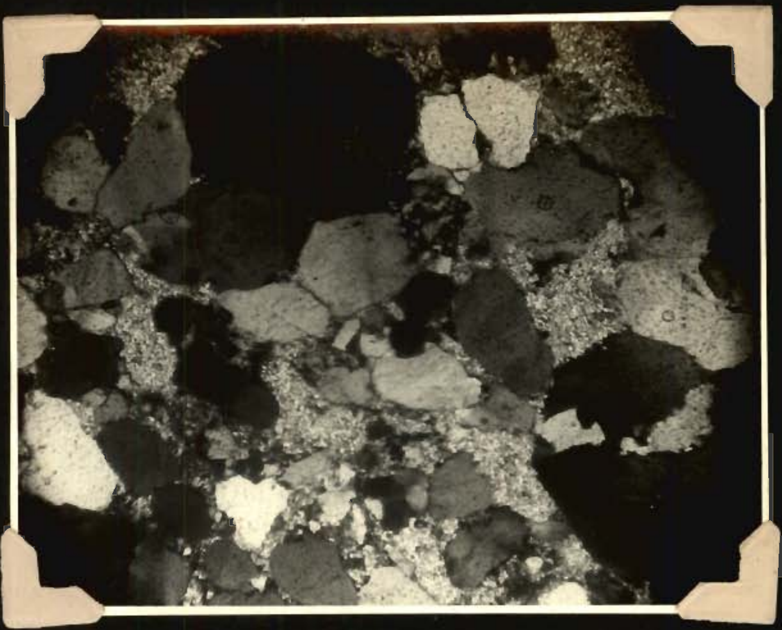


Plate 15: Photomicrograph (80xMag.) of a lithic sandstone from
Fig. 1: Palanpur, Rajasthan (Sp.No. 9 SS) showing a moderately sorted granular fabric. The photograph shows subangular to subrounded medium grained quartz well cemented by a clayey matrix. A detrital fragment of chert showing micro to cryptocrystalline texture is also observed in the central top portion of the photograph.

Plate 15: Photograph of a polished section of a mortar of reactive
Fig. 2: sandstone from Palanpur (Sp.No. 9SS) showing dark coloured reaction rims around the sandstone fragments. (5 x Mag

chert (Micro to cryptocrystalline quartz), into the surrounding cement matrix and joining another reacted fragment of chert. The cracks are generally long, narrow and gel filled. The length of the cracks is found to vary between 0.6 to 1 mm. The phenomena is conspicuously observed in (thin section No. 6 S). The cement matrix adjacent to these cracks exhibits a few distinct microcracks which are also filled up with gel.

Group 2 Lithic Sandstones (thin Section 1 SSM, 9 SSM)

The megascopic as well as the general microscopic features are similar to the mortars of sandstone described previously. Only the specific features regarding the mineral composition, microfractures are given below:-

The minerological composition of the aggregate particles in the mortar is as:

a) Coarse aggregate fragments containing quartz, sericite, kaolinitic clay and minor amounts of detrital chert to a total of 60%.

b) Individual mineral grains of slightly undulatory strained quartz, at times associated with highly decomposed and kaolinized felspar-25%.

c) Individual mineral grain of non-undulatory unstrained quartz -5%

d) Individual fragments of chert, sometimes associated with kaolinized and decomposed fels par.- 10%.

a) Coarse aggregate fragments: The grain size of the coarse fragments of sandstone varies from 0.5 to 0.7 mm. Some of which contain minor amounts of chert and show slight fracturing due to chemical reaction between the chert and the surrounding cement matrix. The fractures are seen to be filled up with narrow seems of isotropic cement matrix. Narrow reaction rims are also developed along the boundaries of these fragments with chert and are absent or indistinct with the fragments devoid of chert.

b) The individual mineral grains of undulatory quartz, vary in size from 0.2 to 0.4 mm but show only faint reaction zones and the reaction appears to be a weak one.

c) Quartz grains showing uniform extinction do not exhibit any symptoms of chemical reaction with the surrounding cement matrix.

d) Chert: An examination of the chert particles (0.3 to 0.5 mm in size) shows that the boundaries are severaly corroded, or dissolved and are extensively fractured in most of the grains. The corrosion rims seem to have been intense along the boundaries. Chemical reaction of the chert particles with the cement matrix appears to have resulted in the production of a gel which is predominantly isotropic and has thoroughly permeated the cement matrix also (Plate 16 Fig. 1).

Microfractures in the mortar

The mortar exhibits a few distinct cracks emerging from the chert fragments. The cracks are distinctly observed in thin section 1 SSM. Three cracks are seen emerging, from a single particle of chert, in different directions (Plate 16 Fig.2). At times the cracks are seen traversing through the adjacent grains of sericitzed and kaolinized felspar, and extend through the cement matrix to form a link with another reacted fragment.

Nature of the cement matrix: The cement matrix in general is isotropic, but slightly carbonated and at places shows patches of microcrystalline moderately birefringent carbonate substance. A few voids varying in diameter from 0.1 to 0.2mm are also observed lined up with the gel.

Important observations: The microscopic observations in the mortars studied are notable in some respects. The disruption of the mortar due to chemical reaction between cement alkalies and the

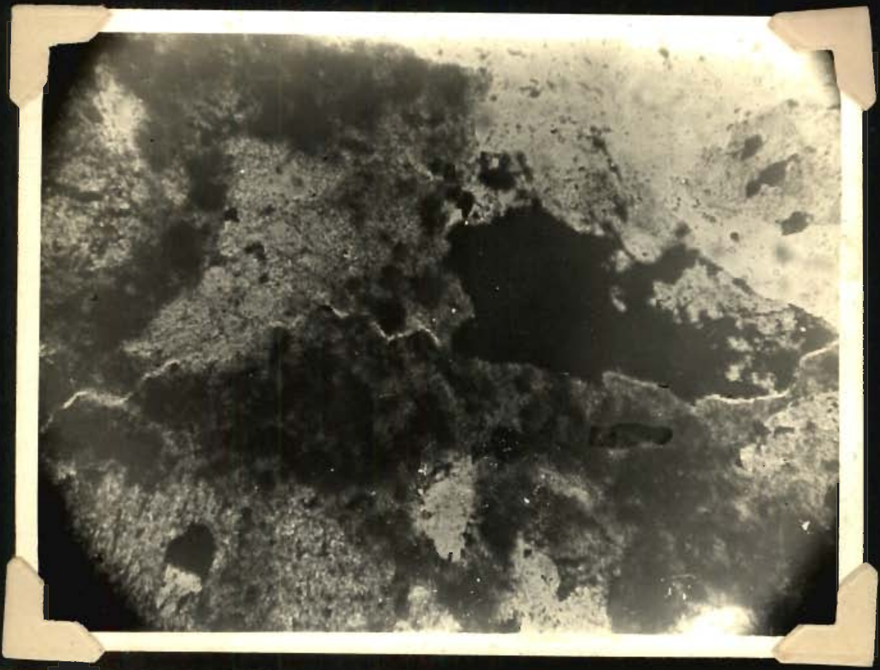


Plate 16: Fig. 1: Photomicrograph (100xMag.) (without nicols) of a mortar of a reactive sandstone (Sp.No. 9SSM) showing a long crack in the mortar, which is seen traversing a heavily reacted and weakened fragment of a sandstone in the mortar. The crack is seen lined up and partially filled with a microgranular gel material. The cement matrix adjacent to this crack is thoroughly impregnated by the gel material.

Plate 16: Fig. 2: Photomicrograph (100xMag.) (without Nicols) of a mortar of a reactive sandstone (Sp.No. 1 SSM) showing radial cracks emanating from a fragment of chert. (Central portion of the photograph). The cracks are lined up and partially filled up with a microgranular gel material.

fragments of sandstone is clearly exhibited. The presence of distinct, long gel filled cracks originating from the boundaries of the deeply altered chert indicate disruption of the mortar due to swelling force imparted by the gel. The evidences observed in the thin sections indicate that the disruption of the mortar is caused by the swelling pressure excerted by reactive particles. As observed in thin section No. 1SSM, it is quite possible that the occurrence of a fairly large amount of kaolinized and sericitized felspars, associated with chert might have accelerated the reaction by releasing the alkalies and thus increasing the alkali content of cement matrix.

QUARTZITES

Quartzites are fairly hard and durable rocks and a re widely used for concrete construction all over the country. The quartzite aggregates described here belong to the Dharwar and Cuddapah formations. The aggregates studied are described in general and important features of some quartzites observed susceptible to alkali aggregate reactions through the mortar bar tests have been brought out. Petrographic features of the less reactive and innocuous quartzites are also given in brief.

Important Petrographic features of quartzites studied

The quartzites studied are found to be hard, compact, fine to medium and coarse grained massive rocks. The colour varies widely. The quartzite from Vijayawada is greyish white in colour, while the quartzites from Delhi, (5 Q) Walajabad and Dadri show grey to dark grey colour with a slight bluish tinge. Quartzite from Prodattur (3Q) is flesh red and the fine grained cherty hematite quartzite from Birmitrapur is reddish grey due to the occurrence of hematite in considerable quantities. An important feature observed in most of the quartzites is a tendency to break through the fracture surfaces and around the individual grains and most of them break with sharp angular edges. The specific gravity of the quartzites varies from 2.58 to 2.70.

Microscopic features: Most of the quartzites display an equigranular granoblastic fabric (thin Section No. 3Q,5Q,8 Q) except those (thin Section 1Q, 4Q, 9Q) from Vijayawada, Walajabad and Nargund which exhibit highly sutured outlines marked by the occurrence of iron oxide and appear to have been highly fused during the metamorphic processes. Most of the quartz in these quartzites also shows strong undulose extinction and at times a series of well developed deformation lamellae. On the other hand the quartzite from Delhi, Dadri, Prodattur (thin Section 3Q, 5Q, 8Q) gives a uniform extinction. Biotite, garnet and magnetite occur as inclusions in two quartzites from Delhi and Dadri (thin Section 5Q,6Q). The quartzite from Prodattur contains only 5 percent chert while the quartzite from Birmitrapur is rich in micro to cryptocrystalline quartz coated with a thick film of hematite which also acts as cementing media.

Important features of alkali reactive quartzites

1) A quartzite (thin Section No.1Q) from Vijayawada (A.P.) is a highly deformed rock and consists of predominantly fused quartz grains, which show sutured outlines marked by the occurrence of iron oxide. In quartz grains, cataclastic effects with conspicuous features are common. The grains vary in size

from 1 to 2.5 mm along the longer axis. A few grains of the strained quartz also show fractures in the core with slight marginal granulation.

Most of the quartz shows well separated zones of undulatory extinction and the angle of undulose extinction with reference to the 'C' axis varies from 18° to 24°. In addition, deformation lamellae are well observed in some grains and there appear to develop a series of narrow lens shaped lamellae. These maintain a regular arrangement except when these are displaced by microfractur At times where the grains are with intense fracturing, the deformatio lamellae are further broken down into smaller fragments of strained quartz. Sometimes the fracture planes are seen filled up with fine shreds and laths of sericite and rarely with recrystallised quartz.

The only accessory mineral is magnetite and is sparingly distributed.

Quartzite (thin Section No. 9Q) from Walajabad, Madras State is a deformed quartzite in which the grains are highly sutured. Like the earlier rock from Vijayawada, cataclastic effects are predominantly marked in all the quartz grains, but the angle of undulose extinction on 'C' Axis varies from 15 to 20°. Sometimes the strained quartz is fractured with planes running parrallel to the zones of undulatory extinction. A few grains exhibit 'Böhm' lamellae which are lens shaped and appear to pinch out before reaching the edge of the grain (~~Plate~~ ~~Fig.~~).

Augite and biotite occur as accessory minerals in the rock.

Quartzite (thin Section No.3Q) (Plate 17 Fig.1) from Prodattur (A.P.). The rock exhibits a granular fabric and most of the quartz grains are rounded to subrounded with well marked boundaries coated with iron oxide, which in turn forms the cementing material. Detrital chert, or cryptocrystalline quartz occurs as fine subrounded grains with thick coating of iron oxide and forms about 5% of the rock.

4) Cherty hematite quartzite (thin Section No.29) from Birmitrapur area (Bihar State) is essentially made up of well interlocked grains of micro to cryptocrystalline quartz. (Size of individual quartz grain is 20-40 microns). Some of this microcrystalline quartz, exhibits wavy irregular extinction. The rock is traversed by a few veins of fibrous quarts.

A few anhedral grains of coarse quartz varying from 0.1 to 0.3 mm in size and characterised by wavy extinction occur as irregular patches in the groundmass of micro to cryptocrystalline quartz. Hematite generally occurs as fine dissiminated grains and as a cement throughout the rock and sometimes as subhedral grains.

Less Reactives and Innocuous Quartzites

The quartzite from Delhi is a bluish grey coloured, coarse grained rock and shows brownish tinged patches due to surface alteration of iron oxides. The only predominant mineral as identified in the hand specimen is quartz which exhibits a characteristic vitreous lusture. The rock is fairly hard and is highly resistant to abrasion. The specific gravity is 2.68. Under the microscope the rock typically displays a mosaic or slightly sutured fabric. Most of the quartz occurs subhedral to anhedral grains with minute inclusions of garnet and iron ore and sometimes muscovite and fine needles of rutile. The grain size varies from 0.8 to 1.8 mm. Most of the quartz shows well marked boundaries coated with iron oxide which also acts as a cementing material. The quartz shows uniform extinction except a few grains which show weak and broad strain shadows.

In the quartzite (thin Section No.8 Q) from Nandalur (A.P.) quartz occurs as angular to subangular grains varying in size from 0.25 to 0.40 mm. The grains are marked with a thick coating of iron oxide which also forms the cementing material. All the quartz is characterized by uniform extinction.

Petrography of mortars: As mentioned in the earlier pages the quartzites studied vary in their texture and minerological composition. Therefore the mortars containing the different varieties of quartzite and showing symptoms of reaction are described separately and are categorised as

1) Mortars with cherty quartzite (thin Section 2 QM)
2) Mortars with crushed fragments of Deformed Quartzites (thin Section 1 QM, 4 QM, 9 QM).

Microscopic features:- The thin section contains fragements of chertyhematite quartzite (Microcrystalline quartz-60%, coarse quartz-10%, Hematite-30%) enclosed in an isotropic carbonated cement matrix. The ratio of the aggregate to cement matrix is roughly 2.5:1. The size of the fragments varies from 0.3 to 0.6 mm and the interspace filled with cement rarely exceeds 0.6mm.

Most of the aggregate fragments exhibit deeply corroded outlines and reaction zones and at times show cracks emanating from margins. Extensive precintation of a low birefringent gel product is well observed all along the boundaries of the fragments and in the surrounding cement matrix. A few of the fragments which are smaller than 0.4 mm are totally dissolved due to the chemical attack by cement alkalies and occur as relict grains engulfed in a thick mass of gel.

The above observations indicate that 1) The chemical attack by cement matrix is progressive from the borders of the reactive particles. Marginal fracturing of the reacted particles probably indicates an intensive reaction. Extensive precipitation of the gel along the boundaries indicates a partial transformation of microcrystalline quartz to a gel rim. 2) The particle size of the reactive particles also is important and the reaction is more in the particles of fine sizes.

Microfractures in the Mortars:

In the thin sections (2 QM) studied, three distinct cracks could be located. These cracks are seen emanating from the boundaries of the reacted fragments of chertyquartzite, and are filled up with a low birefringent gel product. The cracks are generally long and narrow and vary in length from 0.5 to 0.8 mm and at times traverse through some of the heavily reacted and weakened particles and join another reacted fragment forming a link between the two. A few fragments of cherty quartzite, which are partially to totally dissolved, give rise to a gel product causing disruption of the mortar (Plate 17 Fig.2).

Nature of the cement matrix: The cement matrix is highly carbonated but exhibits an intense opaque character around and near the reacted fragments indicating extensive precipitation of the resultant gel product in the cement matrix. A few gel filled voids varying in diameter from 0.1 to 0.2 mm are also observed.

Some important observations: The reaction of the cherty quartzite with the cement matrix has destroyed parts of the fragments of chertyquartzite and has caused weakening of the structure of the rock fragments as well as the mortar. The occurrence of long cracks filled with gel at times are seen cutting through the whole section and indicate a total weakening

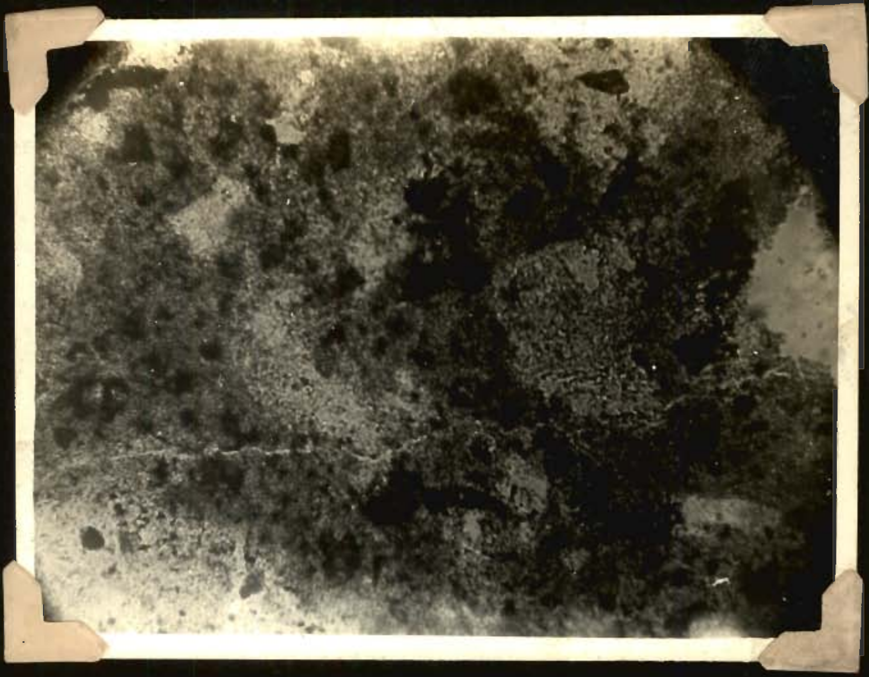


Plate 17: Fig. 2: Photomicrograph (120xMag.) (without Nicols) of a mortar of cherty hematite quartzite (Sp.No.2 QM) showing a long narrow gel filled crack emanating from a coarse fragment of cherty quartzite passing along the periphery of other reacted fragments, traversing a few reacted and weakened fragments, thereby causing disruption and weakening of the mortar.

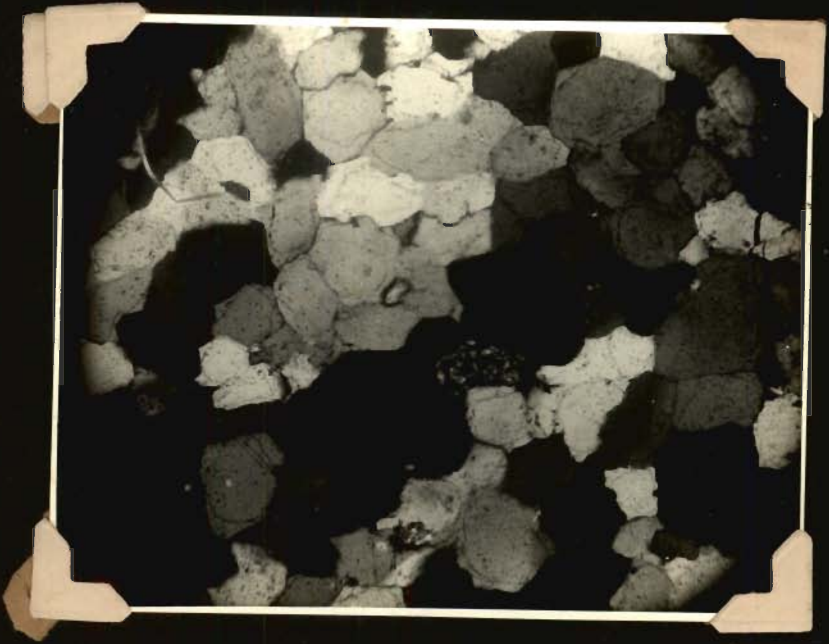


Plate 17: Fig. 3: Photomicrograph (80xMag.) of a quartzite from Prodattur. The central portion of the photograph shows a grain of chert showing micro to cryptocrystalline texture. Another small fragment of chert is also seen in the ~~left hand~~ Lower ~~corner~~ Portion of the photograph.

of the mortar due to the reaction.

Group2- Highly to moderately deformed quartzites (thin Section No. 1QM, 4 QM, 9 QM).

Megascopic features: The mortar shows whitish exudations on the surface and contains voids filled up with a white coloured gel like material. The aggregate fragments exhibit indistinct reaction rims.

Microscopic features: The thin section contains fragments of quartzite enclosed in a slightly carbonated cement matrix. The aggregate cement ratio is roughly 2.5:1. The size of the fragments varies from 0.2 to 0.6 mm. The rock fragments sometimes exhibit highly corroded boundaries and reaction zones. Cracks emanating from the margins of the aggregate particles are sometimes observed.

Minerology: The mortars are made up of crushed monomineralic, deformed quartzite, and obviously the most predominant constituent is the strongly undulatory fractured and slightly granulated quartz. Needle like rutile occurs as common inclusions in the quartz particles. As mentioned above most of the particles of strained quartz show boundary corrosion and slightly fractured margins indicate, partial dissolution due to chemical reaction with alkalies in the surrounding cement matrix. This has resulted in the formation and deposition of low birefringent gel along the margins of reactive quartz creating a sort of reaction rim. The gel has permeated the surrounding cement matrix (Plate 18 Fig.1).

Microfractures in the mortars: The mortar exhibits a few indistinct cracks emanating from the margins of reacted fragments of strained quartz (thin Section No.1 QM, 9 QM) into the surrounding cement matrix. The cracks are partially filled up with a low birefringent gel and rarely exceed 0.3 mm in length. The cement matrix is highly carbonated and microcrystalline grains of carbonate substance are frequently observed, characterized by high birefringence. The cement matrix also contains a few voids varying in diameter from 0.1 to 0.2 mm lined up with the gel. It contains a few patches of isotropic material, as a result of the impregnation of the gel.

The microscopic observations are similar to those observed in the deformed charnockites and granites where strongly undulatory strained and fractured quartz shows a chemical reaction with the high alkali cement.

PHYLLITES AND SCHISTS

The phyllites and schists due to their fissible nature are rarely used for concrete constructions in India. However, a few samples of comparatively hard variety belonging to the Dharwar formations have been obtained from the Mysore state and studied for alkali reactivity. For comparison a sample of phyllite from Himachal Pradesh has also been studied.

Phyllite and schists from the Dharwar formations of the Mysore area is fairly hard, fine grained, dark colourd, foliated rocks. Sometimes the rock is traversed by veins of calcite. The specific gravity varies within very narrow range from 2.75 to 2.78.

Microscopic features: As the rocks studied vary widely as regards their textural features and the minerological composition, they have been described separately.

(Thin Section No.1 SCH) chlorite quartz schist from Hâliyal- Mysore State (Highly reactive).

Texture: The rock exhibits a porphyroblastic texture (Plate 18 Fig.2). Porphyroblasts of quartz and sometimes chlorite occur in a medium to fine grained groundmass of quartz, chlorite, sericitized albite, biotite, sericite and iron ore. The rock is traversed by veins of calcite which is well characterized by high birefringence and twinning.

Minerology: The minerals constituting the rock in an order of decreasing predominance are as follows:

Quartz, chlorite, calcite, sericitized felspar, biotite, muscovite.

1) Quartz: It constitutes about 50% of the rock and occurs as porphyroblasts, as well as a constituent of the groundmass and occurs as subhedral to anhedral grains. The lenticular porphyroblasts sometimes are generally marked by the occurrence of iron oxide at the margins, and vary in size from 0.6 to 2 mm in length. Inclusions of zircon, needle like rutile and iron ore are conspicuously observed in quartz.

Most of the quartz exhibits strong undulose extinction and sometimes the marginal granulation along certain grains is not rare, while some grains are brecciated into much smaller particles which also show an undulose extinction and mortar structure.

2) Chlorite: It forms about 20% of the rock and generally occurs as a part of the groundmass as tiny flakes, arranged parallel. The size varies from 0.1 to 0.2 mm in length, and sometimes as porphyroblasts varying in size from 0.4 to 0.8 mm. Most of the chlorite is strongly pleochroic in green and exhibits straight extinction.

3) Calcite: It forms about 8% of the rock mass, and occurs as subhedral to anhedral grains in the groundmass or as veins

Plate 18: Fig. 1: Photomicrograph (80xMag.) of a mortar of a highly reactive quartzite from Vijayawada (Sp.No.1 QM) showing rimmed zones and deposition of a microgranular gel product along the peripheries of reactive strained quartz. The quartz grains generally exhibit marked undulose extinction.

Plate 18: Fig. 2: Photomicrograph (90xMag.) of a quartz chlorite schist from Haliyal (Sp. 1 Sch) showing coarse porphyroblasts of strained quartz enclosed in a sheared, partially recrystallised matrix of chlorite, quartz, biotite and muscovite. The left hand bottom portion of the photograph shows a few grains of sericitized felspar as occuring in the matrix.

traversing the rock. Cataclastic effects are observed in a few grains marked by slight displacement of the twin lamellae.

4) Sericitized albite: ($Ab_{90}Ar_{10}$):- It occurs as a minor constituent in the groundmass and varies in size from 0.2 to 0.4mm.

5) Biotite occurs as flakes associated with chlorite in the matrix and is strongly pleochroic from brown to green.

6) Muscovite occurs as flakes in the groundmass.

(thin section No. 1 PH)-Slaty phyllite-Hubli-Mysore State (Highly reactive).

Texture and minerology: The rock exhibits a schistose fabric showing sub parallel layers of flaky chlorite, biotite, sericitized felspar and medium to fine grained subhedral to anhedral quartz. Iron oxide is widely distributed throughout the rock and occurs as coarse clusters, lenticular dusty patches and fine disseminations in the matrix.

The rock contains a few fragments of chert (micro to cryptocrystalline quartz) irregularly distributed and varying in size from 0.2 to 0.66 mm. It constitutes about 12 percent of the rock mass.

(Thin Section No. 2PH) Sericite phyllite from Dalhousie (H.P.) (marginally reactive) is a highly argillaceous phyllite containing fine flakes of chlorite, tiny shreds of sericite and fine quartz and kaolinite. The rock is ferruginous and contains iron oxide occuring as coarse clusters and fine disseminations, in an argillaceous matrix.

Petrography of the mortars

Chlorite Quartz Schist -1 SCHM

Megascopic features: The mortar is made up of grenish grey coloured fragments of chlorite quartz schist embedded in a grey coloured cement matrix. The ratio of aggregate to cement is 2.5:1, and the size of aggregate fragments varies from 0.4 to 0.88 mm. Whitish porcellaneous exudations are conspicuous on the polished surface of the mortar after six months of humid storage. The broken surfaces of mortar exhibit dark coloured reaction rims around the fragments. Few of the fragments exhibit slight discolouration to lighter shades.

Microscopic features: The thin section shows fragments of chlorite quartz schist embedded in a partially isotropic carbonated cement matrix. Some of the minerals in the rock fragments occur as independent grains due to crushing to finer sizes in the fabrication of mortars. Some of the aggregate particles exhibit slight to highly corroded outlines and reaction zones. A few of the aggregate particles also show cracks emanating from the margins into the adjoining cement matrix.

The average minerological composition of the aggregate particles in the mortar is given below:

1) Aggregate particles made up of predominantly porphyroblasts of strained quartz in matrix of chlorite, fine quartz, calcite, sericitized felspar, biotite, muscovite and magnetite.	- 70%
2) Individual particles of medium grained strained quartz.	- 18%
3) Individual fragments of granulated quartz-	- 10%
4) Sericitized felspar	- 2%

1) Most of the aggregate particles containing strained quartz in abundance, show boundary corrosion and slight fracturing. The fragments vary in size from 0.4 to 0.6 mm.

2) Corroded margins are conspicuously observed in most of the strained quartz occuring as individual grains and varying

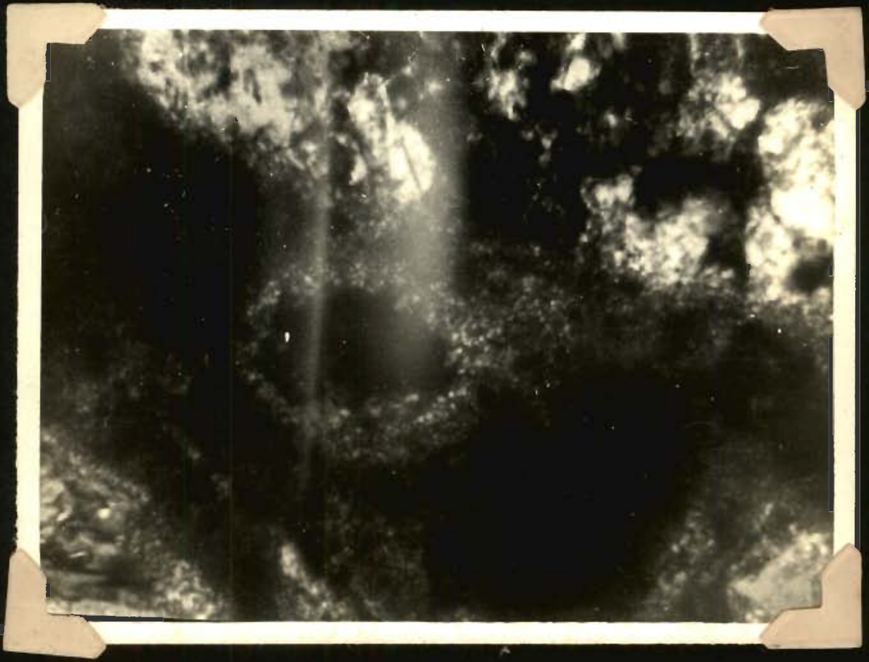


Plate 19: Photomicrograph (400xMag.) of a mortar of reactive schist
Fig. 1: (Sp.1 Schm) from Haliyal showing an elliptical void in the mortar. The void is lined up with the gel product formed due to reactions between the surrounding rock particles of strained quartz. All the reacted particles show deposition of a microgranule gel material along their margins. The gel has sometimes impregnated the reacted particles as seen in the lower right hand corner of the photograph.

in size from 0.2 to 0.4mm. At times the quartz is deeply corrode and dissolved, that only relict grains are found enclosed in a mass of a gel.

Due to the intense chemical reaction between the strained quartz and cement alkalies in the surrounding cement matrix. The boundary zone in most of the individual grains has been transformed into a rim consisting of a low birefringent alkali-silica gel. The thickness of the rim varies from grain to grain and is a function of grain size (Plate 19 Fig.1).

The reaction zones and the rims are not very consipucuous along the fragments of Schist but the intense opaque character of the cement matrix adjacent to the fragments indicate impregnation of the cement matrix by gel.

Microfractures in the mortar

A fe distinct cracks are observed, the cracks vary in length from 0.4 to 0.7 mm and are gel filled.

a) Link cracks: Narrow cracks starting from the edge of reacted fragment of schist, extending through the ambient cement matrix and joining another reacted fragment,

b) Short narrow cracks emanating from a heavily reacted particles of strained quartz and joining an adjacent void.

The cement matrix in general is carbonated with patches of isotropic material.

Slaty phyllite (thin Section No. 1 PHM)

The megascopic as well as the general microscopic features are similar to (thin Section No. 1 SCH). Hence only the specific features regarding the mineral compositon, and microfractures in the mortar are given in the following pages.

The average mineralogical composition of aggregate particles in the mortar

1) Quartz - 25%
(unsatrained)

2) Quartz: Chert (Microcrystalline quartz, disseminated with iron oxide and contains minor inclusions of chlorite -35%

3) Sericitized Albite -20%

4) Chlorite -16%

5) Calcite - 4%

1) Quartz: It generally occurs associated with chlorite, sericitized albite and sometimes as individual grains varying in size from 0.2 to 0.4 mm. No reaction symptoms are observed with quartz of the unstrained type.

2) Cherty (Microcrystalline quartz). It generally occurs in the matrix with other minerals like the unstrained quartz, sericitized albite, calcite, chlorite and iron ore. Sometimes individual particles of microcrystalline quartz are observed scattered in the cement matrix. The fragments of slaty phyllite which contain abundant microcrystalline quartz exhibit intense fracturing and impregnation of the cement matrix through these fractures, indicating that the alkali reactive constituent in the fragment has been subjected to a chemical attack by the surrounding cement matrix. The fractures are generally seen emanating from the microcrystalline quartz occuring in the fragments of slaty phyllite and are seen to be filled up with an isotropic gel matrial (Plate No.10 Fig.2). Reaction rims are observed all along the fragments indicating chemical reaction with the cement. The aggregate fragments containing microcrystalline quartz generally show intense fracturing and sometimes the fractures are seen to extend further in the surrounding cement matrix.

Plate 20: Photomicrograph (120xMag) of a mortar of a highly reactive phyllite (Sp. No 1 Sch) from Hubli Distt., Mysore State containing chert (microcrystalline quartz). The central portion of the photograph shows two circular voids in the mortar partially filled and lined up with the microgranular gel material. Gel filled cracks are seen emanating in different direction from the boundary portion of the voids, probably indicating swelling nature of the gel mater-ial. The two voids are seen interconnected through a crack which is also gel filled. The left hand corner of the photograph shows a heavily reacted fragment of phyllite showing two gel filled cracks emanating from different points along the margins of the fragment and joining a void which is partially filled up with the gel material. The left hand upper corner of the photograph also shows gel filled cracks emanating from a fragment of phyllite. The bottom portion of the photograph shows a few scattered heavily reacted particles of chert.

On the whole the mortar exhibits distinct signs of pattern cracking and disruption.

Microcrystalline quartz, which occurs as scattered grains in the cement matrix exhibits severe corrosion and disintegration, ~~which~~ and generally occurs as relict patches surrounded by a mass of gel (indicating severe chemical attack by the surrounding cement matrix). Most of the individual grains of microcrystalline quartz have been totally dissolved giving rise to gel products which are well dispersed in the adjoining cement matrix, in cracks and voids.

3) Sericitized albite is generally observed in the larger fragments of the phyllite rock. It is free from chemical reactivity with the cement. Chlorite and calcite also do not exhibit any symptoms of reaction and are thus free from chemical attack.

CHAPTER V

MECHANICAL BEHAVIOUR OF MORTARS AND THEIR CORRELATION WITH PETROGRAP

(Tables and graphs given at the end)

Earlier workers have established that rock aggregates containing opal, chalcedony, volcanic glass and chert are susceptible to attack by alkalies in cement and cause expansion and cracking of mortars and concrete masses. But very little is known about the behaviour of the rocks like the granites, charnockites, quartzites, phyllites, schists etc. which are regarded free from the lower forms of silica e.g. opal, chert, chalcedony etc. In India most of the rock aggregates used for concrete constructions belong to the above varieties. Incidently no appreciable systematic study on Indian aggregates has yet been made on the cement-alkali reactivity. In the following few pages an evaluation of the alkali reactivity on Indian aggregates has been attempted. As mentioned earlier the samples studied are obtained from some of the important geological formations of India.

After an initial petrographic examination, the aggregates have been subjected to their potential alkali reactivity, adopting the known standard tests like the mortar bar tests, chemical tests, as has already been mentioned in Chapter III. Petrographic examination of mortars, showing moderate to high expansions was also carried out and the observations have been given in the earlier pages. On the basis of these and the tensile briquette strengths of mortars at different periods, a correlation is attempted.

In addition an attempt has been made to correlate the petrographic features of the aggregate with the observations in other tests. It is interesting to note that the study has revealed of a fairly good degree of relationship between the petrographic features of the rock and the mortar bar expansion results.

However, this relation is poor as regards the chemical tests are concerned. The tensile strengths of the mortars also show some correlation with the degree of mortar bar expansions. These factors are discussed below and a classification of the aggregates studied, based on petrographic features and mortar bar expansions has been attempted.

A) Mortar bar expansion studies: Based on the satisfactory engineering properties, mortar bar expansion studies were carried out on seventy samples of common aggregates. The technique and the methods followed have already been mentioned on pp.35 to 45 in Chapter III and the expansion in the mortar bars reported herein have been recorded at an interval of 30 days and the final reading after a period of six months. As a result of these studies in the first instance, the aggregates studied are further classified into two major groups i.e.(i) Reactive Aggregates- expansion $>$ 0.060% (ii) Innocuous or feebly reactive $<$ 0.060%. Furthermore it may be added that even the reactive rock aggregates show a wide range of expansion between 0.060% to 0.28% and hence on the basis of their petrographic features, these are further subdivided into five groups (See Table 8).

The rates of expansions in each of the aggregate groups are also represented graphically in figures 4,5,6,7,8,9.

TABLE 8

Classification of aggregates studied

Group No.	Nature of Expansion	Range of Mortar bar expansion (6 months)	Rock group and number of rocks.
I.	Extensively Reactive	Above 0.15%	a)Cherty Quartzite-1 b)Sandstones-2 c)Phyllite-1
II.	Highly Reactive	Between 0.10% and 0.15%	a)Sandstones-3 b)Charnockites-2 c)Granite-1 d)Schist-1 e)Basalt-2 f) Quartzite-2

III. Very Reactive	Between 0.09% and 0.10%	1) Granite-1 2) Granodiorites-2 3) Charnockites-2 4) Basalt-1
IV. Reactive	Between 0.08% and 0.09%	1) Granite-1. 2) Charnockites-2.
V. Moderately Reactive	Between 0.06% and 0.08%	1) Granite-1. 2) Quartzite~~s~~-1 3) Sandstone-1. 4) Phyllite-1.
VI. Less Reactive and Innocuous	Less than 0.06%	Many other rocks; studied.

From the study of the table and the graphs it has been possible to explain the phenomenon of alkali-aggregate reactivity in the rocks, from a ~~The~~ detailed examination of the textural characteristics of the rocks and the constituent silica minerals as given in Chapter IV, and the nature of reactive constituents, it is evident that in addition to the reactivity with lower forms of silica such as chert, chalcedony etc., the higher forms of silica with strain effects are also capable of producing alkali-aggregate reactions. Further it is also noted that on the basis of the nature and amount of silica minerals, present in an aggregate, a fairly good estimate can be made of the reactive nature of a rock.

Granitoid rocks (comprising granites, granodiorites, gneisses and syenite).

About 20 specimens of granitoid rocks obtained from different localities, mostly from Andhra, Mysore, Madras, and a few from Gujarat, Bihar, U.P. and Punjab were studied for mortar bar expansions. As has already been noted earlier there is some variation in the petrographic characters of these rocks.

a) Mortar bar expansions studies: In these cases, the mortar bar expansions vary from 0.021% to 0.11% of the twenty specimens, only six show expansions varying between 0.067% to 0.11% and can be classified as reactive. Of these, two specimens (No.14 GR, 15 GR) can be classified under highly reactive group, three specimens

(No.2GR, 8 GR, 9 GR), under reactive group and specimen (No.3GR); to moderately reactive group. The remaining 14 specimens indicatex expansions between 0.021 to 0.42 and thus can be classed as less reactive and innocuous aggregate (Ref. Table-9).

Fig.4 (Graph 1) shows the behaviour of the granitoid rocks. From this it will be seen that even in the reactive granites, the rate of expansion varies. The maximum, of 0.11% is observed with a highly sheared biotite granite (Sp.15GR) containing 40% strongly undulatory, fractured and granulated quartz. Sp.No.14 GR, with an expansion of 0.10% which falls under the "highly reactive group", is also rich in strained and fractured quartz, forming 38% in minerological proportions.

The granites (Sp.No.2GR, 8GR, 9GR) classified under the reactive group show expansions between 0.89 to 0.099 percent contain 35 to 38 per cent moderately undulose, fractured quartz, with the angle of undulose extinction on 'C' axis varying between 15 to 20 degrees. The quartz is generally free from granulation. Sp.No.3 GR is an alkali granite with only 25 percent moderately undulose quartz, generally free from fracturing, shows an expansion of 0.067 per cent and is thus only marginally reactive.

The granites which show lower rate of expansions and thus classed as less reactive or innocuous, contain strained quartz in negligible quantity. Most of the quartz in these rocks constituting 20 to 40% of the rocks show uniform extinction or at times weak or broad strain shadows. The quartz in the gneisses is the recrystallised variety and shows uniform extinction.

Another feature observed in the reactive granodiorites (Sp.No.8GR, 9GR) is that albite in these rocks is highly sericitized and kaolinized. It appears quite probable that the aggregate in these cases might have contributed to some extent in increasing the alkali content of the cement solution, which may accelerate the reaction. (The presence of strained quartz is essential). But no distinct symptoms of reaction are observed with these minerals.

CHARNOCKITES (ACID, INTERMEDIATE, AND BASIC CHARNOCKITES)

Mortars of eleven specimens of charnockitic rocks from different localities (Sp.No.1CH to 8 CH) from the Madras region, Andhra Pradesh (10 CH), and from Bihar (Sp.No.11 CH, 12 CH) have been studied. As observed in the earlier pages (49 to 56) there is a fairly wide variation in the petrographic characteristics of these rocks, and hence on the basis of their petrographic classification i.e. acid, intermediate and basic varieties, the results obtained are interesting, though there are not so spectacular for any of the individual varieties.

Mortar bar expansion studies: (Ref. Table 10): The mortar bar expansions in these rocks vary between 0.010 to 0.12 percent. Of the eleven specimens, seven indicate expansions ranging between 0.076 to 0.12 percent. These specimens are found to belong to the acid and intermediate charnockite varieties. Of these, two of the specimens (Sp.No.1 CH, 10CH) can also be classified under highly reactive group while the other four specimens (Nos.3 CH, 4 CH, 2 CH, 6 CH) come under the reactive group, and a specimen (No. 5 CH) can be classed as moderately reactive and the remaining three specimens, showing expansions between 0.010 to 0.39, are classed as less reactive and innocuous. From a comparision of the expansions the lowest expansions are observed in the basic types (Sp.No.11 CH), while the other three 7 CH, 8 CH, 9CH) belong to the acid variety.

From Fig.5 (Graph II), it may be pointed out that the rate of expansion differs fairly widely in the charnockites. The maximum expansion is observed with an acid type of rock (sp.No.1 CH). From the petrographic description, it contains about 40 percent strongly undulatory, intensely fractured and granulated quartz (Ref.Table 5). Some of the quartz in the rock shows mortar structure and contains small individual grains of quartz, each showing undulose extinction and the intercrystal suturing. The angle of undulose extinction on 'C' axis in the coarser strained quartz grains varies from 22 to 27 degrees, indicating that the intensity of strain in the quartz grains is fairly high. Another sample which shows equally high expansions is a garnet granulite (Sp.No.10 CH). It also contains a high proportion of strained quartz and shows similar textural characteristics in quartz grains.

The varieties showing moderate expansions between 0.080 to 0.088 (Sp.No.3 CH, 5 CH, 2 CH, 6 CH) contain about 30 to 40 percent strained fractured quartz. The angle of undulose extinction on 'C' axis varies widely between 10 to 24° and the quartz exhibits only slight marginal granulation. The specimen (No.5 CH) shows a comparatively slower rate of expansion and contains only 30 percent strained quartz.

The acid charnockites classified under the less reactive group contain about 30 to 40 percent quartz which exhibits weak and broad strain shadows in a few grains while most of the quartz shows uniform extinction. The basic charnockite (Sp.No.11 CH) contain only 12 percent unstrained quartz (Ref.Table 5).

Most of the reactive charnockites contain a certain percentage of strained oligoclase felspar. The charnockites showing high expansions (Sp.No.1 CH, 10 CH) exhibit cataclastic features in biotite, which shows a wavy extinction. However, these constituent in the mortar do not show any symptoms of reaction.

BASALTS

Seventeen specimens of basalt from different localities in Maharashtra, Gujarat, Madhya Pradesh and a few from Andhra Pradesh and Bihar have been studied for mortar bar expansions. As stated in the earlier pages, the petrographic characters of the basalts studied show only a very slight variation, particularly in the presence of secondary minerals like chalcedony, zeolite, filling up the amgdular cavities and veins.

Mortar bar expansion studies: (Ref.Table 11)

The mortar bar expansions observed in the basalts studied vary between 0.031 to 0.14%. Out of the seventeen specimens, three indicate expansions between 0.097 to 0.14% and can be classed as reactive. Out of these three, two specimens (No.5T,15T) may be classified as highly reactive and the third specimen (No.3T), only as moderately reactive. The remaining 14 specimens, with expansions varying between 0.031 to 0.039 percent are thus classed as innocuous.

From the Fig.6 (Graph III), it could be seen that the maximum expansion of 0.14 percent has been observed by the porphyritic olivine basalt (Sp.No.5T) with 9% percent chalcedony and 6% interstitial glass. The specific feature of this chalcedony is that it contains inclusions of tridymite. Another (Sp.No.15T) porphyritic basalt containing 8% chalcedony, 4 percent interstitial glass, and traces of opal, also shows high expansion of 0.12 per cent. The specimen No.3T, indicating expansion of 0.097% contains 7% palagonite and 8% interstitial primary glass. Particular attention has been paid to the zeolitic basalts (Sp.No.1T, 2T), but the expansions were observed tc be less than 0.039% and are thus classed as innocuous.

The large variations in the expansions in the reactive and innocuous basalts can thus be ascribed to the presence of secondary minerals chalcedony and palagonite or opal in the reactive basalts. (Sp.5T, 15T). The occurrence of a fairly good percentage of palagonite (Sp.No.3T) is also responsible for the reactive tendency of basalt.

The limited range of variation from 0.031 to 0.039% in the innocuous basalts can be attributed to the fairly homogenous petrographic characters of these rocks. These are predominantly rich in labrodorite and pyroxene and other mafic minerals, but do not contain reactive constituents like chalcedony or palagonite.

SANDSTONES

The sandstone samples studied mostly belong to the Vindhyans, (Upper and lower) Cuddapah (upper and lower) and the Siwalik Series. Ten specimens from different localities of Andhra Pradesh, Madhya Pradesh, Rajasthan, Uttar Pradesh and Himachal Pradesh were studied. As has already been indicated in the previous chapters there is a wide variation in their petrographic characteristics.

Mortar bar expansions studies: The mortar bar expansions observed in the sandstones are given in Table 12. From this it is clear that as in other rocks, there is a variation between 0.022 to 0.25 per cent. Out of the ten specimens, six indicate expansions ranging from 0.062 percent to 0.25 percent and can be classified as reactive rocks. Two of these sandstones are extensively reactive (Sp.No.455, 653) while three specimens (No.1 SS, 3 SS, 9 SS) can be classified as highly reactive while Sp.No. 7 SS could be classed as moderately reactive. Only, the remaining four specimens show expansions ranging between 0.022% to 0.034% and thus are innocuous.

A look at the Fig.7(Graph IV) indicates that the rate of expansion in the reactive sandstones also varies widely, which is quite natural because of their heterogeneous petrographic characters.

A study of the petrographic characters of these highly and extensively reactive sandstones shows that the mineral chert or micro to cryptocrystalline quartz is a common constituent in these sandstone In the sandstone sample (Sp.No.6SS) indicating the highest expansion about 20% chert is present both as mineral and also as the binding matrix. It is further observed that the rate of expansion increases with the chert content in the sandstones, which often occurs as a detrital constituent. Rocks belonging to extensively reactive group contain 15 to 20 percent chert, while those classified under highly reactive group contain 8 to 10% chert.

The argillaceous sandstone (Sp.No.7SS) is only marginally reactive as it is devoid of any chert or similar matter. A few of the sandstones which contain a few grains of moderately to strongly undulatory quartz are innocuous.

The innocuous sandstones are purely quartzose sandstones and are devoid of other low forms of silica i.e. are free from chert, chalcedony or opal.

QUARTZITES

The Quartzites studied, are from different localities of Andhra Pradesh, Mysore, Madras, Bihar, Maharashtra, Haryana and Delhi areas and belong to the Dharwar and Cuddapah systems. As observed in Chapter Iv there is a wide variation in the petrographic characteristics of these rocks.

Mortar bar expansion studies:

The mortar bar expansions vary widely between 0.020% to 0.28% of the ten specimens, five indicate expansions varying between 0.076 to 0.28 percent. One is a cherty hematite quartzite (Sp.No.2Q) and could be classed under the extensively reactive group. Three specimens (No.1Q,3Q,4Q) are highly reactive and only one specimen (No.9Q) falls under moderately reactive group (Ref.Table 13). Five Specimens (No.5Q,6Q,7Q,8Q,10Q) are innocuous and show expansion

Fig.8 (Graph V) indicates that the rate of expansion of quartzites containing strongly undulatory quartz is comparatively much lower than the quartzite which contain about 60 percent chert. It is also further observed that the expansion observed in case of a quartzite containing only 5 percent chert is as high as a deformed quartzite containing about 40 to 50% strongly undulatory strained and fractured quartz. This supports the observations made during the petrographic studies on mortars that the chemical reactivity with cement alkalies is very much higher in case of micro to crypto-crystalline quartz as compared to the medium to coarse grained strongly undulatory strained quartz. Thus this shows that the chemical reactivity of silica minerals is directly a function of internal surface area. Two quartzites from Vijayawada and Nargund (Sp.No.1Q, 4Q) which are classified as highly reactive are mostly made up of strongly undulatory fractured quartz in which the deformation lamellae are conspicuously observed.

Sp.No. 9Q, classified as moderately reactive is also a deformed quartzite and contains high amount of moderately undulose, fractured quartz. The angle of undulose extinction on the 'C' axis varies between 15 to 20 degrees.

The quartzites which are classed as less reactive and innocuous contain strained quartz in negligible amounts.

SCHIST AND PHYLLITES

Only three specimens of Schist as rocks found to satisfy the requisite engineering properties were studied for mortar bar expansions. Stratiagraphically these belong to the Dharwar group of rocks. Two specimens are from Mysore and the third from the Himachal Pradesh. All the three are found to be reactive, when studied for mortar bar expansions. The three specimens differ widely in petrographic characters belong to the following varieties. Ref. Table 14.

1. Chlorite quartz schist- Sp.No.1SCH
2. Slaty Phyllite -Sp.No. 1 PH.
3. Sericite Phyllite -Sp.No. 2 PH.

The maximum expansion of 0.18% has been observed with slaty phyllite, which is found to contain 12% micro to crypto crystalline quartz. The chlorite quartz schist shows an expansion of 0.12% and is found to contain about 40% strained granulated quartz, which exhibits a mortar structure, and also contains a number of small individual grains of quartz showing undulose extinction and extreme intercrystal suturing.

The sericite phyllite (Sp.No.2 PH) is marginally reactive and shows an expansion of·0.60 per cent is made up of fine shreds of sericite, chlorite, admixed with the fine quartz and kaolinite of the matrix.

From Figs. 10 and 11, it is evident that the aggregates studied could be classified only on the basis of mortar bar expansion and the relative percentage of reactive silicious constituents like strongly undulatory strained quartz, chert, chalcedony, and palagonite. In case of deformed granitoid rocks, charnockites, quartzites, the percentage of strained quartz is directly related to the rate and amount of expansions. It is further noted that the rate of expansion is comparitively much higher with rocks containing chert and chalcedony. The rate of expansion with basalts containing only palagonite is comparitively much lower that the one containing chert on chalcedony but is slightly higher than the rocks rich in strained quartz. From these graphs it can therefore be interpreted that the rate of expansion with the alkali reactive silicious contituents in a decreasing order is as:-

chert and chalcedony, palagonite, strained quartz.

Studies on tensile Briquette strengths of mortars containing reactive and nonreactive aggregate

Further studies on the behaviour of reactive and non-reactive aggregates with high alkali cement have been carried out by casting mortar briquettes made with different varieties of aggregates. As in the mortar-bar tests the gradation of the aggregates, the water cement ratio, the aggregate cement ratio, have been kept the same and these tensile briquettes have also been stored under identical conditions.

The aim of this experiment is to study the engineering aspects of the mortars from the highly reactive and non-reactive aggregates, and to make a correlation between their mortar bar expansions and their related engineering behaviour. As will be seen later in the following pages, the experiment gives further confirmation to the phenomena of alkali aggregate reactivity with strained quartz, chert and chalcedony.

Six briquettes of mortars were made for each aggregate and about fifteen aggregates were studied. The tensile strengths for each rock type have been measured at periods of 28 days and 90 days, using the standard tensile briquette strength apparatus as are used in engineering laboratories (Ref.Table 15). The table 16 also gives the changes in the tensile strengths of the mortars containing reactive as well as non-reactive aggregates alongwith the mortar expansions.

Each figure against the tensile strength gives a mean of the three sets of readings obtained on these briquettes prepared from the same type of material.

The experimental results point to the following conclusions:

1) Mortars with high expansions (more than 0.10 percent) always show abnormal decrease in the tensile strengths. The reduction in the tensile strengths varies between 14% to 22%. Though only a broad correlation is observed between the mortar expansions and the reduced tensile strengths, still it can be seen that it is reduced appreciably in the cases of mortars containing highly reactive aggregates with age.

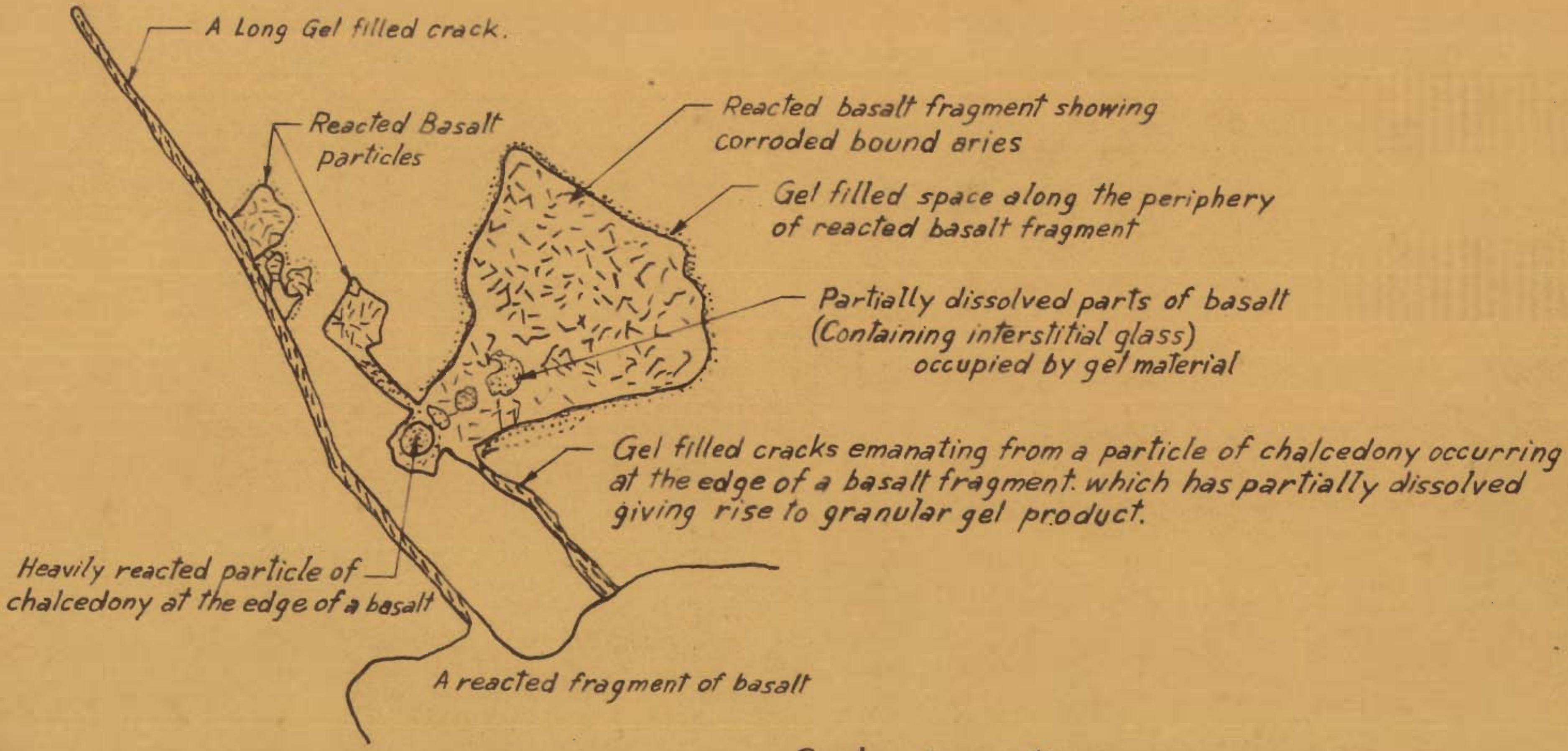
2) Mortars which show moderate expansions (between 0.08% to 0.10%), the reduction in the tensile strengths is between 5% to 8%.

3) Mortars made up of less reactive or non-reactive aggregates (Mortar expansions less than 0.06%) generally show a gain in the tensile strength upto 5%. This indicates that the alkali aggregate reaction is negligible or ineffective. These mortars do not expand abnormally and their tensile strengths thus remain unaffected.

Discussion: These reductions in the tensile stengths of the mortars of reacted aggregate can be explained with the help of the petrographic properties of their mortars. As observed in the earlier chapters, particularly during the petrographic examination of the highly reacted mortars, it has been noted that the affected fragments of the strained quartz, chalcedony or chert particles show cracks emanating from the margins. The cracks in these mortars give a useful clue about the behaviour of the aggregate in mortars. It is also observed that a large number of reactive particles in the aggregate produce a system of "link cracks" and "chain cracks" due to swelling nature of the reactive particle which is also a cause of disruption of the mortar. This probably accounts for the reduction in tensile strengths of these mortars.

CAMERA LUCIDA SKETCH SHOWING MICROSCOPIC PHENOMENA IN A DETERIORATED MORTAR OF REACTIVE BASALT (SP. 5TM) DUE TO ALK. AGG. REACTION.

FIG. 2

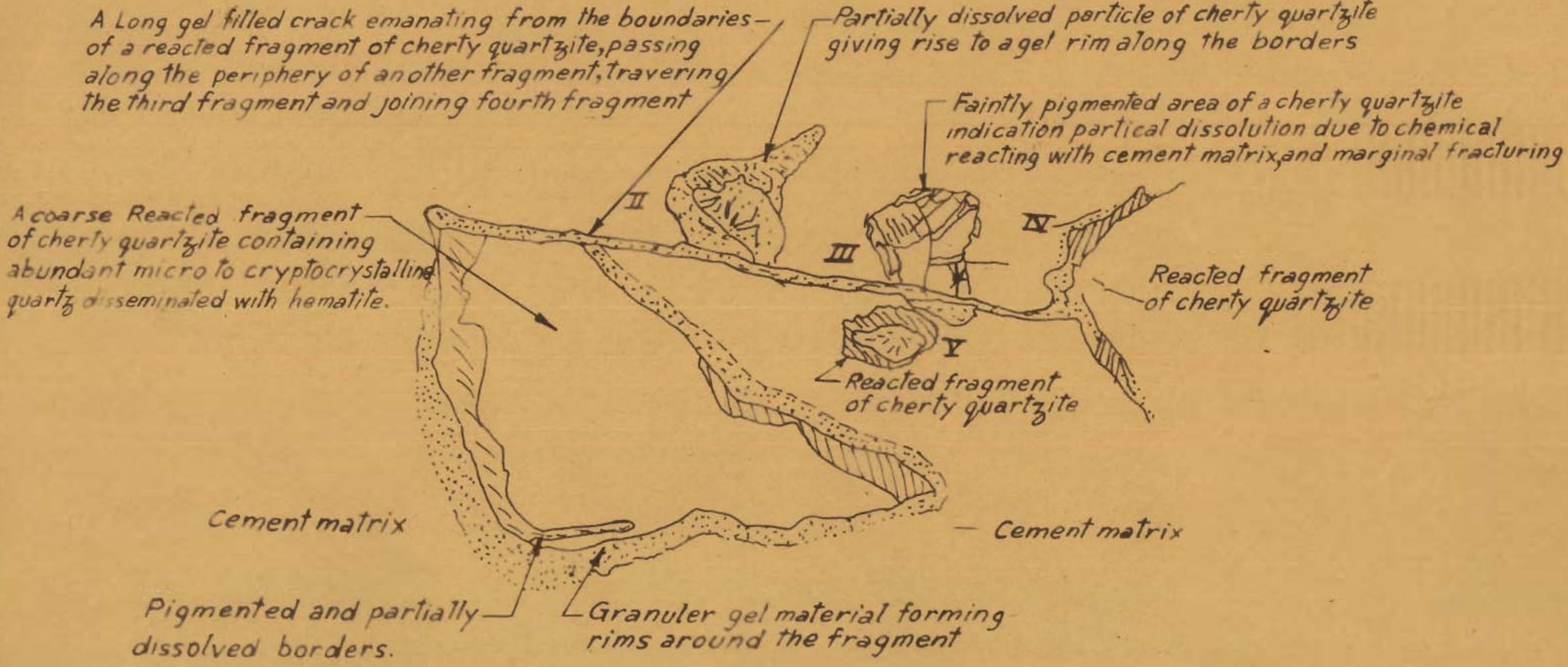


Scale:-1mm=10cm.

CAMERA LUCIDA SKETCH SHOWING ALK. AGG. REACTIONS IN A MORTAR OF CHERTY HEMATITE QUARTZITE. (SP. 2QM)

MICROSCOPIC OBSERVATIONS

FIG. 3



Scale :- 1mm = 10 cm

Similar observations have been made by Vivian in 1950. According to him the reduction in tensile strengths of mortars of alkali reactive aggregates give a useful clue to the possible behaviour of the aggregate in mortar or concrete and about the future performance of the mortar or concrete, when used in engineering structures. The severity of cracking according to him depends "On the number of reactive particles in the aggregate and to some extent to the size of the reactive particles".

On the other hand the mortars with moderate expansions, show only a few cracks and the less reactive mortars do not show any reaction nor contain any microfractures. Thus the tensile strength studies of the mortars appear to fairly predict about the degree of reactivity of an aggregate and their behaviour in mortars.

Evaluation of Potential Alkali Reactivity of Aggregates by Chemical tests and their correlations with mortar bar tests and Petrographic characteristics.

The test results on the different aggregates generally show that there is a very poor correlation between the chemical behviour and the mortar bar tests of the rocks under study. The results obtained through chemical tests have been found to be misleading with certain varieties of aggregates. It is further observed that even in the aggregates belonging to certain geological formations with very nearly similar petrographic features (such as texture of the rock, texture of individual mineral grains and minerological composition), the values obtained with the tests differ considerably and are highly misleading as far as their behaviour with cement alkalies are concerned.

In the following paragraphs the results of chemical tests with each group of rocks are discussed and a comparison is made with the results obtained with the mortar bar tests.

Granitic Rocks:(Table-9): In most granites, granodiorites and gneisses it is observed that there is no consistent relationship between the Sc/Rc Ratio and their mortar bar expansions. For example a granite (Sp.No.15 G.R. from Bhongir) indicates a maximum expansion of 0.11% in the mortar bar test but according to the chemical behaviour the Sc/Rc ratio is less than unity (Sc/Rc=18/24). Petrographically the rock contains a high proportion of strained quartz while the petrographic examination of the mortar also shows clear symptoms of reaction. Similar inconsistency between mortar bar expansions and chemical tests is also observed in the case of other granites (as seen from the table (Sp.No. 2 GR, 3 GR, 9 GR, 14 GR) also. On the other hand a granite gneiss (Sp.No.10GR) shows negligible expansion in mortar bar tests, while under the chemical tests its gives a higher value i.e. of the order of 50.6/24. Moreover, it is notable that the mortar (10 GRH) does not contain any strained quartz nor it shows any indication of deterioration.

2) CHARNOCKITES: In the case of charnockites also there does not appear any correlation between the mortar bar tests, and the chemical tests. For example, the Acid charnockite, (Sp.No.1 C H) indicating maximum expansion of 0.12 percent in mortar bar expansion studies, give the value as Sc/R6- 5/16, under the chemical tests, i.e. a very low ratio, which has been found to be least indicative of the behaviour of the rock with the high alkali cements. The petrographic examination of the mortar of the rock shows a disruption, due to a distinct reaction with strained quartz in a specimens with 40% strained fractured and granulated quartz. Similar inconsistent relationship between the mortar bar tests and chemical tests is observed.

in other charnockite type of rocks also (SP.No. 2 CH, 3 CH, 4 CH, 5 CH, etc.).

3) BASALTS : In the case of basalts, the relations between the mortar bar tests and the results between the chemical data is far from satisfactory. Basalts which do not contain even traces of chalcedony or opal produce high Sc/Rc values in the chemical test (Table 11) though in mortar bar test, may show negligible expansions. Petrographically, even in basalts showing high mortar expansions, and indicating disruption the correlation is not consistent. However, out of the three reactive basalts, a correlation between the mortar bar tests, and chemical test is observed only in one case (Sp.No.5 T) (Table 11).

4) SANDSTONES: The correlation between mortar bar tests and the chemical tests is somewhat better in the case of sandstones, though there is some inconsistency. For example the sandstone (SP.No. 6 SS) shows mortar bar expansion of 0.25 percent and the sandstone (Sp.No. 1SS) gives an expansion of 0.11 percent, but according to the chemical test the Sc/Rc ratio is 2.1. for (Specimen No. 6 SS) and is 2.8 for (Sp.No.1 SS).

The petrographic examination of all the reactive sandstones shows that chert forms a common constituent. The sandstones (Sp.No.1 SS, 9SS) have a good percentage of clayey material of finely divided sericite, chlorite and kaolinite. They also contain 8 to 10% chert and are found to be reactive both in mortar bar expansion test as well as under the chemical test.

As observed in other types of rocks, however there is some discrepancy in the test results. For example sandstone (Sp.No. 2 SS) shows negligible expansion under mortar bar test but produces a very high Sc/Rc ratio of 6.0. This sandstone is purely a quartzose rock with iron oxide as cementing media and does not contain even traces of chert, opal or chalcedony.

5) QUARTZITE: In the case of quartzites, correlation between the mortar bar expansions and the chemical test is observed only in about 25 percent cases. (Sp.No.1Q, 2Q), while the reactive quartzite. (Sp.No. 3Q, 9 Q)indicate high to moderate expansions, are innocuous according to chemical test (Table 13). On the other hand some quartzites show negligible mortar bar expansions and do not contain any chert or strained quartz (Sp.No. 5 Q, 7 Q, 10Q)are classed as reactive through the chemical tests.

6) PHYLLITES AND SCHISTS: In the two specimens studied (1 SCH, 1 PH) in this class, there is some correlation between the mortar bar tests, chemical tests and the petrography. In the case of highly reactive phyllite and schist showing deleterious mortar expansion (above 0.10%), the Sc/Rc ratio is higher than unity (Table 13), thus indicating a fairly good correlation between chemical test and mortar bar test. The aggregate also appears reactive according to petrographic examination (Chapter IV) and found to contain appreciable amounts of strongly undulatory quartz (Sp.No.SCH 1) and microcrystalline quartz (Ph 1).

The experiments of chemical test points to the following observations.

It is observed that even in the highly reactive granites, charnockites and quartzites, the silica release (Sc) is not always related to their behaviour with high alkali cement. Some of the highly reactive charnockites, granites, quartzite show a lower silica release than the non-reactive rocks of the same group. It is also observed that the granitic rocks with high percentage of sericitized albite, weathered felspar, altered micas, chlorite show a high silica release even if they do not produce mortar expansions. On the other hand fresh granite and charnockites rocks containing strained quartz, and felspars in appreciable quantities show low silica release. From this it appears that though sericitized felspars, altered biotite are not found reactive with cement alkalies still they indicate high silica release under the chemical tests and the silica release does not truly represent, the reactivity of the rock. In the basalts some of the ferruginous silicates and microlites of labrodorite may be responsible for such a phenomena. Such discrepancies between the chemical effects and the mortar bar expansions have been observed by many others workers including Benton (1955), Mielenz (1958). The anamolous behaviour of the aggregate in alkaline solutions has been attributed by them to the presence of certain altered micas, sericite and carbonates.

Studies made by various other research workers of the U.S.Bureau of reclamation (1958) have also reported of anamolour behaviour of aggregates under chemical test.

Tables (9 to 14) Showing results obtained during mortar expansion studies and chemical test.

TABLE 9

GRANITES

Sp. No.	Rock type	Stratiagraphic Unit		Nature of reactivity	Percentage of reactive constituent	Mortar-bar expansion in six months (%)	Reactivity according to chemical tes Sc/Rc ratio
		Locality	Stratiagraphic unit				
1.	2.	3.	4.	5.	6.	7.	8.
1 GR	Microcline Granite	Hyderabad (A.P.)	Archean	Innocuous	The rock contains strained quartz in negligible quantity	0.031	$\frac{21.6}{24}$ =0.90
2 GR	Microcline Granite	Kazipet (A.P.)	"	Very Reactive	Contains 38% moderately undulose, Fractured Quartz	0.093	$\frac{21}{32}$ =0.65
3 GR	Alkali Granite	Kawali Tq. (Nellore Distt.)A.P.	"	Moderately reactive	Contains 25% moderately undulose slightly fractured quartz.	0.077	8/18 =0.44
4 GR	Biotite Granite	Gudur(A.P.) Patrigmdum	"	Innocuous	Contains strained quartz in negligible quantity.	0.037	-
5 GR	Biotite Granite	Karimnagar (A.P.)	"	Innocuous	Most of the quartz shows uniform extinction.	0.025	$\frac{18.6}{16}$ =1.15
6 GR	Biotite gneiss	Tumkur (Siddaganga quarry)Mysore State.	"	Innocuous	Quartz is recrystallised and shows uniform extinction.	0.024	$\frac{18}{20}$ =0.90
7 GR	Microcline Granite gneiss	Kherulu (Guj.State)	"	Innocuous	Recrystallised rock, quartz shows uniform extinction	0.025	-
8 GR	Biotite Granodiorite	Dhone M 25/1 (M.B.) Benaras Cape Comorin road	Archean, Peninsular Granites	Reactive	Contains 38% Moderately undulatory, fractured quartz	0.084	26/16 = 1.62

1.	2.	3.	4.	5.	6.	7.	8.
9 GR	Biotite Granodiorite	Kandi (A.P.) M 20/4 Hyderabad Sholapur Road	Archean	Very Reactive	35% Moderately undulatory fractured quartz.	0.098	-
10 GR	Biotite Granite Gneiss	Madanapally M-158/1, Madras-Bombay Road	"	Innocuous	Recrystallised rock contains unstrained quartz.	0.030	50.6/24=2.1
11 GR	Augite Granite	Khammam	"	Less Reactive	Contains strained quartz in negligible amount	0.056	18/16= 1.2
12 GR	Quartzose Gneiss	Bangarpet (Mysore State)	Dharwar	Innocuous	Recrystallised rock contain unstrained quartz	0.027	-
13 GR	Quartz Syenite	Kangayam(Siwamalai quarry) Coimbatore Distt. Madras State	Archean	Innocuous	Contains negligible amount of quartz.	0.012	-
14 GR	Biotite Granite	West Chittor (Ammaswamypally quarry) A.P.	"	Highly reactive	Contains 38% strongly undulatory, fractured quartz.	0.10	11/24 =0.4
15 GR	Biotite Granite	Bhongir (A.P.)	"	Highly reactive	Contains 40% strongly undulatory quartz.	0.11	18/24=0.75
16 GR	Quartz Gneiss	Gaya (Bihar)	"	Innocuous	Contains negligible strained quartz.	0.023	10/21= 0.4
17 GR	Microcline Granite Gneiss	Jhansi (U.P.)	"	Innocuous	Contains strained quartz in negligible amount.	0.024	14/25=0.56
18 GR	Tonalite	(Kharak quarry) Bhiwani, Haryana	Precambrian	"	Contains un - strained quartz totally.	0.021	8/40=0.20

TABLE 10

CHARNOCKITES

Sp. No.	Rock type	Stratiagraphic Unit		Nature of reactivity	Percentage of reactive constituent	Mortar bar expansion in six months	Reactivity according chemical test Sc/Rc ratio
		Locality	Stratiagraphic unit				
1.	2.	3.	4.	5.	6.	7.	8.
1 CH	Acid Charnockite (Enderbite)	Tholudur M-127, Veppur Trichy road (South Arcot distt.) Madras State.	Unclassified crystallines of perimsular India	Highly reactive	Contains 40 % strongly undulose, fractured, granulated quartz.	0.12%	5/16 =0.31
2 CH	Acid Charnockite (Enderbite)	15 miles north of Madras City (Madras State)	"	Reactive	30% moderately undulose quartz	0.086%	8/18=0.44
3 CH	Acid Charnockite (Bikermite)	Coonoor, M-9/6 Ooty Mettue Palayam road, Madras State	"	Reactive	40% strained quartz.	0.088%	23/36=0.68
4 CH	Intermediate Charnockite	Thirukali Kundram (Madras State)	"	Reactive	35%	0.083%	-
5 CH	Acid Charnockite (Enderbite)	Walajabad (Patamalai Quarry) Madras State	"	Modrately Reactive	38 % strained quartz.	0.076%	-
6 CH	Acid Charnockite (Bikermite)	Acharapakkam (Palipettai Quarry)	"	Reactive	32% moderately undulose, fractured quartz.	0.080%	16/48=0.33

1.	2.	3.	4.	5.	6.	7.	8.
7 CH	Acid Charnockite	Dumka (Pasabal quarry) Bihar	Archean	Innocuous	Quartz shows uniform extinction.	0.010	7.3/40 - 0.19
8 CH	Intermediate Charnockite	Nammakkal (Goolipally quarry)Madras State	Unclassified crystallines of peninsular India	Innocuous	-do- strained quartz in minor quantity.	0.039	2/20 -0.10
9 CH	Acid Charnockite	Tennipally (Madras State)	"	"	"	0.030	-
10 CH	Garnet granulite	Adoni (A.P.)	"	Highly reactive	40% strongly undulatory fractured and granulated quartz.	0.116	-
11 CH	Basic Charnockite	Daltonganj	Archean	Innocuous	Strained quartz in negligible amount only 12%.	0.010	-

BASALTS

Sp. No.	Rock type	Stratiagraphic Unit		Nature of reactivity	Percentage of reactive constituent	Mortar bar expansion in six months(%)	Reactivity according to chemical tes Sc/Rc ratio
		Locality	Stratiagraphic Unit				
1 T	Zeolitic Basalt	Panwal, M 44/7 Bombay-Poona Road(Maharashtra)	Cretaceons to Eocene	Innocuous	No reactive constituent observed	0.031	11/28 =0.51
2 T	Zeolitic Basat	Surat (Gujarat State)	"	"	"	0.034	$\frac{36.3}{48.0}$ =0.756
3 T	Glassy Basalt	Bhuj (Mile 23 Bhuj-Mandvi Road, Maharashtra).	"	Very Reactive	Contains 7% Palagonite & 8% primary glass	0.097	$\frac{131.8}{192.0}$ =0.68
4 T	Basalt	Thana- M-19 Bombay-Agra Road, Maharashtra	"	Innocuous	No Reactive constituent	0.030	7.3/24.0=0.30
5 T	Porphyritic Olivine Basalt	Khamgaon, M-31, Akola Khamgaon road (Maharashtra)	"	Highly Reactive	Contains 9% fibrous chalcedony with inclusion of tridymite. Primary glass-6%.	0.14%	$\frac{154.2}{100}$ =1.542
15 T	Porphyritic Basalt	Gondal (Gujarat State)	"	Highly Reactive	Contains 8% Chalcedony, and 4% primary glass.	0.12%	-

TABLE 12 SANDSTONES

Sp. No.	Rock type	Stratigraphical Unit		Nature of reactivity	Percentage of reactive constituents	Mortar bar expansions in six months(%)	Reactivity according to chemical test Sc/Rc ratios
		Locality	Stratia-graphic				
1 SS	Lithic Sandstone	Kundaghat (Himachal Pradesh)	Siwalik	Highly Reactive	Contains 8% chert (microtocrypto-crystalline quartz)	0.11	68/24 -2.89
2 SS	Quartzose Sandstone	Kota(Rajasthan)	Upper Vindhyan	Innocuous	No reactive constituent composed wholly of quartz showing uniform extinction.	·0.34	54/9 -6.00
3 SS	Quartzose Sandstone	Durg Madhya Pradesh	Lower Vindhyan Cuddapah	Highly Reactive	Contains 10% chert.	0.13	32/20 -1.60
4 SS	Quartzose Sandstone	Bilaspur Distt.(Madhya Pradesh)	"	Extensively Reactive	Contains 15% chert.	0.18	$\frac{32}{22}$ - 1.60
5 SS	Quartzose Sandstone	Bhind, Madhya Pradesh	Upper Vindhyana	Innocuous	No reactive constituent. composed wholly of unstrained quartz.	0.033	- -
6 SS	Quartzose Sandstone	Chinthala M.86/1,Kurnool-Gudur Road (A.P.)	Kurnool formations (Lower Vindhyan)	Extensively Reactive	Contains 20% Chert which forms the binding matrix.	0.25	34/16 -2.125
7 SS	Argillaceous Sandstone	Near Kalka ½ mile on Kalka-Simla Road (H.P.)	Siwalik	Moderately Reactive	Contains highly clayey and argillaceous material consisting of fine shreds of sericite, Kaolinite.	0.062	24/18= 1.33

1.	2.	3.	4.	5.	6.	7.	8.
8 SS	Quartzose Sandstone	Sagar	Upper Vindhyan	Innocuous	No reactive constituent contains totally unstrained quartz.	0.022	$\frac{26}{33}=0.79$
9 SS	Lithic Sandstone	Palanpur (Chitrasani Quarry) Rajasthan	Tertiary	Highly reactive	Contains 8% chert and matrix is clayey in nature.	0.13	39/16-2.44
10 SS	Quartzose Sandstone	Mirzpur	Upper Vindhyan	Innocuous	No reactive constituent contains unstrained quartz & a minor percentage of clay.	0.022	48/43 -1.11

TABLE 13

QUARTZITE

Sp. No.	Rock Type	Stratiagraphic Unit		Nature of Reactivity	Percentage of Reactive Constituents.	Mortar bar expansions percent.	Reactivity according chemical te Sc/Rc ratio
		Locality	Stratia-graphic unit				
1.	2.	3.	4.	5.	6.	7.	8.
1 Q	Quartzite	Vijayawada (A.P.)	Dharwar	Highly Reactive	Strongly undulose fractured quartz. About 75 percent.	0.114	25/24= 1.44
2 Q	Cherty hematite quartzite	Birmitrapur Shimdiga Road M.128/1,(Bihar)	*	Extensively	60% Micro to crypto crystalline quartz (chert)	0.28	244/64= 3.81
3 Q	Quartzite	Prodattur (A.P.) M.118/6 Nellore-Bombay Road.	Cuddapah	Highly Reactive	5% Micro to crypto crystalline quartz (chert)	0.115	33/72 =0.46
4 Q	Quartztite	Nargund Tq.	Dharwar	Highly reactive	Strongly undulose fractured quartz constitutes more than 60%.	0.11	-
5 Q	Quartzite	Badarpur Delhi State	Aravalli (Delhi system) Cuddapah	Less reactive	Most of the quartz shows uniform extinction.	0.058	44/2[illegible]=1.89
6 Q	Quartzite	Dadri (Gurgaon Distt.)Haryana	Navalli (Delhi system) Cuddapah	Innocuous	Most of the quartz shows uniform extinction	0.038	-
7 Q	Quartzite	Baria (Maharashtra)	Dharwar	Innocuour	All quartz shows uniform extinction	0.020	$\frac{26.7}{16}$ =1.04
8 Q	Quartzite	Nandalur (Cuddapah Distt) Andhra Pradesh	Cuddapah	Innocuous	All quartz shows uniform extinction	0.023	-

1.	2.	3.	4.	5.	6.	7.	8.
9 Q	Quartzite	Walajabad (Kovolkud quarry) Madras State	Unclassified crystalines of peninsular India	Moderately reactive	Contains more than 40% Moderately undulose fractured quartz.	0.076	20/33 =0.60
10 Q	Quartzite	Nuzwid (Andhra Pradesh)	Unclassified crystallines of peninsular India.	Innocuous	Most of the quartz shows uniform extinction.	0.039	$\frac{38.5}{22}$ =1.75

TABLE 14

PHYLLITES AND SCHISTS

Sp. No.	Rock Type	Stratiagraphic Unit		Nature of Reactivity	Percentage of reactive minerals	Mortar bar expansions percent	Reactivity according to chemical test Sc/Rc ratio
		Locality	Stratiagraphic Unit				
1PH	SlatyPhyllites	Hubli distt. (Mysore State).	Dharwar	Extensively Reactive	Contains 12% micro crystalline quartz (Chert)	0.18	42/40 =1.05
2 PH	Sericite phyllite	Dalhousie (H.P.)	Dharwar	Moderately reactive	Contains argillaceous material made up of fine shreds of sericite, kaolinite and chlorite.	0.62	38/25 = 1.50
1 SCH	Chlorite quartz Schist	Haliayal (Mysore State)	Dharwar	Highly Reactive	Contains about 50% strongly undulatory and sheared quartz.	0.14	58/55 =1.54

TABLE 15 : TENSILE BRIQUETTE STRENGTHS OF REACTIVE AND NON-REACTIVE AGGREGATES

Sp. No.	Locality, Rock type, Texture of Silicious Constituent.	Mortar bar expansion percent in six months	Tensile briquette strength		Loss in Tensile strength of mortar in 3 months.
			28 days	3 months	
1.	2.	3.	4.	5.	6.
2 GR	Microcline Granite-Kazipet (A.P.) contains about 38% strained, fractured quartz.	0.093 % Reactive	260 lb/sq" (18.30 kg/cm^2)	240 lb/sq" (16.90 kg/cm^2)	Loss in tensile strengt is 7.7%
4 GR	Microcline Granite-~~[illegible]~~ Nellore (A.P.). Most of the quartz is free from strain effects.	0.043% Less reactive	240 lb/ssq" (16.90 kg/cm^2)	250 lb/sq." (17.60kg/cm^2)	Gain in strength of 4.1 percent.
8 GR	Biotite Granodiorite-Dhone (A.P.). Contains about 35% strained quartz.	0.084% Moderately Reactive.	280 lb/sq" (19.71 kg/cm^2)	260 lb/sq." (18.30 kg/cm^2)	Loss in tensile strengt is 7.1%.
1 CH	Acid Charnockite- Veppur area Madras State. Contains 40% strongly undulatory fractured and granulated quartz.	0.12% Highly Reactive	260 lb/sq." (18.30 kg/cm^2)	220 lb/sq." (15.49 kg/cm^2)	Loss in strength-15.3%
3 CH	Acid Charnockite-Coonoor (Madras State). Contains strained quartz about 40%	0.088% Moderately Reactive.	265 lb/sq." (18.66 kg/cm^2)	250 lb/sq." (17.60 kg/cm^2)	Loss in strength =5.7%
10 CH	Garnet Granulite-Adoni (A.P). Contains 40% strongly undulatory, fractured and granulated quartz	0.116% Highly Reactive	240 lb/sq." (16.90 kg/cm^2)	200 lb/sq" (14.89 kg/cm^2)	Loss in strength =16.6

1.	2.	3.	4.	5.	6.
5 T	Basalt-Khamgao(Maharashtra). Contains interstitial glass in minor quantity and about 9% amgdular chalcedory (chalcedony contains traces of tridymite).	0.14% Highly Reactive	280 lb/sq." (19.71 kg/cm^2)	220 lb/sq." (15.49 kg/cm^2)	Loss in tensile strength of mortar of about 21.4%
13 T	Basalt-Nirmal Taluqua (AP). Free from interstitial glass or amgdular chalcedory.	0.40% Innocuous	260 lb/sq" (18.30 kg/ cm^2)	300 lb/sq." (21.12 kg/cm^2)	Gain in strength of about 14.13%.
15 T	Basalt-Gordal(Gujarat State).Contains interstitial glass in minor quantity and amgdular chalcedory about 8%.	0.11 % Highly Reactive	290 lb/sq." (20.41 kg/cm^2)	250 lb/sq." (17.60 kg/cm^2)	Loss in tensile strength of 13.9%.
1 SS	Lithic: Sandstone- Kurdaghat'H.P.) Contains 8% chert and predominantly clay.	0.11% Highly Reactive	240 lb/sq" (16.90 kg/cm^2)	200 lb/sq." (14.89 kg/cm^2)	Loss of about 16.6% in tensile strength.
6 SS	Quartzose sandstone.Chinthala(AP). Contains 20% chert, which also forms the cementing matrix.	0.25% Extensively Reactive	260 lb/sq" (18.30 kg/cm^2)	210 lb/sq." (14.98 kg/cm^2)	Loss in strength of about 19%.
1 Q	Quartzite-Vijayawada (A.P.). Contains predominantly strongly undulatory fractured quartz.	0.114% Highly Reactive.	200 lb/sq." (14.89 kg/cm^2)	160 lb/sq." (11.26 kg/cm^2)	20.0% loss in strength
2 Q	Cherty Hematite Quartzite, Birmitrapur-Bihar. Contains more than 60% micro to crypto crystalline quartz.	0.20% Extensively Reactive	270 lbs/sq." (19.01 kg/ cm^2)	230 lbs/sq." (16.20 kg/cm^2)	14.2 % loss in strengt
3 Q	Quartzite-Prodattur (A.P.). Contains 5% micro to cryptocrystalline quartz. (chert)	0.115% Highly Reactive	280 lbs/sq." (19.79 kg/cm^2)	220 lb/sq." (15.49 kg/cm^2)	21.4% loss in strength
5 Q	Quartz ite-Delhi. Free from Strained quartz.	0.058% Less Reactive	240 lb/sq." (16.90 kg/cm^2)	260 lb/sq." (18.30 kg/cm^2)	Gain in strength of 8.

FIG. 4 SHOWING MORTAR BAR EXPANSIONS WITH GRANITOID ROCKS (GRAPH-1)

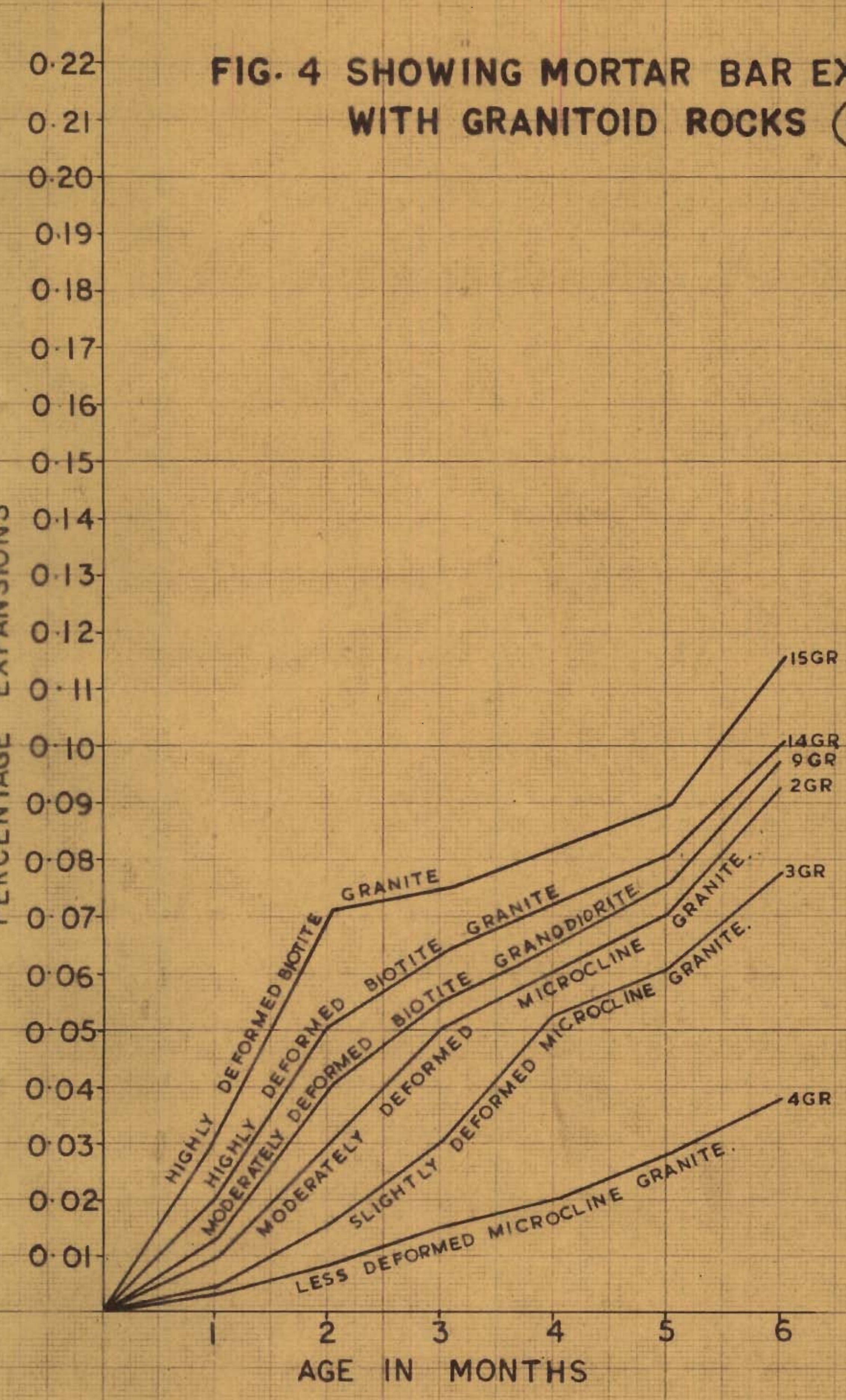
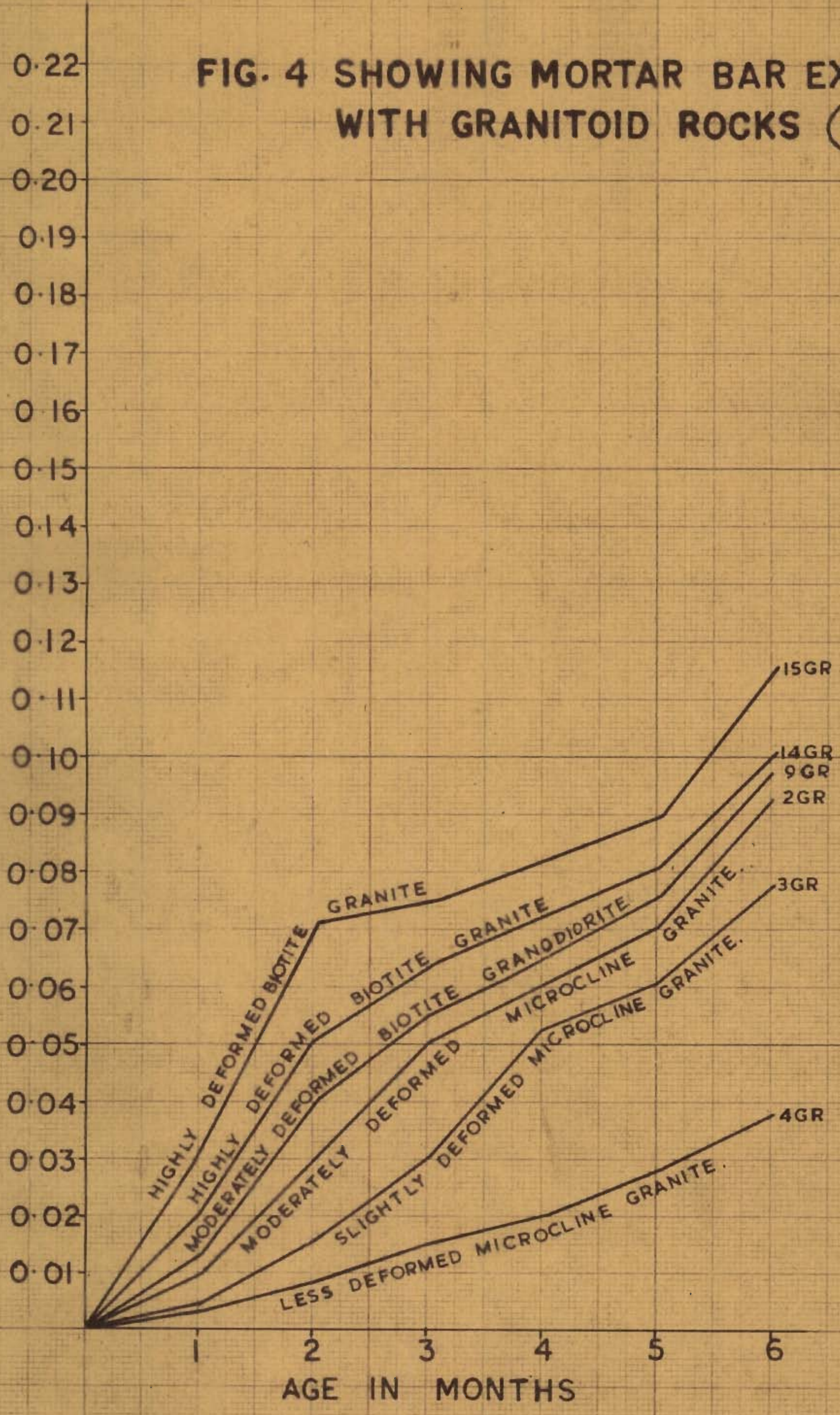


FIG. 4 SHOWING MORTAR BAR EXPANSIONS WITH GRANITOID ROCKS (GRAPH-I)



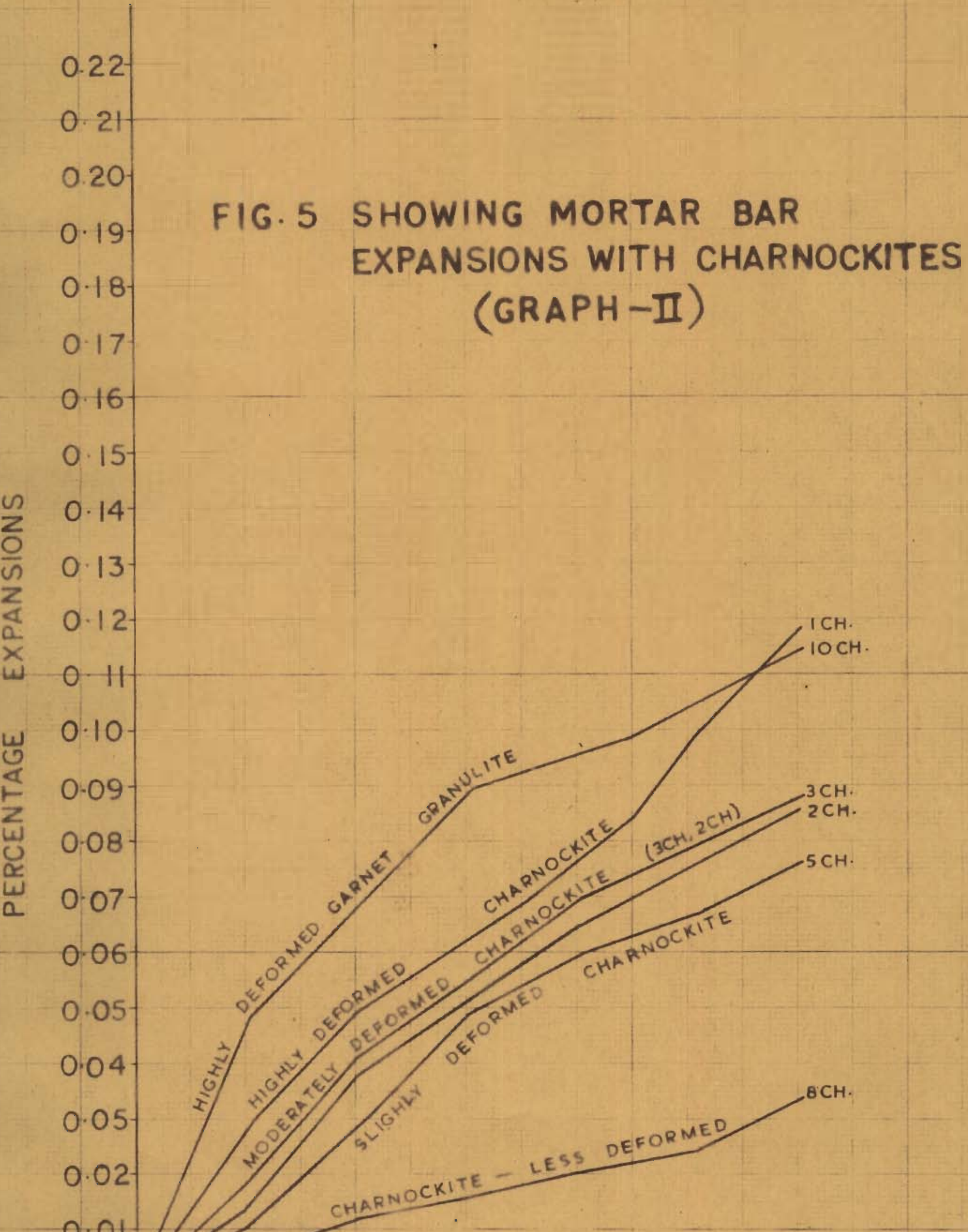


FIG. 5 SHOWING MORTAR BAR EXPANSIONS WITH CHARNOCKITES (GRAPH – II)

FIG. 6 SHOWING MORTAR BAR EXPANSIONS WITH BASALTS (GRAPH-III)

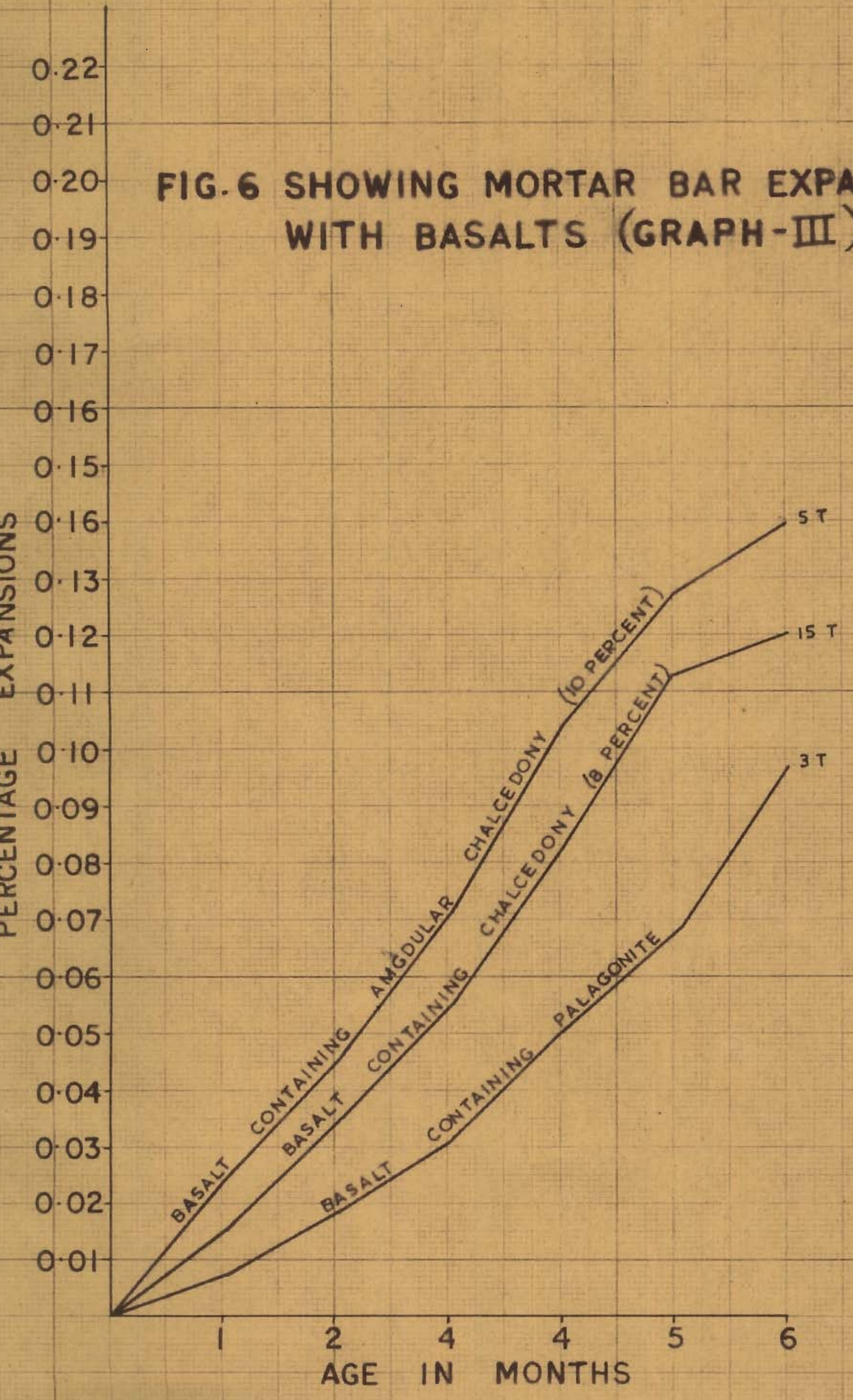
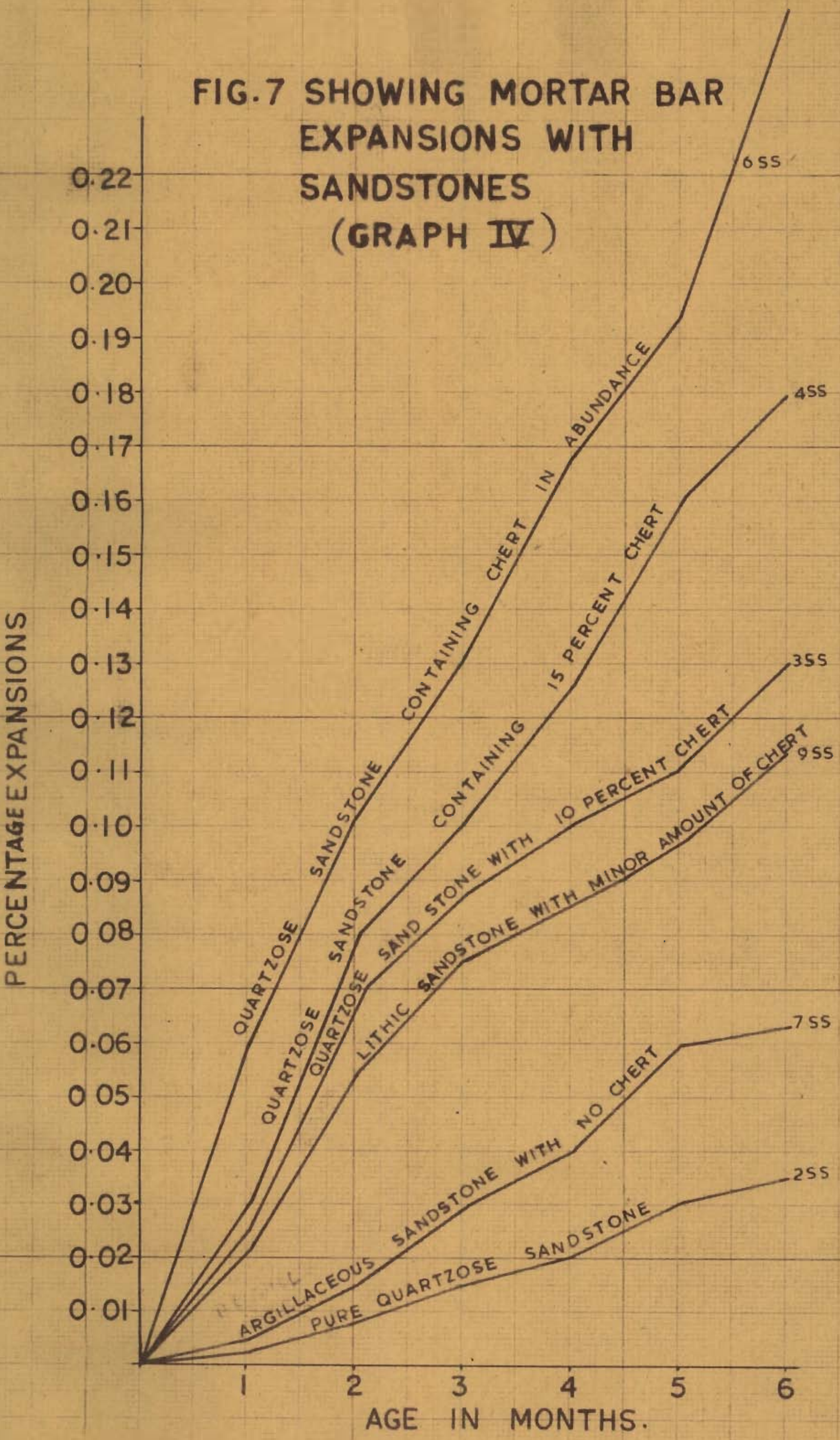


FIG.7 SHOWING MORTAR BAR EXPANSIONS WITH SANDSTONES (GRAPH IV)



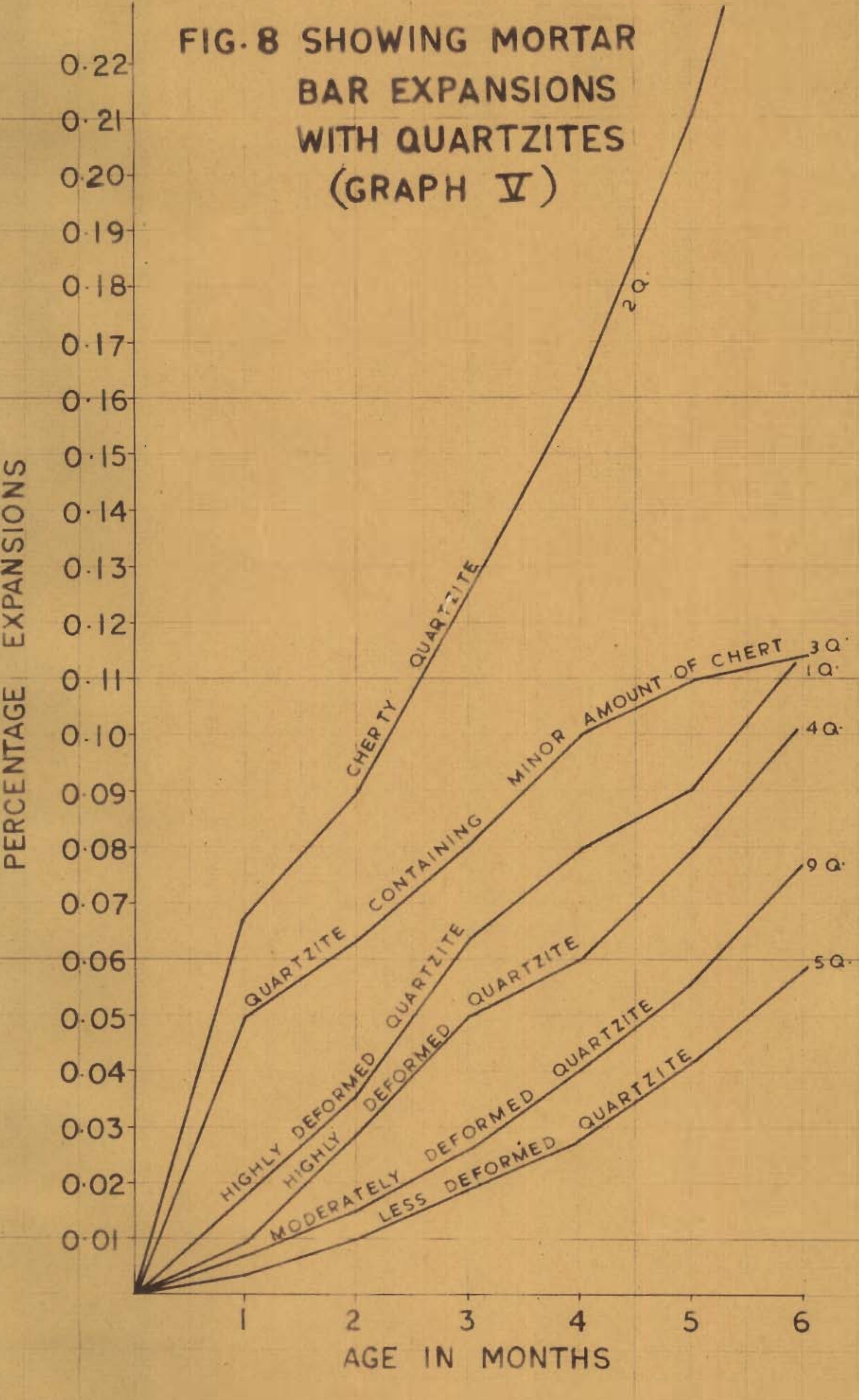


FIG. 8 SHOWING MORTAR BAR EXPANSIONS WITH QUARTZITES (GRAPH V)

FIG. 9 SHOWING MORTAR BAR EXPANSIONS WITH PHYLLITESAND SCHIST (GRAPH VI)

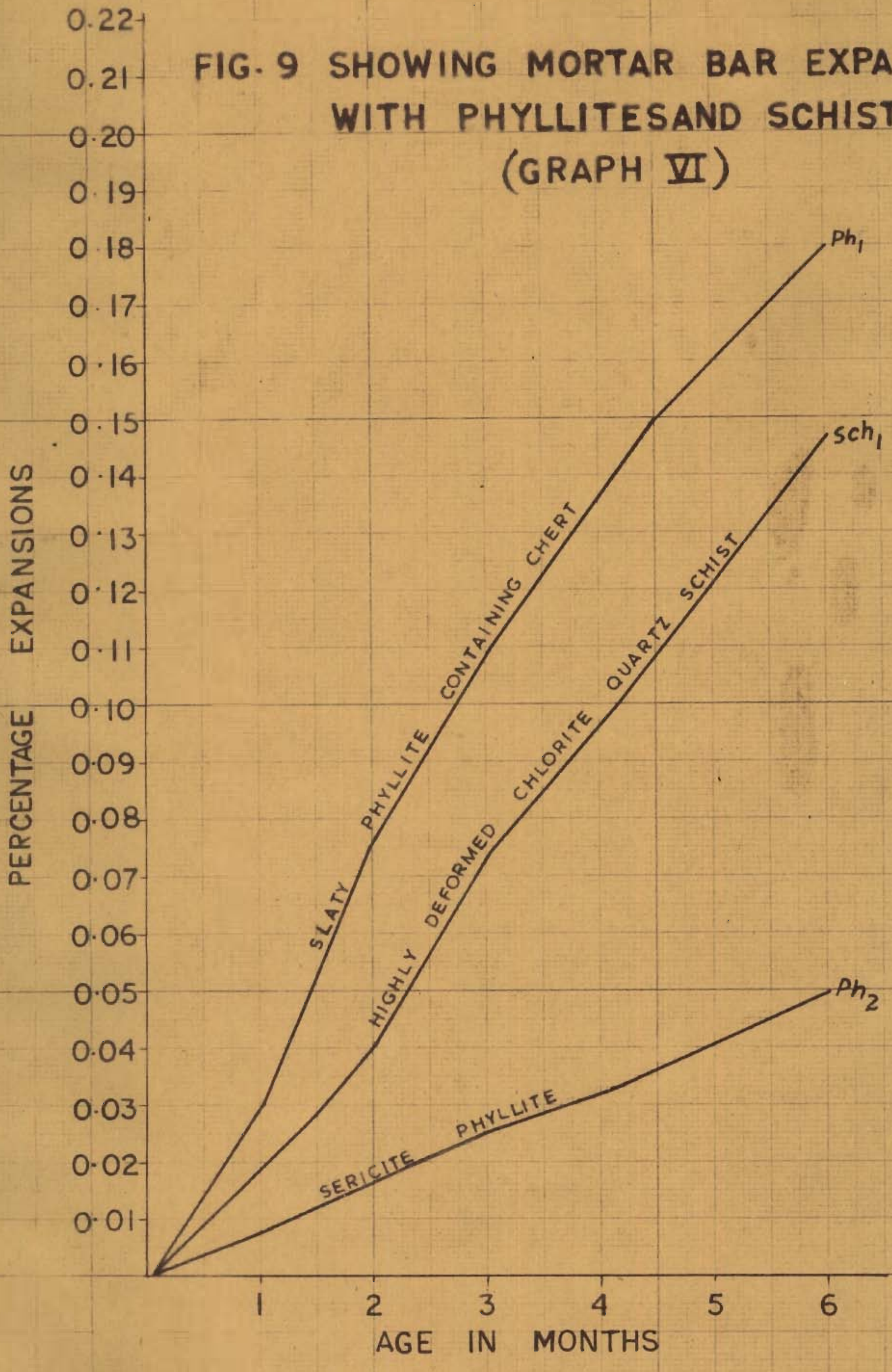
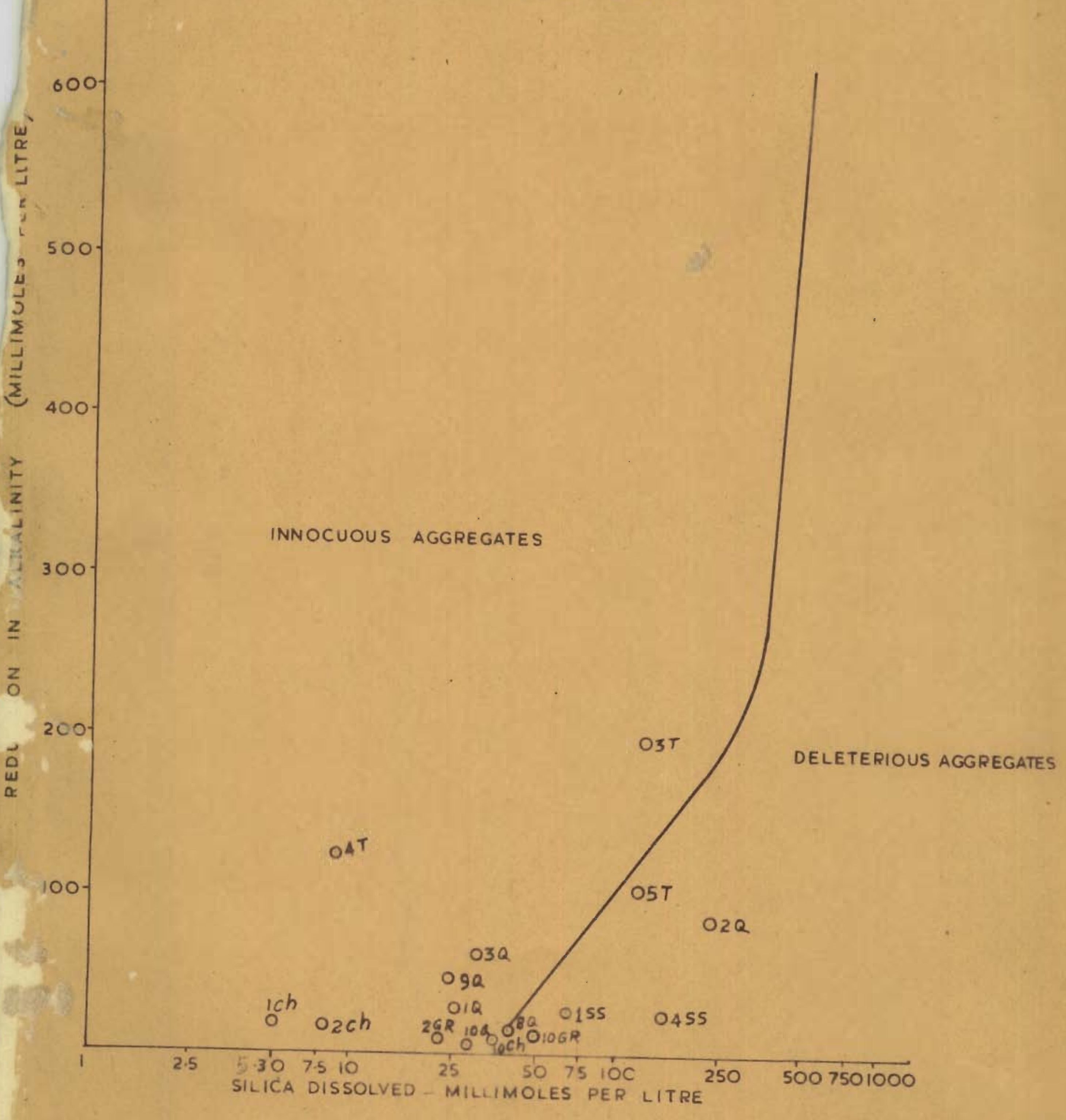


FIG. 12 GRAPHICAL ILLUSTRATION OF DIVISION BETWEEN INNOCUOUS & REACTIVE AGGREGATES BY CHEMICAL TEST ASTM C-289-57T



CHAPTER VI

QUARTZ AND OTHER ALLIED SILICA MINERALS AND THEIR SUSCEPTIBILITY TO ALKALI AGGREGATE REACTIONS

A review of the earlier works on alkali aggregate reactions in foreign countries has revealed that the lower forms of silica viz. opal, chalcedony, chert, volcanic glass, and tridymite are not only associated with the reactions but are considered as the prime-reasons for the same. However, the present study though limited in nature indicates that the alkali reactivity in certain Indian aggregates, (apart from the rocks containing the above reactive constituents) may be caused in a number of seemingly innocuous rocks like granites, charnockites, quartzites and schists also. It has been observed that this reactivity in these rocks may be due to the higher forms of silica i.e. the strained quartz. These rocks are commonly used as concrete aggregates in India. In this chapter an attempt has been made to classify the reactive constituents in these rocks occurring in the various geological formations of India. The optical properties in silica minerals have been observed to vary widely and appear to be related to the lattice defects, which make them susceptible to chemical reactivity with cement alkalies.

Based on the microscopic observations on the affected mortars, their expansions etc., the present study also attempts to discuss the mechanism of alkali aggregate reactions with the silica minerals.

In the following table the silica minerals, their occurrence and the general textural features in the rocks under study, are given.

TABLE 16

No.	Silica Mineral	Textural characters in the rocks studied	Occurrence in the rocks studied.
1)	Quartz	a) Medium to coarse grained Quartz, showing Uniform Extinction. b) Medium to coarse grained quartz showing slight undulose extinction. (angle of undulose extinction on 'C' axis less than 5°. c) Medium to coarse grained, sometimes fractured quartz, showing moderate undulose extinction (Angle of undulose extinction above 5° but less than 20°). d) Medium to coarse grained, fractured quartz, showing strong undulose extinction. (Angle on 'C' axis above 20°). e) Granulated quartz showing mortar structure. f) Recrystallised quartz.	In granitoid rocks, charnockites, quartzites, schists, phyllites and sandstones.
2)	Chert	Micro-to crypto-crystalline quartz.	In quartzites phyllite and sandstone.
3)	Chalcedony	Fibrous and feathery structure. Fibrous extinction conspicuous, low birefringence	As amygdular fillings and veins in basalts.
4)	Opal	Isotropic, low refreactive index of about 1.44 to 1.47	In traces in a basalt.
5)	Tridymite	Pseudohexagonal grains characterized by low birefringence and low relief.	In traces, as inclusions in chalcedony in a basalt.
6)	Volcanic glass	Fibrous extinction, slightly vescicular texture, low birefringence.	Interstitially in the ground mass of basalts.

I. HIGHER FORMS OF SILICA

QUARTZ

As indicated in the Table 16 above, on the basis of the extinctions quartz can be classified as:

Unstrained, Strained, Granulated Strained, quartz, etc.

i) Medium to coarse grained quartz with uniform extinction:-

This is observed mostly in the sandstones and less reactive and innocuous granites, granodiorites, syenite, gneisses, charnockites and quartzites. In these rocks, the mineral quartz usually occurs as subhedral grains varying in size from 0.5 to 1.8 mm and sometimes contains inclusions of iron ore and rarely chlorite and biotite. Zircon and needle like inclusions of rutile are generally observed in quartz. Generally the extinction is uniform and the grains are free from fracturing. The percentage of this type of quartz in the rocks studied varies from 5 to 80 percent.

As observed earlier on pp. 59,60 ,72, 87,this quartz does not show any indications of reaction with cement alkalies in the mortars. Most the grains show sharp and distinct outlines and symptoms of reactions are negligible if not nil, and thus can be classed as innocuous.

ii) Quartz with slight undulose extinction: This is predominant in all the reactive sandstones, and less reactive granites, charnockites, gneisses and quartzites. The mineral generally occurs as subhedral grains, almost in all rock types and exhibits weak and broad strain shadows. The angle of undulose extinction is generally between 2°-5° and never exceeding 10°.

This variety of quartz is generally free from fracturing, and does not show any reaction with cement as described in the Chapter IV

iii) <u>Moderately undulose quartz</u>:- This type is common in all the reactive granites, charnockites, quartzites, schist and rarely in the sandstones and varies between 25% to 30%. The quartz grains are from subhedral to an hedral and varying in size from 0.6 to 2 mm. The common inclusions are iron ore and sometimes needlike rutile and pink garnet or zircon. The mineral generally shows an undulose extinction and the angle of extinction varies between 10 to 20°. Sometimes the grains are fractured and the fracture planes are filled with laths of sericite.

Most of the quartz grains show symptoms of chemical reaction with cement alkalies in the mortars. But only a very thin film of gel is seen deposited along the periphery of the reactive quartz particles. Very rarely the cracks emanating from the boundaries of the grain cause only a slight disruption of the mortars, and thus appear to be only moderately reactive.

As reported on p.p. 105,106 (Chapter-V) the expansion of mortars made up with crushed rocks rich in this type of moderately undulose quartz vary between 0.62%to 0.90%.

iv) <u>Medium to coarse grained strongly undulatory fractured quartz</u>:

This is the most abundant form of quartz in the highly reactive granites, charnockites, quartzites and the sample of schist.(Sp.No.1 CH, 10 CH, 15 GR, 14 GR, 1Q, 9Q, 1SCH). In these cases the grain size varies between 0.7 to 2.5 mm, and the inclusions are very similar to those present in the other varieties of quartz and include, iron ore, zircon and rutile. This type of quartz generally shows a peripheral granulation and most of the grains show well separated zones of undulatory extinction with an angle varying from 20° to 27°. In a few specimens, particularly in quartzite (1 Q, 9 Q) deformation lamellae are also observed in a majority of the quartz grains. The lamellae are generally long shaped and appear to pich out before reaching the margin of the grain (as described in Chapter IV P. 57,58,68, 90). In most of the rocks the quartz is often fractured and exhibits different patterns of fracturing, which can be classified as

a) fracture in the core with a clear granulated marginal rim

b) fractures running parallel to the undulatory bands

c) fractures running across the undulatory bands. The fracture planes in these quartz are sometimes filled up with laths of sericite and rarely with brecciated grains.

When examined petrographically the quartz in mortars show distinct symptoms of chemical reaction with the cement alkalies (as described in Chapter IV). The mineral in the mortars shows boundary corrosion and marginal fracturing, with a clear rim of a low birefringent gel product along the peripheries. Moreover some of the smaller grains of strained quartz, show a strong reaction with cement alkalies and are seen eveloped in a thick mass of gel.

Another notable feature is the occurrence of gel filled cracks, sometimes seen emanating from the boundaries of the highly reactive quartz. Most of these reacted particles are seen interconnected through these cracks. The occurrence of such cracks associated with strained quartz indicate a swelling of the particles due to reaction with cement alkalies.

The rocks rich in this variety of quartz show high mortar expansions varying between 0.10 to 0.14 percent (see pp.105,107,111).

v) Granulated strained quartz: This variety is observed only in the highly reactive granites, charnockites and a schist (sp. No. 15GR, 1CH, 10 CH, 1 SCH) and constitutes about 10 to 15 percent of the total quartz grains in these rocks. Generally each in which each part exhibits an undulose extinction and show extreme intercrystal suturing. The quartz is very often associated with coarse grained and strongly undulose quartz.

This quartz shows distinct symptoms of chemical reaction with cement alkalies in the mortar bar test. The rocks with about 10 to 15% granulated quartz generally show high mortar expansions varying between 0.11 to 0.14 percent.

vi) Recrystallised quartz: This variety is developed prominently in the less reactive and innocuous aggregates and to a very minor extent in a few reactive granites and the quartzites. The recrystallised granites, gneisses and migmatized rocks show negligible expansions in mortars.

Strained (Undulatory) quartz:- In metamorphic processes like deformation and recrystallisation development of undulatory (strained) quartz is a common feature. Fairbairn (1941), Ingerson and Tuttle (1945), Turner (1948) Christie and Raleigh (1957), Carter etal (1964) have noted that undulatory extinction in quartz is a common feature of the metamorphosed rocks where plastic deformation due to dynamic pressure is predominant. All the above authors observe that this undulatory quartz is common in deformed rocks but not in the recrystallised types. According to them recrystallisation would generally tend to form a new strain free quartz which will not show undulatory extinction unless it is again subjected to deformation processes.

Very little work has been reported about the imperfections in quartz grains and their deformation structures due to metamorphic processes. However, Cottrell (1949), Guinnier (1952), Read and Shockley (1952) observed that if a crystal is deformed plastically it would contain a large number of dislocation zones. As a result of the 'x' ray studies of quartz from various sources Bell (1953) noticed that "Laue" photographs of quartz from certain rocks show asterism while in some others splitting of spots takes place instead of well defined and sharp reflections as may be expected from a relatively perfect crystal. Further studies by Bailey etal (1958) not only confirmed the observations of Bell, but also demonstrated that the 'Laue' patterns of deformed quartz crystals depends on crystallographic orientation. The appearance of such laue patterns changes with the intensity of deformation in a specimen. They also observed that there is a fair degree of correlation between 'Laue' patterns and the degree of undulatory extinction- exhibited by the quartz grains. In specimens with strong undulatory extinction in quartz, accompanied by fracturing and marginal granulation, the quartz produced 'Laue' patterns which are both greatly elongated and show polygonized asterism streaks. On the other hand according to Bailey etal the quartz grains with uniform extinction or very slight undulatory extinction give sharp 'laue' patterns. After a careful study of a number of 'x' ray patterns Bailey et.al (1958) concluded "The optical features and the details of 'x' ray patterns may be explained and correlated by a theory involving dislocations and polygonization in quartz, whereby the bent crystal is transformed into a number of elongate, relatively perfect crystallites inclined to each other at small angles and separated by regions of atomic misfit. Undulatory extinction can thus be explained as an optical expression of the results of bend gliding and polygonization". They further argued that as the deformation of quartz increases in intensity the extinction bands become regular, narrow and more pronounced. This character is thought to be a consequence of the greater concentration of the unit cell dislocations.

Bomel etal (1955) in their monumental paper estimate that the unstrained natural quartz has a density of stable dislocations of approximately 10^3 dynes per cm^2. They argued that strained quartz will have higher dislocation densities. Carter etal (1966) have established, and is now widely accepted that quartz may deform in a ductile manner like a metal. Thus the dislocation theory applied to metals by cottrell (1949), Read and Shockley (1952) can be applied to quartz also.

Carlie and Janieson (1964) subjected quartz crystals to a pressure of 600 kilobars and then examined these under X-rays and indicated of a splitting of spots. On the basis of X-ray patterns they concluded that a great many dislocations in quartz are due to high pressures indicating a disordering of the quartz structure.

Solubility of Quartz: Experiments conducted by Fredrickson and Cox (1954) on the solubility of quartz at elevated temperatures (300 to 500°C) and pressures (300 kilo bars) have shown that solubility of quartz is due to the dissolution of cement binding the quartz grains. It was argued that this cement may be a strained zone. On further experiments at 360°C and 3 kilo bar pressures, in(1955) they concluded that quartz has a pronounced mosaic structre. The smallest mosaic units are tiny rods approximately 0.0009 mm. in diameter and 0.009 to 0.05 mm in length. Thus the solubility of quartz was attributed to the mechanical loosening of the rods (forming the crystal) so as to produce a relatively large surface area, easily attacked by solvents.

<u>Increased Chemical reactivity due to strain:</u> On the basis of published literature it is common knowledge that the chemical and physical behaviour of solids are influenced by processes likely to

introduce strain energy, which is a manifestation of defects, and the molecular dislocations. Foldham (1949) found that strained crystals of ammonium nitrate appeared to grow relatively faster in a solution than the unstrained ones, indicating a greater chemical reactivity of ammonium nitrate with the solution due to strain. Similar observations has also been recorded by Buckley(1951) on Cadmium iodide crystals. Frank (1951) has reported similar observations on silicon carbide crystals and observes that "growth of a crystal in a solution is affected by the number of dislocated zones existing in a crystal and it should be possible to promote growth of crystals which have ceased to grow by mechanically deforming them."

In (1965) Bush and Williamson reported that mechanically strained synthetic crystals of magnesium oxide, in contract to the unstrained crystals produce greater amounts of Foresterite and protoenstatite due to solid state reactions with quartz cristobalite mixtures at 1200-1400°C. While discussing the phenomena, they are of the opinion that the enhanced surface energy of strained magnesium oxide might have resulted in greater chemical reactivity.

From the above conclusions, derived by different workers like Bailey (1958), Bomel (1955), Fredrickson (1955), it can therefore be said that strained quartz, characterized by undulatory extinction, is more reactive towards cement alkalies than the unstrained quartz, because of the presence of large number of dislocated zones of silica. The weakening of the silican-oxygen-bond due to strain also is an important factor, which makes it conducive to chemical reactivity with cement alkalies. The deformation of quartz in the rocks not only induces strain energy but as a result of shearing could involve penetrative intergranular movement, the repeated renewal of surfaces of contact and the increase of specific surface by grain size reduction. This could also be a cause for a greater reactivity of strained quartz, besides the large number of dislocation zones present in the strained quartz.

As has been observed (p.105,107, Ch.V) during the studies, the mortar bar expansions for aggregates of granites, charnockites quartzites (Sp. No. 1 CH, 10 CH, 15 GR 1Q, 9Q) with sheared and granulated quartz are slightly higher as compared to the rocks containing moderately undulose quartz.

Observations of Fordham (1949), Buckley (1951), Frank (1951), Bush and Williamson (1965) also indicate of greater chemical reactivity in deformed and strained crystals, which has been ascribed to the presence of dislocations, and enhanced surface energy.

Another important factor which is considered to have contributed for a greater reactivity of strained quartz is the presence of fractures. These fractures are helpful for an easy penetration of cement alkali, solutions into the quartz lattice. According to Christie and Raleigh (1959) the fracture planes in strained quartz may be considered as planes of discontinuity in the crystals. According to Christie and Raleigh (1959) "the most obvious and common indication of post-crystalline deformation in quartz is the appearance of undulose extinction in zones subparallel to (0001). When the strain is slight the variations in extinction is continuous over a grain, but when the strain is more intence the grain is divided into distinct zones bounded by sharp surfaces of discontinuity. These boundaries are not distinctly planer and their orientation cannot be measured with a 'U' stage, indicating that they are not rational crystallographic planes but rather curved or irregular surfaces." Thus the presence of fractures can also be the cause of greater reactivity of strained quartz. Mielenz and Brown (1955) also observed that a quartzite rock with abundant strained, fractured and granulated quartz reacted with cement alkalies and produced a gel. Similar observations have also been made with a sheared quartzite aggregate which showed alkali aggregate reaction, in a structure in South India (1961).

Thus it can be said that the textural characteristics in quartz as interpreted above are directly related to its chemical reactivity with cement alkalies. A strongly undulatory, fractured and granulated quartz in a rock whether granite, charnockite, quartzite in appreciable quantity may be harmful.

II. Low forms of Silica

a) Micro to Cryptocrystalline Quartz (Chert): Chert is essentially a micro to cryptocrastalline quartz according to many workers like Folk and Weaver (1952) Jones (1952) etc. During the present studies chert has been found in reactive sandstones from Chinthala, (Kurnool formations of Lower Vindhyan), Durg and Bilaspur, Palanpur (Tertiary) and Kundaghat (Siwalik), in which the mineral occurs either as a detrital constituent or as a cementing media. Two quartzites (Sp. No. 2 Q, 4Q) from Birmitrapur (Dharwar), and Prodattur (Upper Cuddapah) also are found to contain Chert and are highly reactive. A reactive phyllite also contains microto cryptocrystalline quartz. Thus, it is observed mostly in the sedimentary and a few metasedimentry rocks. It is observed that if a rock contains even 5% chert it shows a high mortar bar expansion.

As discussed on pp. 109,110 the percentage of mortar bar expansion has been found to be generally related to the percentage of chert in the rock aggregate. In most specimens, studied chert is generally found to be dissiminated and is coated with iron oxide and at times contains minor inclusions of chlorite (Sp. No. 6SS Sandstone from Chinthala).

Behaviour of chert with cement alkalies:

It has been observed that most of the chert is heavily reacted with cement alkalies and exhibits deep corrosion and dissolution. Sometimes the chert fragments are seen to occur as relict grains engulfed in a thick mass of gel. The boundary zone of the deteriorated chert fragments is generally characterized by an intense opacity of the cement matrix. The intense chemical reaction of chert particles with cement alkalies in the surrounding matrix gives rise to a low birefringent, gel product. At times due to its high chemical reactivity the chert particles are totally altered to a gel. The reacted fragments show long narrow cracks emanating from the boundaries. These cracks ~~are~~ are generally filled up with the gel material. The cracks ~~are~~ generally appear as 1) Link Cracks 2) Peripheral cracks (as described on p.p.85,86,87 Chapter IV). Link cracks can be described as those which interconnect two reacted fragments of chert and are commonly gel filled. Their occurrence in the mortar indicates swelling of the reacted fragments of chert. The peripheral cracks indicate shrinkage of the chert fragements due to reaction with cement alkalies.

The high chemical reactivity of chert with cement alkalies may be ascribed to its large internal surface area, and poor crystallinity. The transitional structure which interlocks a number of grains of micro to cryptocrystalline quartz in chert is a strained region and thus contains a large number of dislocated zones which make it conducive to chemical reactivity as discussed in the previous pages.

b) Chalcedony: It is found to occur as in the reactive basalts from Khamgaon and Gondal (Sp.No. 5T, 15T) as amygdular fillings and vein

Microscopic features:- The grain of chalcedony occurring as amgdular filling vary in size from 0.5 to 0.8 mm and are generally colourless with impurities of iron ore. Fibrous extinction is conspicuous and the length of the fibers vary with size of the grain, which is about 0.3 to 0.5 mm. In a highly reactive basalt from Khamgaon (Sp.No. 5T) chalcedony is found to contain inclusions of tridymite, which occurrs as preudohexagonal grains characterized by low birefringence. The percentage of chalcedony in the basalts studied varies between 8 to 10%.

c) Basaltic glass: The reactive basalts were found to contain minor amount of interstitial glass in the groundmass. However, a basalt from Bhuj (Sp.No. 3T) contains about 10 percent palagonite, characterized by pale brown colour and vesicular nature.

Behaviour of basalts containing chalcedony and palagonite in the mortar

As described in Chapter IV most of the fragments show corroded boundaries and reaction zones. Partial dissolution of the groundmass is indicated in the basalt containing palagonite. Chalcedony, which many times occurs as individual fragments shows deeply corroded boundaries and is seen enclosed in a mass of gel. Another important feature is the occurrence of gel filled cracks emanating from the mineral particles and sometimes from the margins of basalt fragments. As described earlier the occurrence of the peripheral cracks and link cracks indicate the swelling of the reactive particles, as are confined by the cement matrix and cause microfracturing of the mortar.

It has been also observed that the basalts containing chalcedony show a comparaitively higher rate of expansion, than the basalts with more reactive than palagonite. The basalt from Gondal (Sp.No.15T) which contains traces of opal also show a fairly high rate of expansion.

It has been observed that basalts, with the absence of palagonite, chalcedony, opal, and tridymite show negligible mortar expansions.

Chert, chhlcedony, opal and Tridymite: Considerable work has been done by different workers on the natura~~l~~ of these minerals and the exture of these minerals has been variously interpreted as:-

i) Sosman (1927), Donnay (1933) consider that chalcedony contains opal as an essential constituent.

ii) Folk and Weaver (1952) divide the microforms of quartz into

a) microcrystalline quartz made up of interlocking grains of quartz crystallites set in a random orientation.

b) Chalcedonic quartz consisting of radiating or sheaf-like bundles of fibers. 'X'-ray studies conducted by Folk and Weaver on chalcedony showed that chalcedony essentially consists of microcrystalline quartz.

iii)Raman and Jayraman (1955)conducted 'X'ray studies on chert, chalcedony and opal and have shown that chert and chalcedony consist essentially of quartz while opal is essentially a microcrystalline aggregate of disordered cristobalite.

iv) Jones (1952) has noticed that chert essentially consists of quartz crystallites. He considers chert as a strained form of quartz.

v) White (1955) observed that opal rarely exists in nature above 100°C and that at higher temperatures it crystallizes to chert or chalcedony and concluded that "The low thermodynamic stability of opal probably accounts for its rare occurrence in the older sediments".

vi) According to Florke (1957) tridymite is essentially a

vii) White and Corwin (1961) have opined that chert consists essentially of quartz crystallites which are somewhat misoriented and interlocked together by a strained transitional structure. They have also supported the view that opal is made up of disordered Cristobalite. According to them the large and variable water content in opal is primarily a consequence of extreme small particle size or large internal surface area. Similar observations have been made by Carr and Fyfe (1961).

Thus these studies discard the presence of opal in chalcedony and chert and have shown that all these minerals consist essentially of microcrystalline quartz. Pelto (1956) has made a detailed studies of the properties of chalcedony and its reactivity with sodium hydroxide. The chalcedony studied by him showed a strong reaction with sodium hydroxide X-ray study of the original specimen failed to indicate even traces of opal. The fibrous extinction in chalcedony according to Pelto is an effect of strain. He compared the biaxial character of chalcedony with that observed in strained metamorphic quartz and observed "It is well known that quartz subjected to mechanical stress becomes biaxial. Probably the simplest explanation of the optical properties of chalcedony, other than the refractive index is that they are strain induced". Later according to him "Chalcedony consists of quartz crystallites somewhat misoriented from fiber to fiber than within fibers. Differences in orientation of fibers are normally adjusted by means of a transitional structure. The fiber interface is marked by a set of dislocations". He has thus attributed the reactivity of chalcedony with alkaline solutions due to the presence of large number of dislocated zones in the mineral caused by the weakening of the silicon-oxygen bond due to strain.

Thus the Oft repeated, explained and attributed by chemical reactivity of chert, chalcedony, by the chemists can be ascribed to their micro-crystalline texture and therefore a large internal surface area. In addition, the presence of a large number of dislocation zones in these minerals are responsible for their chemical reactivity with cement alkalies. The chemical reactivity of volcanic glasses could also be due to the disturbed atomic structure and due to strain in the silican-oxygen bonds, formed as a result of rapid cooling. The reactivity of Opal and tridymite can also be said to be due to poor cystallinity and disturbed lattice structure with large internal surface area, and most of the strained forms of silica would react with cement alkalies though they may not contain any opal.

Plate 21: Fig. 1: Electron micrograph (8370x Mag) of cherty~~mf~~ quartzite (Sp. 2Q). The ragged and denticular outlines observed in the mineral indicate poorcrystallinity. The aggregate is highly reactive with cement alkalies.

Plate 21: Fig. 2: Electron micrograph (8370xMag.) of a quartzose sandstone from Kota. The mineral grains exhibit straight, sharp and distinct outlines indicating well developed crystallinity. The aggregate is found to be innocuous towards reaction with cement alkalies.

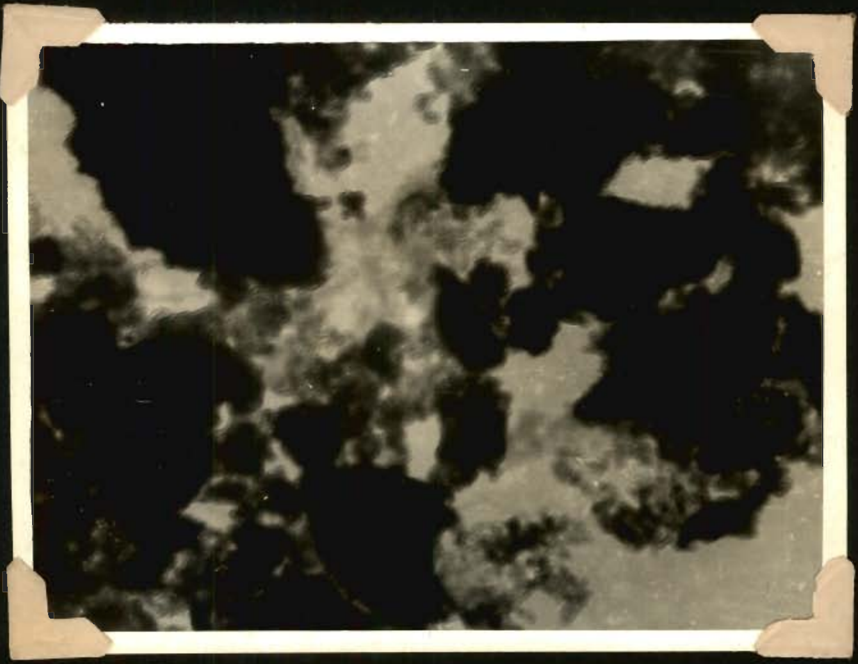


Plate 22: Electron micrograph (8370x Mag.) of an alkali silica gel. The roundness of the grains indicate an amorphous nature.

CHAPTER VII

SUMMARY AND CONCLUSIONS

The phenomenon of alkali aggregate reactions in cement concrete first became known in the year 1940, when the deterioration of some of the concrete structures in California (U.S.A.) was attributed by Stanton to the chemical reactions between cement alkalies and certain silicious constituents in the aggregate. The problem has been well studied in most of the developed countries, while almost nothing is known on the vulnerability due to the attack of cement alkalies, in this country. With this in view, the present studies have been carried out and an evaluation of Indian aggregates has been attempted.

A review of the work of different authors, as given in the second Chapter leads to the important conclusions that:-

a) Deterioration of concrete structures, in addition to sulphate attack, also takes place due to chemical interaction between cement alkalies, as released during the hydration of cement and certain silicious constituents like opal, chalcedony, chert and volcanic glass in the aggregate.

b) Deterioration is more prevalent when the percentage of alkalies in cement is high i.e. 0.6% or more, though a few cases with lower alkali content are also known. From this, it appears that it is therefore not possible to fix the maximum and the minimum safe alkali content in cement in concrete masses, so as to prevent against this type of deterioration in concrete structures.

c) Two important mechanisms namely the "Osmotic Pressure theory"(Hansen-1944) and the "Gel theory" (Vivian-1950) have been advanced to explain the disruption of concrete due to alkali aggregate reactions. The first is based on the assumption that, the reaction product (alkali silica gel) exists in the form of acqueous sodium silicate causing cracks due to osmotic pressures in the concrete masses, while the "gel theory" explains the disruption of concretes due to the swelling nature of the reaction product and consequent pressures in concretes.

d) However, it appears that the problem has not been well studied from the point of view of minerals in the aggregate, their textures, though such reactions and the resultant failures have been reported on the use of rocks like glassy rhyolites, andesites, i.e. volcanic types, a few opaline sandstones and rarely even with massive quartzites and granites. Only a few investigators, namely Brown (1955), Mielenz (1958) and Idorn (1961) have paid some attention to the petrographic characters of the rocks, their mortars and the concretes.

As regards the Indian aggregates, mostly the aggregates used are prepared from the plutonic and metamorphic types and only rarely from the sedimentry or metasedimentry rocks.

Since the resultant concrete mass is also a product similar to the rocks, the problem of ascertaining the potential chemical reactivity in aggregates is fairly complicated. Therefore the commonly acceptable mortar bar expansion tests for concrete testing at different periods along with the petrographic examination of the aggregates, and the affected mortars have been adopted. In later Chapters, on the basis of these studies, fairly good relations with the petrographic nature of the rock and the textural characteristics of the reactive constituent and the behaviour of aggregates with cement alkalies have been established.

Chapter IV described the petrography of aggregates and their mortars, from the important construction centres in India. The aggregates studied for potential alkali reactivity belong to a number of widely separated localities and stratiagraphical horizons. Most of the aggregates are found to be hard and durable and satisfy the requisite engineering properties for concrete purposes but their compressive strengths are variable from 845 to 3380 kg/cm^2 and the shear strengths between 140 to 220 kg/cm^2. As established by other earlier workers, these variations in the engineering behaviour of rocks may be due to the variations in their textural and minerological characteristics.

The common rock aggregates have been classified into six major varieties as i) Granitoid rocks- including various biotite and microcline granites, granodiorites and gneisses, syenites. ii) Charnockites-acid, basic and intermediate types. iii) Basalts, iv) Sandstones v) Quartzites, including metamorphic quartzites and metasedimentry quartzites. vi) Phyllite and schist.

On the basis of their reactive and non-reactive nature both types may be found in the same geological horizons. The reactive character of the rock seems to be considerably changed due to a higher percentage of silicious minerals and the effects of metamorphism on these. It is observed that the Archean and pre-cambrian granites, charnockites, quartzites etc. with distinct cataclastic effects in quartz and sometimes in the plagioclase or biotite etc. are susceptible to alkali aggregate reactions. Similarly in the volcanic flows of the same regions, basalts with or without amgdules and nodules of chalcedony, palagonite, opal or tridymite, or absolutely massive and holohyaline types could be reactive or non-reactive. The sandstones and quartzites with chert, either as a cementing material or as a detrital constituent are highly reactive. On the other hand those varieties not containing chert or strained quartz are innocuous. The sandstones of the upper Vindhyans are generally free of chert and are innocuous, while those of the kurnool formations contain chert and are deleteriously reactive with cement alkalies. Metasedimentry quartzites and phyllites of Dharwar formations with chert are highly reactive.

The most important criteria which may be of importance with respect to the occurrence of reactive and non reactive aggregates in engineering structure are the i) Lithological composition ii) Grade of metamorphism iii) Hydrothermal reactions and iv) the nature of original sediments.

On the basis of the petrographic examination of the deteriorated mortars it is observed that the disruption is due to a gel formation around or in the vicinity of silicious constituents in the aggregates e.g. i) Strongly undulatory (strained) quartz, ii) Micro to cryptocrystalline quartz, (chert) iii) Chalcedony , iv) Volcanic glass, v) Opal, vi) Tridymite.

The reaction progresses from the outer margins of the reacted particles and is indicated by a) Boundary corrosion and embayments b) Deposition of a low birefringent granular gel product along the periphery of the reactive particles or disseminated in the surrounding cement matrix identified by patches of isotropic material c) Cracks of varying length (0.3 to 0.7 mm.) and wholly or partially filled with the gel are seen emanating from the boundaries of the reacted particles. About four types of cracks were identified during the study i) Link cracks, ii) Marginal or peripheral cracks, iii) Chain cracks, iv) Radial Cracks. The reacted fragments in the mortar are generally seen inter-connected through one or more type of these cracks. The occurrence of gel is a result of the chemical reaction between the reactive silicious constituents and the cement alkalies. Of these the peripheral or marginal cracks around a reacted grain may be due to shrinkage, while the cracks emanating from the boundaries (Link cracks, radial cracks) are caused due to the swelling of the reactive particles confined in the cement matrix. Nevertheless the total dissolution of a cherty, chalcedonic or opaline particles into a gel, filling the slender elongated cracks in the surrounding cement matrix, indicates that the gel product has an excessive tendancy to swell.

It can therefore be stated that the disruption of mortars due to alkali aggregate reaction is caused by the swelling action of both the reacted particles and the reaction product.

In Chapter V, a correlation between the petrographic characters of the aggregates and the engineering behaviour of their mortars is attempted. As a result of this study, it is noted that rocks of identical characters (megascopic) are found to differ considerably in their expansion characteristics in the mortars, indicating that if an aggregate is to be studied for alkali reactivity, its petrographic nature must also be studied, through microscopic examination. It is further noted that even if an aggregate possesses remarkably good engineering properties, it may be highly reactive towards cement alkalies, and hence there does not exist any relation between their engineering properties and their chemical reactivity with cements.

It is observed that 1) in the cases of granites, charnockites, quartzites and schist, the mortars showing expansions more than 0.10% are rich in highly fractured, strongly undulose or highly granulated quartz and sometimes deformed felspars. In mortars with expansions more than 0.10% the angle of undulose extinction in quartz varies between 18 to 27° (on 'C' axis) while in rocks with mortar expansions between 0.06 to 0.10 this angle is between 10° to 20°. On the other hand rocks with unstrained or recrystallised quartz show negligible mortar expansions. Thus it can be inferred that the alkali reactivity is directly related to the percentage of straining effects in quartz. As a result of this a rock with 40% or more undulatory or fractured and granulated quartz may be highly susceptible to alkali reactions. A rock with 30 to 40% strained, fractured quartz is moderately susceptible, while a rock with less than 30% strained quartz is marginally reactive. Similarly rocks having less than 20% strained quartz are less reactive or innocuous, followed by those devoid of strained quartz which are totally innocuous.

Of the charnockites, the basic types can generally be considered as innocuous along with the recrystallised granites or gneisses.

Most basalts from Deccan plateau are free from reactive constituents and hence are innocuous. However, only a few basalts from Gujerat and Maharashtra with chalcedony, opal or tridymite, or palagonite show deleterious mortar expansions. Palagonite glass in the basalts may also be considered as highly reactive form of a silica. Of the basalts those containing even 4 to 5% primary glass along with 8 to 10% chalcedony are highly reactive. In the Indian basalts opal or tridymite are generally rare, but it may be stressed here that the presence of these two well known alkali reactive constituents even in minor amounts may prove very harmful in the aggregates.

There seems a broad correlation between the mortar bar expansions and the tensile strengths. The tensile strength of mortar decreases with the age in case of reactive aggregates. This property can be used as a supplementry test in the evaluation of the alkali reactivity of aggregates.

In Chapter VI, the chemical reactivity of strained quartz and the other silica minerals are discussed. As a result of these discussions it is concluded that the undulatory extinction in strained quartz indicates that there are a set of dislocations or islands of atomic misfit, which give rise to possible planes of weak energy and thus help a greater reactivity of strained quartz with cement alkalies. On the other hand, the unstrained quartz is fully bonded with silicon-oxygen bonds and there is no possibility of weak energy planes and thus remains innocuous in contrast to the strained quartz.

The chemical reactivity of chalcedony, chert,opal and volcanic glass can also be considered due to distrubed atomic structure.

The problem of alkali aggregate reaction, thus needs to be reviewed from the point of view of textural characteristics in the rocks and the lattice displacements in the silica minerals indicated by the micro to crypto crystalline structure and the undulatory extinction in quartz.

Thus it can be said that the petrographic studies and examination of concrete aggregates have decidedly got an advantage as compared to other methods, that it is fairly reliable and gives the quickest results.

The present study had been somewhat limited in nature and further studies would be useful to explore the alkali reactivity of such minerals like chert, palagonite and strained quartz.

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APPENDIX I

Table showing location of some of the important quarries of the rock aggregates studied.

Specimen number	Rock type	Locality	Longitudes and Latitudes.
1 Q	Quartzite	Vijayawada(A.P.)	16° 28' N, 80° 15' E
2 Q	Cherty Hematite quartzite.	Birmitrapur-Shimdiga road M.128/1 (Bihar)	22°32' N; 84°26' E.
3 Q	Quartzite	Prodattur M 118/6 Nellore Bombay Road (A.P.)	14°44'N; 78°28' E.
Q	Quartzite	Delhi (Badarpur quarry)	28°44' N; 77°10' E.
6 Q	Quartzite	Dadri (Gurgaon Distt.) Haryana.	29° 5'N;75°8' E
8 Q	Quartzite	Nandalur (Cuddapah Distt) (A.P.)	14°12'N; 78°44' E.
1 Ch	Acid Charnockite	Tholudur M-127, Veppur-Trichy Road(South Arcot Distt) Madras State).	12°44'N; 79°04'E.
2 Ch	Acid Charnockite	15 Mile North of Madras State	13°06'N; 80°14' E.
3 Ch	Acid Charnockite	Coonoor; M9/6, OOty Mettupalayam Road, Madras State.	11°14'N; 76°42'E.
7 Ch	Acid Charnockite	Dumka(Pasabal quarry) Bihar State)	87°21'N; 24°18E.
8 Ch	Intermediate Charnockite	Nammakhal(Goolipally quarry) Madras State	12°44', 79°28'E.
10 Ch	Garnet granulite (Acid Charnockite)	Adoni Distt.(A.P.)	15°48'N; 77°13' E.
1 GR	Microcline Granite.	Hyderabad City(A.P.) (Malakpet quarry).	17°26'N; 78°27'E.
2 GR	Microcline Granite.	Kazipet	18°0'N; 79°28'E.
4 GR	Microcline granite	Gudur Tq. (Patrigundam quarry)	14°26'N; 79°15' E.
5 GR	Biotite Granite	Karimnagar (A.P.)	18°26'N; 79°10'E.
6 GR	Biotite gneiss	Tumkur (Siddaganga quarry) M.5 from Tumkur on National Highway No.4, Mysore State.	13°26'N; 76°52'E.
8 GR	Biotite Granodiorite.	Dhone. M.25/1, Benaras-Cape Comorin Road; (A.P.)	15°42'N; 79°34'E.
9 GR	Biotite Granodiorite.	Kandi-(Bandalguda quarry) M.20/4, Hyderabad-Sholapur Road, (A.P.):	17°28'N; 78°12' E.

Specimen Number	Rock type	Locality	Longitudes and Latitudes.
10 GR	Biotite granite gneiss.	Madanapally. M 158/1 Madras-Bombay Road (A.P.)	13°28'N; 78°20'E.
13 GR	Syenite	Kangayam (Sivamalai quarry) Coimbatore Distt.Madras State.	11°44' N; 78°22'E.
14 GR	Biotite granite	West Chittor Distt. (Annaswamy Palli Quarry)(A.P.)	13°07'N; 79°05' E.
15 GR	Quartzose gneiss	Bangarpet Tq.Mysore State	13°07° N; 78°15' E.
16 GR	Biotite gneiss	Darjeeling.W.Bengal	27°01'N; 88°12'E.
17 GR	Quartz-magnetite gneiss	Gaya Distt.(Homba quarry)	24°48'N; 85°02'E.
1 Ph	Slaty Phyllite	Hubli-Distt.(Mysore State)	15°13'N; 75°09'E.
2 Ph	Sericite phyllite	Dalhouzie (H.P.)	32°28'N; 76°1' E.
1 Sch	Chlorite quartz schist	Haliyal Tq.(Mysore State)	15°24'N; 75°03'E.
1 SS	Lithic sandstone.	Kundahat (H.P.)	31°7'N; 77°2' E.
2 SS	Quartzose sandstone.	Kota Distt.(Rajasthan)	25°12'N; 75°35' E.
6 SS	Quartzose sandstone.	Chinthala.M. 86/1. Kurnool Gudur Road (A.P.)	15°45'N; 78°6' E.
7 SS	Argillaceous Sandstone.	Near Kalka.on Kalka Simla Road- H.P.	30°50'N; 77°04'E.
1 T	Zeolitic Basalt	Panwel Tq. M 44/7 Bombay-Poona Road, Maharashtra.	19°12'N; 73°5' E.
3 T	Glassy Basalt	Bhuj Tq. M.23/0 Bhuj Mandwi Road Gujarat State.	23°15'N; 69°42'E.
5 T	Basalt with chalcedony.	Khamgaon Tq., Distt. Akola M 31/3 Akola Khamgaon Road Maharashtra.	20°44'N; 77°3' E.
15 T	Basalt with chalcedony.	Gondal- 4 miles from Gondal on National Highway No. 8 B Gujarat State.	22°03'N; 70°55' E.

No.	Rock type and area	Percent water absorption	Compressive Strength (kg/cm2)	Shearing strength (kg/cm^2)	Modulus of Elasticity	Los Angles abrasion value wear (%)	Aggregate impact value.
13.	Basalt from Gordal	1.18	2250	200.0	3000	10.3	17.0
14.	Basalt from Naldurg.	2.80	2215	195.00	-	14.8	16.00
15.	Sandstone from Kota(Rajasthan)	0.82	1140	105.00	1240	17. 50	15.34
16.	Sandstone from Palanpur(Rajasthan)	1.10	1100	98.50	1050	22.30	11.10
17.	Sandstone from Kalka (H.P.).	1.40	858	74.20	920	31.50	9.30
18.	Sandstone from Durg (M.P.)	1.20	1110	82.50	1100	18.30	-
19.	Quartzite from Dadri(Haryana).	0.32	1800	125.00	4450	23.20	12.40
20.	Quartzite from Vijayawada.	0.42	1680	112.50	4220	22.15	11.43
21.	Quartzite from Walajabad.	0.40	1720	110.00	4550	20.25	12.21.

Engineering Properties of rock aggregates

No.	Rock type and area	Percent water absorption	Compressive strength (kg/cm^2)	Shearing Strength (Kg/cm^2)	Modulus of elasticity	Los angles abrasion value wear(%)	Aggregate Impa value.
1.	Microcline Granite Hyderabad(A.P.)	0.45	2110	208	2800	24.7	14.5
2.	Granodiorite-Kandi A.P.	0.48	2215	238	2850	22.8	14.
3.	Biotite Granite W.Chittor area A.P.	0.37	2100	220	2800	23.0	14.6
4.	Microcline granite Kazipet (A.P.)	0.40	2200	232	2750	25.4	15.0
5.	Biotite granite Madanpalli.	0.38	2440	235	-	21.2	15.5
6.	Biotite granite Bhongir.	0.42	2320	215.4	-	23.50	15.0
7.	Acid charnockite from Madras.	0.34	2210	-	2850	18.30	16.0
8.	Acid charnockite from Veppur area.	0.20	2420	228	3000	16.1	16.50
9.	Acid charnockite (Nilgiri hills) Cooroor area Madras State.	0.32	2340	219.5	2810	17.20	16.
10.	Basic charnockite from Daltonganj area(Bihar).	0.40	2450	208.30	2200	18.3	15.
11.	Acid charnockite Pallavaram,Madras State.	0.48	2100	198	2150	21.3	14.42
12.	Basalt from Khamgao Tq. Maharashtra.	1.00	2900.20	212.5	3780	9.5	18.