PART I

CORAL LIMESTONE AND ITS USE

PART II

CHEMICAL STABILIZATION OF CORAL SURFACES

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PART I

CORAL LIMESTONE AND ITS USE

ABSTRACT

Limestone of coral origin was abundantly used for construction of Military and Naval bases in the Pacific during World War II. Its use was almost always spectacularly successful and contributed largely to the successful operations against the Japanese Empire. Nevertheless a rigid analysis of the coral used reveals it to be a rather poor material. This study briefly reviews the theoretical concepts of the origin of coral deposits and describes the nature of the various types of deposits. From this a guide is established to assist the construction engineer in finding the coral he needs, sometimes a difficult problem.

The characteristics of coral deposits are explained and a method of processing the coral for desirable results is given, along with the reasons for the method. A logical explanation for the "setting up" phenomena is established.

PART II

CHEMICAL STABILIZATION OF CORAL SURFACES

ABSTRACT

The possibility of chemical stabilization of the top surface of coral bases to prevent dust is explored. The process involved is analysed and an order of magnitude of quantities determined. The necessary experiments to prove the process and tentative field procedures are outlined.

SECTION I

INTRODUCTION

Limestone, one of the earth's abundant construction stones, is plentifully available in most tropical and semi-tropical waters of the world in the form of coral reefs. Throughout the Indian and Pacific Oceans the bulk of the land formations are coral reefs. They occur in three general forms; fringing reefs, barrier reefs, and atolls, and reefs originally formed in one of the above forms and later elevated above sea level. In the same general forms coral is also present in quantity in the Red Sea, the Caribbean and as a component of the Florida keys. There is considerable evidence that many of the present land limestone formations, far removed from the present sea, originated as coral reefs in the ocean. As an example, fossil coral of the Mid Devonian period of the Paleozoic era have been identified in limestone deposits of Ohio.

In spite of the extensive use of land limestone and the widespread deposits of coral limestone the use of coral as construction stone was generally frowned upon prior to World War II. It was considered, at best, just a poor substitute to be used when other material was not economically available. This erroneous concept was so generally believed that Army and Navy Construction agencies even discussed the possibility of shipping acceptable grades of crushed rock for the construction of advanced bases on islands in the Pacific. In the Hawaiian Islands, where these discussions took place, coral had been used for many years for secondary roads by the Territorial Highway Commission and there existed in good condition several concrete structures built with coral, some subject to the destructive action of the surf. The main reason aggregate was not shipped, at least at first, was probably due to the critical shortage of ships. The later extensive and almost universal satisfactory use of coral by engineers, who were generally unfamiliar with its characteristics and, often as not, who were quite inexperienced, in construction of the many military bases in the Pacific has not only reversed this concept, but has led many to believe that coral is a construction panacea. While there is considerable reason for the latter belief it is not entirely true.

Coral limestone deposits occur in all varieties, from calcareous clay beds and banks of rotten coral to dense hard formations. Before discussing the source and use of the various varieties it is well to establish a definition of terms.

Vaughan defines a coral reef as "a ridge or mound of limestone, the upper surface of which lies, or lay at the time of its formation, near the level of the sea and is predominantly composed of calcium carbonate secreted by organisms, of which the most important are coral (polyps)". The term coral reefs will be used in this sense.

The word "coral" will be used to signify a mass of limestone that is a part of, or originated as a coral reef.

The organisms which are largely responsible for the formation of coral reefs will be referred to as coral polyps.

Coral clay is used to signify that material, originally produced by the coral polyps, that has been reduced to clay particle size by processes to be described.

The terms "soft" coral and "hard" coral will become clear when their source and use are described.

The term coral island is generally used to signify an island whose visible mass consists of coral reef formations. The characteristics attributed to coral islands are equally applicable to the coral reef section of those lands whose non calcareous basement foundation is visible, even to the extent of forming the principle portion of those lands. The term islet is used to identify the land mass, above high tide, on atolls. Figure 1 illustrates an islet on a typical cross section of an atoll reef, also showing the other component parts in proper relation.

The strand line of a land mass may be moved in vertical relations to that mass in two ways, either by a shift, upward or downward of the sea level, or a shift upward or downward of the land mass itself. Both will be described as an elevation or subsidence, an elevation indicating a lowering of the sea level or a raising of the land mass and a subsidence indicating the opposite.

SECTION OF AN ATOLL

Typical Values Given

Vertical Scale Exaggerated

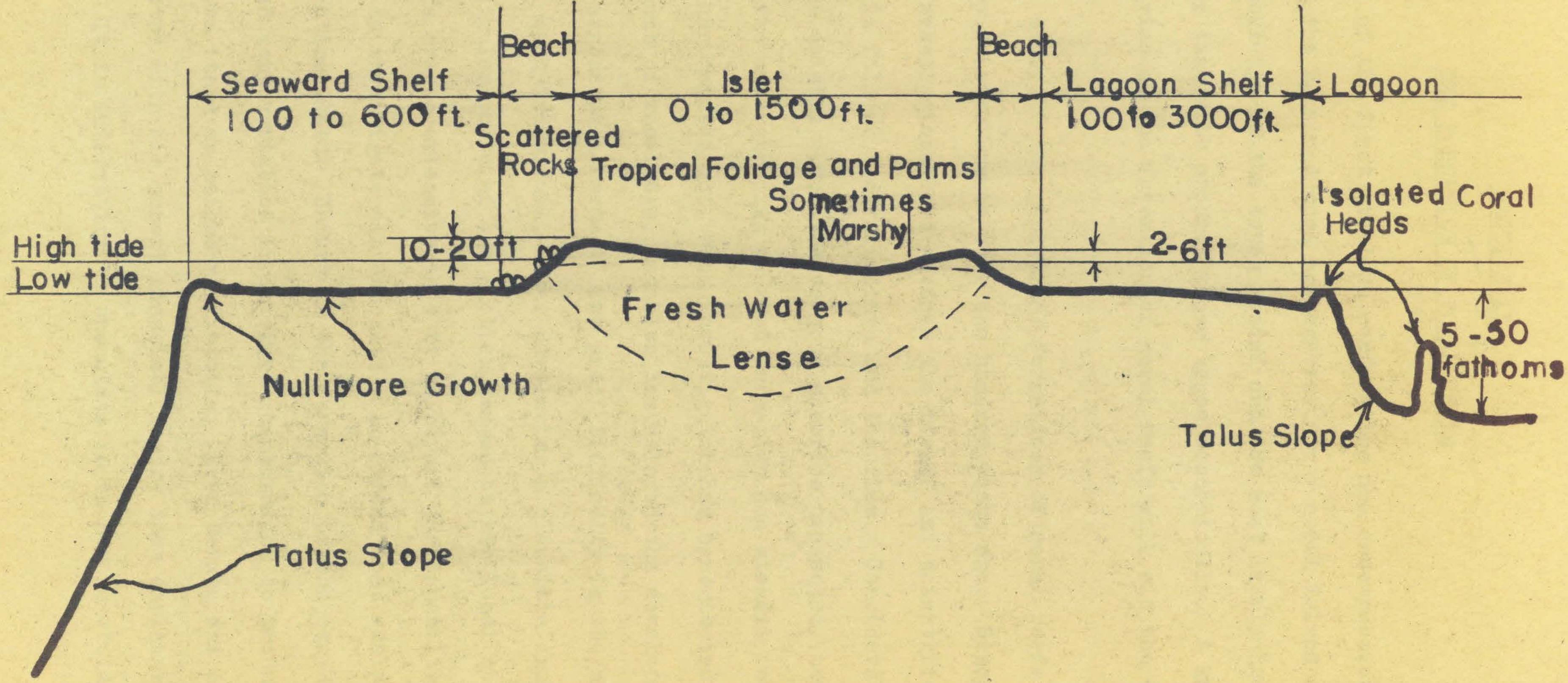

Figure 1

SECTION II

THE FORMATION OF CORAL REEFS

One of the first problems confronting the construction engineer is locating the required rock aggregates. On a coral island this involves a knowledge of the types needed and the most likely locations for quarries that will produce those types economically. A knowledge of the theories of the formation of coral reefs will aid the engineer materially.

The study of the geological formations of coral reefs was commenced by Charles Darwin over one hundred years ago. Since that time many investigators have entered the field, and scientific literature is full of their findings and theories. Considerable controversy has existed about the various theories presented, nevertheless the scientific understanding of reef formation has steadily advanced. As Vaughan has pointed out, each investigator has contributed to the growing amount of knowledge, but also has delayed the development by presenting erroneous theories. The great difficulty is the natural tendency of each individual, after developing a plausible explanation to one particular phase of the problem, based on his local observation (coral reefs are so extensive that it is beyond the capabilities of an individual to investigate all deposits), to extend that explanation to cover the entire field. Nature in the formation of the earth's surface has employed many variables in intricate combination to produce even two such like items as neighboring atolls. Even Darwin was delinquent in this matter with his superb classical theory that explains everything so nicely. It is interesting to speculate as to how he would reform his theories with present day tools of knowledge - as he readily accepted the soundness of some of his contemporary opponents' ideas to local conditions, but was generally able to prove their inadequacy when applied as a universal rule.

A thorough study of coral formation necessitates an extensive knowledge of a variety of sciences - Biology, Paleontology, Geology, Geophysics, Chemistry, Ecology and Oceanography with their special reference to limestone depositing organisms and the limestone masses so formed. Nevertheless, the basic fundamentals used by the theorist in explaining reef formation may be relatively easily understood by the layman.

The Environment of the Polyps

Coral is basically limestone, calcium carbonate, with few impurities which are assumed to be unimportant for the purposes of this study. Its immediate origin is the calcium carbonate in solution in sea water which is deposited as exoskeletons by unknown means of the life processes of certain organisms, principally the polyp. The polyp is an animal, but, when present in sufficient numbers to form massive coral reefs is dependent on sunshine as are plants. Polyps grow in bush or plant like shapes because there is insufficient oxygen in solution in sea water to support the dense multitude of polyps required. The Zooanthellae, a low form of plant algea, while parasitic on the polyp, provides it with not only its necessary oxygen, but some carbohydrate food. Polyps of massive growing reefs have been found to have many of these organism, while those live polyps found on dormant reefs have relatively few.

Polyps feed on plankton found in abundance in the top layers of the seas; but again, in order to provide sufficient food for the many polyps of a growing reef the water passing them must be constantly circulating. The temperature of the water has been proven to govern the activities of the polyps. Any silt or clay carried by the water has a disastrous effect on the polyps by clogging up the passages to the stomach and loading down the tiny hairs (celia) that keep the water circulating through the stomach. Exposure to the air for only a few hours will kill the polyps. However nullipore, a form of algae which also deposit a calcareous skeleton, seems to flourish well where it is alternately covered and uncovered by the tide, provided it be kept constantly moist as by the spray of surf. Because of this characteristic nullipore almost invariably caps the seaward edge of coral reefs, blanketing the polyp built structure into a dense calcareous mass, capable of withstanding violent ocean storms. Vaughan has outlined the above characteristics of the polyps into a set of conditions required for the development of coral reefs as follows:

a. Depth of water, maximum about 45 meters.

b. Bottom firm or rocky without silty deposits.

c. Water circulating, at times strongly agitated.

d. An abundant supply of small animal plankton.

e. Strong light.

f. Temperature of water, annual minimum not below 18°C and mean of the coldest month not below 21°C.

g. Salinity of water between 27 and 38 part per thousand.

These conditions are apparently necessary but not all inclusive, as no coral reefs of consequence exist in some large areas that satisfy all these conditions. There is little or no coral along west coast of North and South America in tropical water.

The Forms of Coral Reefs

With the environment of the polyp understood, a description of the form of coral reefs is needed as a background to a brief review of the foremost theories of reef origin. The fringing reef is a reef that boarders on existing land mass, with a flat surface generally alternately covered and exposed or nearly exposed by tides and whose seaward edge breaks sharply to deep water. A barrier reef is an extended or broad fringing reef with a lagoon or channel between the reef flat and the land mass. As with the fringing reef the exterior edge generally drops abruptly to deep water. Along the coast of a single island barrier reefs quite often develop from fringing reefs, and yet the lagoon formed in other instances may be many miles broad, as is the case with the Great Barrier reef of Australia, 200 miles from shore. The land masses within the lagoon of barrier reefs may have small fringing reefs about them. The atoll is a barrier reef without any appreciable land mass within the lagoon, though there may often be shallow shoals of coral, generally in the neighborhood of breaks in the reef line where food is more plentiful. On barrier reefs and atolls islets may form that become covered with palms and tropical growth and are often inhabited. The bottoms of all lagoons are quite flat and of limited depth, 5 to

50 fathoms. Small atolls are possible with lagoon missing (Baker Island). Raised or elevated reefs were originally one of the above three forms that were once level with the sea and have subsequently emerged, either by lowering of the elevation of the sea, or by raising of the foundation. The original form is often difficult to recognize because of changes caused by tipping of the strata and by subarial erosion of rain and wind.

Foremost Theories of Reef Origin

Darwin's classical theory, supported by Dana, is based on gradual subsidence of the foundation from within 100 to 150 feet or higher of the sea level to unfathomable depths at a rate such that the coral polyp could grow upward an amount equal to or greater than the subsidence. The coral first forms as a fringing reef, then as the land subsides the interior coral is starved off, forming the lagoon of the barrier reef, and finally the foundation itself disappears entirely below the surface and the atoll is formed. Darwin stated that a level foundation is not necessary as the coral of the fringing reef starts on the natural slope below the sea level, and thereafter provides its own platform. Accordingly the outside depth of coral on broad reefs such as the Great Barrier must be tremendous. The lagoons are kept from becoming deep by what coral can grow in them at a slower rate, plus the accumulation of detritus broken off the reef proper and washed in, and the accumulation of calcareous clay, produced in the digestive tracts of lower organisms, which bore into coral branches or gorge on the beach sands in search of small bits of organic food.

Darwin pointed out that reefs grow outward as well as up, indeed that growth seems most prominent to us as for our short period of observation all healthy coral reefs have reached the limit of their upward growth. However he pointed out the extremely slow rate of outward growth because of the necessity for it to build its own deep base by the accumulation of detritus broken off from the top living edge. Figure 2 is after Darwin showing the three forms of reefs succeeding each other as the land subsides, (indicated by raising the water table for clarity). Darwin exploded the former theory of atolls being coral fringes on the edges of **extinct volcanoes** by pointing to the tremendous numbers of volcanoes which must all have had the same crater rim height in spite of a great variety of sizes; however, he admits the possibility in local instances*. He explained the formation of islets on reefs as detritus piled up by waves showing how they are most prevalent on the windward side, particularly the points where the reefs are attacked by surf from two directions. Darwin noticed the extreme hardness of the outer reef flat of atolls over the inner flats and explained it by the more massive growth of the coral with a plentiful supply of food plus the cementing action of the nullipore, always present growing over the coral as the mass subsides.

The greatest objection to Darwin theory is that without platforms or benches for the coral to grow on, it predicated a tremendous

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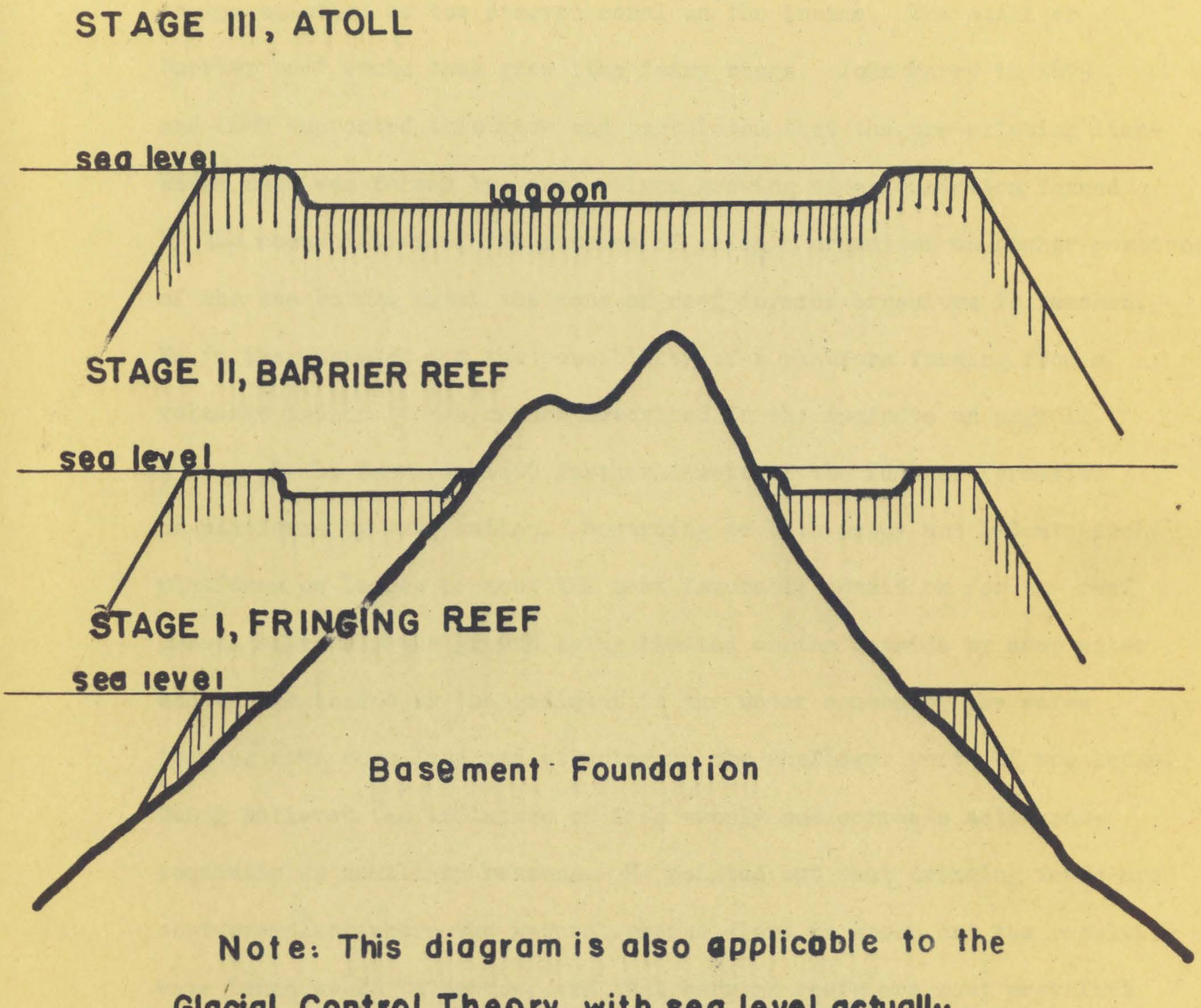
* In 1883 a volcanic island named Falcon Island was formed by eruption off Tongo Island. Though its cone pile was built up to 250 feet above sea level it was entirely levelled by wave action to a platform four fathoms deep by 1902. In 1912 coral polyps were observed growing on it; however the development was broken in 1927 when it erupted again building a cone pile 450 feet above sea. This further indicates the unlikelihood of atolls being fringes on the rims of craters as in leveling the cone pile all evidences of a crater were eliminated.

FORMATION OF THE THREE BASIC TYPES OF CORAL REEFS

After DARWIN, Vertical scale exaggerated



Note: This diagram is also applicable to the Glacial Control Theory, with sea level actually rising as shown during deglaciation.

Figure 2

subsidence over large areas of the world.

Carl Semper in 1863 first proposed that lagoons could be formed by the dissolving action of sea water of a pre-existing limestone mass, the exterior coral being capable of growth at a rate equal or greater to the solution of the starved coral on the inside. The atoll or barrier reef would thus grow like fairy rings. John Murry in 1879 and 1880 supported this view and postulated that the pre-existing limestone mass was formed by coral polyps growing on a foundation formed by the accumulation of the remains of pelagic organisms on higher portions of the sea bottom until the zone of reef forming organisms is reached. He further pointed out the possibility of a platform forming from a volcanic island in the manner described in the footnote on page 11.

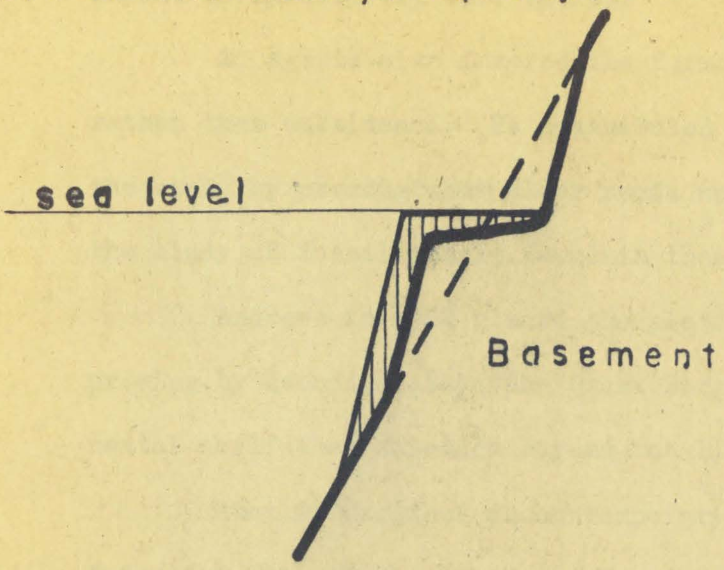
H. B. Guppy in 1890 further developed the idea of formation of platforms by wave action. According to both Guppy and LeConte such platforms or ledges present the most favorable condition for the reef growth of coral, the growth being limited on the outside by deep water and on the inside by the sediment in the water caused by the waves tearing down more land and stirring up the shallower parts of the ledge. Guppy believed the influence of food supply and currents acted subsequently as auxiliary reasons. He pointed out that fringing reefs are most prevalent where the natural ground slope is steep and the resulting wave bench would be narrow, and that barrier reefs are most prevalent where the natural ground slope is flat with broad wave benches resulting. Atolls of course would be formed where the entire land mass was torn down by wave action. See Figure 3.

Admiral Sir. W. J. L. Warton determined the uniform depth of

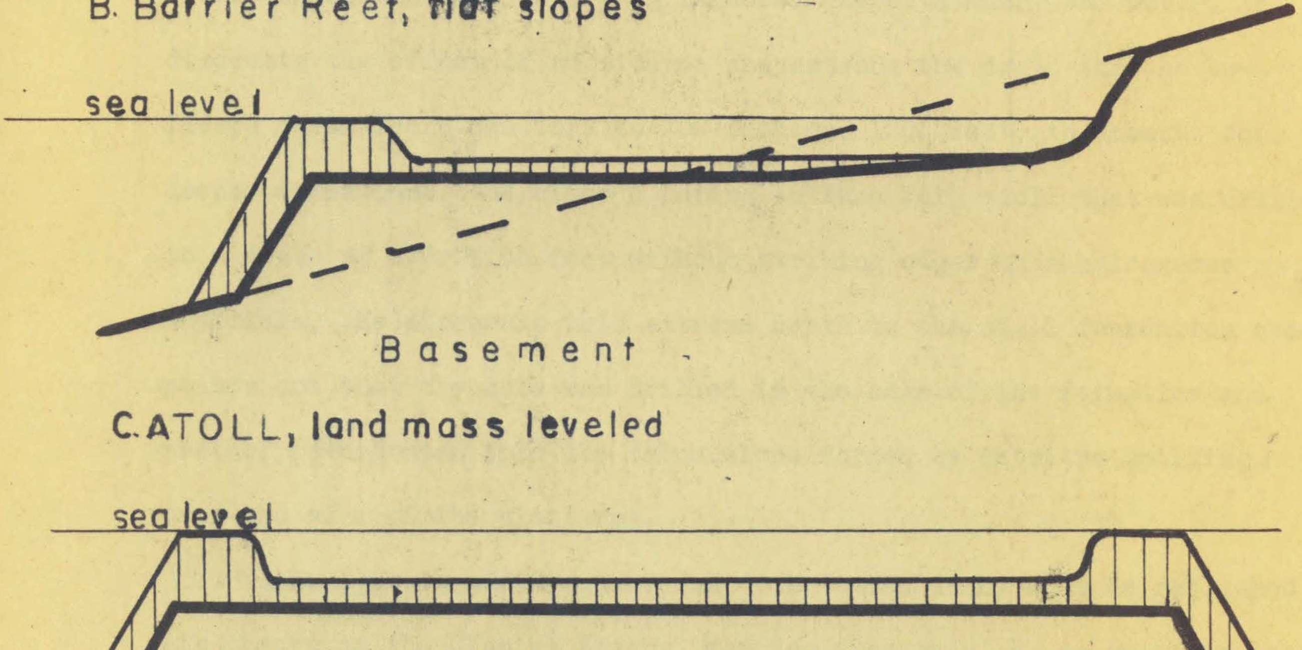
THE WAVE CUT PLATFORM

Vertical scale exaggerated

A. FRINGED REEF, steep slopes



B. Barrier Reef, flat slopes



C. ATOLL, land mass leveled

Figure 3

lagoons regardless of size and reasoned that the atolls must have been formed from a flat platform such as would be formed by volcanic island leveled off by wave action.

A. Agasiz also favored the formation of lagoons by solution rather than subsidence. He contributed notable to a newer branch of the study by proving that older reefs were covered by newer reefs from the study of fossil corals found in them.

Andrews in 1902 placed the platform theory on firm footing, proving by soundings that the Great Barrier Reef existed on a continental shelf that extended beyond the limits of the reef.

Stanley Gardiner in contemporary writings favors both the platforms and the solution theory. He cites many observations of the effect of solution in enlarging lagoons. As with Murry and Gubby, he discounts the effect of subsidence and extends the depth that he believes coral reefs can form to 200 fathoms, 1200 feet, to account for deeper formations. He cites a boring on Funa Futi atoll that was drilled to a depth of over 1100 feet without striking other than calcareous materials. He discounts this extreme depth to the atoll foundation and points out that the hole was drilled in the edge of the formation and probably penetrated into the talus slope formed by detritus spilling over the edge of the platforms.

L. Agassiz added a powerful tool to the study when he published his theory on the Glacial Epoch. Working from this, R. A. Daly has been the primary proponent of the glacial control theory of coral reef formation. In this theory the changes of sea level as a result of glacial action replace the subsidence of Darwin's theory and extend the variable elevations of platform possible for foundations. (The unlikelihood of many such platforms all within a hundred feet or so of the same height led Darwin to discard the platform theory).

Daly points out that during the Glacial Epoch there were four glaciations and four deglaciations, the last of which has been going on for the last 10,000 to 50,000 years. Between the second and third glaciation the ice caps were completely melted, as they were prior to the Glacial Epoch. The Glacial Epoch, estimated to be 1,000,000 years long took place in the Pleistocene, the most recent of the modern, Cenozoic, era. Though glacial ages are believed to have existed in the Mesozoic era, Middle Ages, over 150,000,000 years ago the effect of them is obscure. Daly estimates that on complete deglaciation the ocean level was approximately 150 feet higher than at present, while at the peak of the glacial epoch it was 300 feet lower than at present. Daly proposes that the platforms for present reefs were prepared prior to the Pleistocene, and that the present uniform depth of lagoons, was caused by the formation of reefs on the outer edge of the platforms during the last deglaciation, which has caused a rise of 33-38 fathoms. He supports this theory with a boring on Michalmas Cay of the Great Barrier Reef, which ran into non calcareous material at 241 feet below sea level and explains the extreme depth of the Funa Futi hole as being drilled into the talus slope beyond the edge of the platform. However, accurate evaluation of the Glacial control theory is difficult because of the possible large errors in estimating the size of both the present and the past ice caps and because of the elastic and non elastic deformations of the earth surface as well as changes in gravitational effect due to the shifting of such tremendous masses of water from polar to central ocean regions.

Both Daly and Gardiner show evidences of a recent lowering of ocean level, possibly in the last 8,000 years, amounting to 10 feet to 15 feet. Gardiner attributes it to the formation of more ice in the Antartic, while Daly feels it is a result of the elastic deformation of the earlier shift of ice in the polar regions to water in the oceans (which would tend to lower the foundations of mid ocean islands). Gardiner believes that an elevation is necessary for formation of islets on atolls, which, if true, would indicate the ocean lowering was a result of the formation of more ice rather than as an elastic deformation.

C. Hedley and T. Griffiths developed the influence of currents and winds on reef formations. They have shown how the atoll form of an island can be developed from a linear reef perpendicular to the ocean currents and believe some reefs off Florida developed in this manner.

T. H. Vaughan of the Smithsonian Institute has made a considerable study of oceanograph - the depths, currents, composition, and temperature of ocean water, and their effect on coral growth, and further, into the archealogical fauna. By fossil corals he has identified many imbedded coral reefs as originating in eras prior to Pleistocene. He supports the glacial control theory but discards the solution theory because of the following results of four separate investigations by himself and others.

a. All bays, sounds, and lagoons of the Florida reefs and keys region are filling with sediment.

b. Drew's investigation of dentrifying bacteria show that chemical precipitation of calcium carbonate is taking place within lagoons.

c. Chemical examination by R. H. Dole of samples of sea water flowing into and out of the Tortugas lagoon, collected twice a day for a month show that although both carbonate, and bicarbonate ions are present uncombined, carbon dioxide is not present and that the water possesses no capacity for further solution of calcium carbonate by virtue of its content free carbon dioxide. (Though the latter statement may be sound it hardly seems possible that there would be no carbon dioxide present and still have the laws of equilibrium in effect).

d. The determination of Dole of the salinity of the water within Tortugas Lagoon, and at the southern end of Biscagne Bay show a higher salinity than that in open sea water, indicating that tidal action is insufficient to mix sea and lagoon waters and that concentration by evaporation is taking place.

Vaughan states further that his investigations of the islands of the Pacific show those waters can dissolve no further calcium carbonate.

He points out that if Darwin's subsidence theory is correct the floor of lagoons would be bowl shaped, with the central depth proportional to the size of the lagoon. As Admiral Wharton established, this is not so. One of Darwin's objection to the platform theory was the unlikelihood of large number of shoals at the correct depth, however Vaughan points out that such shoals do exist in non tropical waters, such as the Great New Foundland bank, hence there should be no reason for them not to exist in tropical waters.

Both Vaughan and Gardiner have estimated the growing rate of coral and both have concluded that there has been sufficient time in the post Glacial Epoch to develop the deepest existing reefs. Vaughan further believes there was sufficient time in each of the glacial forming periods and during the glacial peaks, at which times the sea was at its lowest, to tear down most coral reefs built up above the level in a previous deglaciation; thereby providing fresh platforms for the next deglaciation. In the process the natural destructive action of the surf is made more effective by the decreased growth rate of new coral, due to colder waters and greater amount of silt in the waters from exposed beds.

H. T. Stearns has recently advanced "the hypothesis that great eustatic shifts of sea level occurred in Pleo-Pleistocene time as the result of changes in configuration of the ocean basins, and that many great reefs and atolls formed during the periods of rising sea level on shelves and platforms of many different types before glacial fluctuation of sea level. He does not maintain that the living part of present reefs were formed by these shifts". This hypothesis is based on extensive studies of eustatic shore lines in the Pacific and is the logical step to explain the existence of the platforms needed by the glacial control theory. It also explains the presence of elevated coral reef lines with cliffs as high as 600 feet, such as exist on Guam. Using Daly's figure of approximately 250 feet for post glacial rise of the sea level, and Vaughan's figure of 150 feet for the depth reefs can commence development, the maximum depth of such coral would be 400 feet. Stearns further divides the coral islands into two great groups, Sialic (Continental) bordering Australasis and underlain by folded rocks, and Simatic (Oceanic) Islands. The boundary line is roughly north south, west of the Gilbert-Marshall group. The Sialic group generally have the basement foundation of exposed folded rock, and have a geological history of general elevation (it is believed that such elevation must have been arrested from time to time, or surpassed by elevation of the sea, in order to form the massive reefs, such as the one on Guam by subsidence). While the Simatic group have volcanic basement foundation that have subsided in the manner outlined by Darwin. Stearns reports the last to shift as downward, causing an elevation of 25 and 5 feet.

Following Stearn's development it is probable that non calcareous foundations are considerably deeper than Daly predicts, particularly of Simatic Islands. Recent drilling for oil in the Bahamas disclosed that the Bahama limestone deposits are about 10,000 feet thick. It is believed that carefully located core borings of sufficient number to be conclusive could not only prove or disprove the above theories, but examination of the cores for fossil corals might give much valuable evidence to the science of oceanography and geology. Considering the interest the various subjects have it seems strange there have not been more borings.

The above presentation of the theories of coral reef formation is meant merely as an outline of the work of the principle investigators. It does not do justice to the many observations they have made as basis for their theories, or to the detailed development of their theories. However, it is believed to be a suitable background for the construction engineer.

Recapitulation of the Theories of Reef Formation in Regard to Sources of Construction Material.

The parts of the theories that are usable to the engineer in developing sources of construction material will be outlined without reference authorships.

Coral occurs in all forms from a fine calcarious clay to a dense hard calcite rock. In natural growth that coral subject to the **pounding** of the surf grows in the densest form, while that protected from the surf grows in fragile form. In many cases the voids between the coral branches of the dense coral are filled with calcareous deposits, nullipore growths, and by a natural cementing action to be discussed later, making the mass even more dense. While the much larger voids of the protected coral are generally filled with sand, shells, clay and other detritus of the reef, they are cemented together only by the structure of the fragile coral (though again, a natural cementing process may take place). In spite of the constant growth of the coral, the constant pounding of the surf is continually tearing off fragments of the coral structures, grinding some up into sand, and depositing some in practically unchanged form. As noted above some of this material is deposited in voids of the basic coral structure, the remainder being deposited in low banks on the reef itself or falling over the edges of the reef to form talus slopes on both sides. All reefs, whether atolls, fringed, or barrier, or elevated reefs of these three types are formed in the same way. Where lagoons exist it is, of course, easy to identify the protected and non protected sides. Similarly a fringed reef is almost entirely non protected. However, some atolls may be only partially developed, having one or more sides open to the sea, or a barrier reef may run far out to sea and terminate opening its inside face to the sea. All possible variations of conditions lead to a gradation of deposit from hard, dense coral to soft coral conglomerate. On the larger raised reefs, such as exist in the Hawaiian, Mariana, Okinawan, etc. Islands, it is particularly difficult to determine which areas were protected and which were not. In a raised island further variables are present. During the elevation the action of the surf on unprotected talus slopes generally removed that slope as the land emerges, leaving a cliff or steep bluff. There is a possibility that, with slow elevation, the surf removed the reef entirely, but in that case no elevated reef remains. However, if the raised reef is located on a broad foundation, such destructive forces will tend to reduce the reef to a low mound on that platform, or, if insufficient time exists to tear down the reef, the talus slopes may merely be distributed on a flatter slope. Protected talus slopes will not be altered to any great extent and will exist at about the slope that they formed in under the sea. In the event that non calcareous deposits are nearby, and may be washed over coral reefs, the voids of the various parts of the reef many become filled with that material. Both hard and soft corals may be so contaminated.

Generally, in raised coral reefs the coral exist in a series of benches and bluffs or cliffs. The latter represent exterior reef lines and may be either protected or unprotected. In many cases all such bluffs look as if they had been unprotected, however, it is often possible to determine, by their shape, that certain locations were less subject to the surf than others, generally by having a larger talus slope. Occasionally no bluffs as such can be identified, just a series of rolling hills. In this case, as well as that of talus slopes, the bulk of the material will be detritus and hence will probably be soft. Calcareous clay is present in small percentages in most detritus deposits. It is also found in considerable quantities in deep water surrounding reefs (as would be expected by Stoke's Law) and occasionally in deposits in broad shallow lagoons where tidal movement is insufficient to remove it.

A further variable complicates the number of conditions coral can exist in, that of solution and redeposition. All raised coral, to a variable extent, is subject to solution by rain water. The amount depends on the amount of carbon dioxide in solution in the water, the volume of such water passing over or through the coral, the amount of calcium carbonate picked up prior to reaching a particular mass of coral and the rate of evaporation of such water. As conditions change the water may become super-saturated with carbonate and deposit lime stone; or a layer of silt may protect coral from rainfall and consequent leaching action. The normal result of the above actions is to soften the upper layers of coral by solution leaving the lower layer unchanged, however, occasionally the reverse process is noticed, and sometimes vertical layers exist that are either softened or hardened. This can be explained by water flowing through higher strata of limestone becoming saturated, than flowing out over or through lower strata and partially evaporating. The result of solution and deposition often reverses the condition one would normally expect to find.

Natural Cementing Action

Periodically along the littoral zone of Islets on reefs are strata of a cemented rock, or piles of such rock broken loose from the strata. This rock is a conglomerate of shells, broken reef fragments and sand cemented together. Stanley Gardiner explained the formation of this rock as a result of two processes.

a. Sea water, on each high tide saturates the uncemented material. On each low tide part of the pore water left in the material evaporates, depositing salts, primarily the least soluble and saturated calcium carbonate, in the voids. On the next high tide the more soluble salts are washed out and the remaining void space again filled with water saturated with calcium carbonate. As this process continues the voids are gradually filled, and if the material is not disturbed, a cemented rock will result. In order to prevent disturbance by waves the material cemented must either be below the surface where evaporation is slower, or have been partially cemented before being exposed.

b. Gardiner states the more general cause may be in the solidification of sand along the line where the fresh water from the land and the tidal salt water from the sea meet one another. The former is supersaturated with limestone and this at once precipitates on the meeting of the salt and fresh water. The same precipitate is is noted in the milkiness noticed off the mouth of a river draining a limestone country.

From both Gardiner's and others observations, plus some to be added here, the result of the second process he gives obviously takes place. However, the reaction is much more complicated than he presents. First, the ground water is not supersaturated as it is constantly in contact with calcium carbonate in the solid phase. Secondly, the sea water has more calcium carbonate in solution (220 parts per million) than ground water under the influence of atmospheric carbon dioxide (60 - 70 P.P.M.), indicating that no precipitate would result on adding fresh water to sea water. However the controlling factors of the solubility of calcium carbonate of such a mixture are the Ph and the ionic strength, the latter can be expressed in terms of salinity. Temperature and partial pressure of carbon dioxide, also controlling factors, both remain relatively constant. The sea has a higher Ph, 8.1 to 8.3, than the ground water, 6.2 - 6.5 which would tend to make the carbonate less soluble in the sea. The effect of the salinity (ionic strength) of the sea in reducing the activity of the ions increases the solubility to a greater extent than the higher Ph reduces it. Both the sea and the fresh water are saturated as both have been in the presence of the solid phase for sufficient time for equilibrium to be reached. The solubility is not a linear function of either the Ph or the salinity. Therefore it is possible that at some range of dilution from 100% fresh water to 100% sea water, with both components saturated, the mixture will become supersaturated and a precipitate will be formed.

Because of the porous nature of elevated coral there are generally no stream lines on coral islands, all rainwater falling percolates into the coral and soon reaches the water table, at/or slightly above sea level. Though natural coral is porous the pores are generally small, preventing free circulation of water. As a result the fresh water does not mix immediately with the sea water, but forms what is known as the fresh water lens that floats on the sea water with a zone of mixture extending from strand line to strand line in an arc under the fresh water. The thickness of this zone of mixture is dependent on the tidal fluctuations and on the permeability of the coral. The thickness and approximate volume of the fresh water lens may be estimated by the water table elevation. Because of the differences in density between fresh water and the sea water (ratio approximately 40:41) for every one unit the fresh water is above the sea water table it will extend 40 units below the table to balance hydrostatically*. From the above discussion it would appear that the zone of mixture is cup shaped with the rim at approximately the strand line. On high tide there will be movement of salt water through this zone towards the interior, while on low tide there will be a slightly greater movement of the fresh water out through this zone. The intrusion of salt water at high tide is evidenced by the raising of

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* The relationship of course also indicates the danger of drawdown in wells, drawing from the water lens, as for every unit of drawdown, salt water rises forty units toward the intake. To avoid this the Maui type well was developed which is simply a shaft to the water-table with a sump at the bottom, and a series of horizontal collecting galleries leading to a sump. This allows a greater volume of water to be skimmed off the top of the water line without appreciable drawdown.

the water level in wells, and a higher salt content in wells near the coast line. In addition to the converse being true visible weeping of water out of the banks exposed by low tide is quite prevalent. The differential head that causes this weeping exists over the entire surface of the cup shaped zone of mixture, hence, with equal permeability a much greater volume of water would percolate out below low tide level. From the observation of the volume of water weeping out of the banks this is not possible as such a flow would lower the water table nearly as rapidly as the tide went down, leaving practically no visible weeping. The resulting conclusion is that the zone of mixture is relatively impervious. Such would be the result of precipitation in the zone, the voids being filled up except in the most permeable spots where channels would develop due to the increasing velocity, as the area of transit was reduced, preventing the accumulation of precipitate. The flow would then be confined to over the rim of the cup and to the few subsurface channels that develop. It should be noticed further that, though the zone of mixture is cup shaped, the exterior surface of the dense material extends on down vertically, as an enveloped surface to the cup as it rose with the growing reef from its basement foundation.

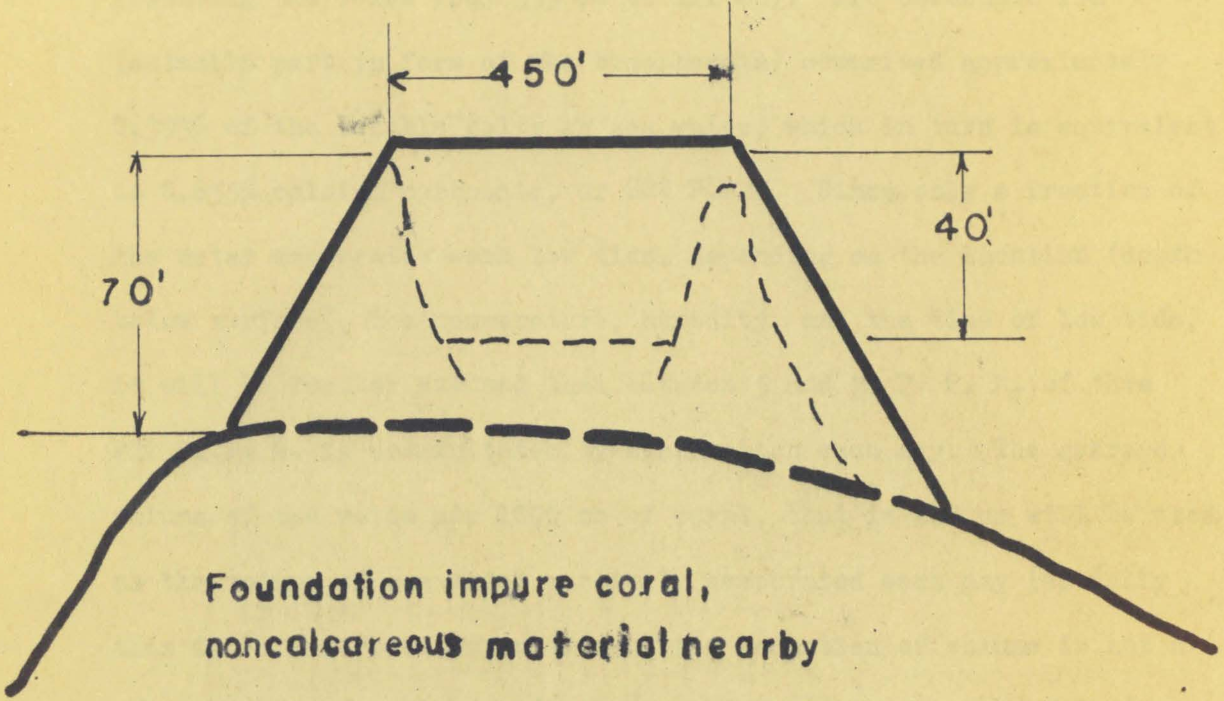
The best example illustrating this action exists on Ie Shima, just west of Okinawa. The entire north coast of this island is lined by rugged coral cliffs over two hundred feet high, with a relatively narrow fringe reef at the present sea level. Flowing out of this cliff, above high tide level is a large spring. At an orifice its velocity was estimated as about five feet per second and its flow at approximately four million gallons per day. On the southern coast, lined by sand banks on a reef surface, considerable weeping can be seen at low tide. The above spring developed to be the main supply of water for our armed forces on the island. As it was desirable to have an alternate supply for security reasons, the entire north coast was searched at low tide for additional springs. None were found.

Another indication of this cementing action is shown by a group of wells drilled in the vicinity of a raised bluff line on Saipan. The well located closest to the crest line took the longest time to drill. After drilling 30 feet below sea level without striking a flow of water the bottom was blasted heavily; however even this failed to open up a flow. The other wells located near the bluff, but at distances from 300 feet and up from both sides all developed good flows at slightly below sea level.

A third indication of this cementing action, as well as an illustration of the location of hard and soft corals in a typical atoll formation was uncovered in Hill Top Quarry at Saipan. This quarry was located in a mound of coral shaped like a truncated cone with a flat elliptical top about 450 feet by 600 feet, on the top of a bluff just east of Charan Kanoa, Saipan. As the cone seemed to be just a pile of loose coral a quarry was developed in one side. When this soon ran into hard coral quarrying activities were shifted to the top. Soon a crater was developed with hard coral on all sides forming an irregular bowl. As the crater became deeper it was necessary to blast roads through the hard shell, and also to blast the irregular projections in order to maintain floor space and progressive excavation. After about 200,000 yards of coral had been removed the quarry was abandoned for one requiring less blasting. Figure 4 represents an East-West cross section of the cone, with the dotted line representing the surface after excavation, and also, except on the West (left) side where no quarrying was done, the approximate boundary between hard and soft coral. The outside slope represents the exterior talus slope while the interior was filled with fragile coral forms and detritus. The hard core represents the denser, hard coral, subject to wave action and possible later cementing action.

Empirical relations for the solubility of calcium carbonate have been developed in the ionic strength range of normal hard waters, and of salinity in the range of sea water. In the first range the Ph is the controlling factor and in the second the salinity. No experimental data is available for the extensive range between these limits and considerable experimental work is necessary to establish complete empirical relations. It is therefore not now possible to determine an order of magnitude of the precipitate and resulting cementing action, or to state conclusively that such a precipitate occurs.

It is possible, on the basis of broad assumptions, to determine an order of magnitude of the cementing action of the evaporation process. Sea water contains 34,000 P.P.M. soluble salts; of these salts magnesium and calcium carbonate, in that order, are the most insoluble. Sufficient of either, the calcium and magnesium ion are present to bind all carbonate ions, the latter being at saturation. In such cases calcium carbonate will be the principle initial precipitate on evaporation, and, for simplicity of calculation will be assumed



HILL TOP QUARRY
SAIPAN
Vertical scale exaggerated

Figure 4

the only precipitate for limited evaporation. It will further be assumed that the porous coral structure has a void ratio of 50% and that structure becomes firmly cemented and relatively impervious when the voids ratio is reduced to 10%. To accomplish this, 222 c.c. of calcium carbonate per 1000 c.c. of coral must be precipitated (reducing the voids from 333 cc to 111 cc). The carbonate ion (actually part in form of the bicarbonate) comprised approximately 0.393% of the soluble salts in sea water, which in turn is equivalent to 0.655% calcium carbonate, or 222 P.P.M. Since only a fraction of the water evaporates each low tide, depending on the location (depth below surface), the temperature, humidity, and the time of low tide, it will be further assumed that between 5 and 50 P. P. M. of this 222 P. P. M. is precipitated by evaporation each day. The average volume of the voids per 1000 cc of coral, that is 222 cc will be used as the volume of sea water partially evaporated each day (actually this is an incorrect assumption as the reduction of volume is not a straight line function, reducing each day as the volume reduces). 222 cc of sea water then will deposit between 5 and 50 P.P.M. or between .00111 and .0111 grams per day. Taking the specific gravity of calcite as 2.93 this amounts to between .000379 and .00379 cc per day per liter. At this rate it would take between 1,600 years and 160 years to cement sand rock. By comparing this to the time of formation in the post glacial period of 10,000 to 40,000 years it is clear that the cementing action is fairly rapid. A precipitation of between 5 and 50 P.P.M. by the second process would yield identical results.

The above development of the formation of sand rock has been included as a background to the so-called "setting up" phenomena that has been observed in corals, to be discussed in the next section.

SECTION III

CONSTRUCTION USE OF CORAL AGGREGATE

Coral has been used extensively as aggregate for base and wearing surfaces of roads and runways and to a lesser extent for both portland and asphaltic cement. The type needed, the value and the method of use differs in each case.

Type Coral Needed for Concrete Aggregate

One of the greatest causes for the pre-war unfavorable reputation of coral was that concrete made from it was generally poor. Its general use in concrete during the war has done little to improve its reputation in this regard. Floors made of it often dust badly and fail under the steel wheels of warehouse trucks. Compression tests were usually poor, many falling below 1000 pounds per square inch and few exceeding 2000. The cause for these faults was not due primarily to the coral but to the lack of knowledge of the characteristics of various type of coral and lack of proper control in the manufacturing of concrete. Because of lack of crushing and screening equipment, and for convenience, the coral aggregate used was generally soft coral taken directly from the same quarries that were developed primarily for road or runway bases. This coral quite often appeared to have a suitable gradation with the possible exception of too high a percentage of fines. Figure 5 shows the grain size distribution of typical coral from two such quarries on Saipan and for several other quarries in the Pacific. A knowledge of the formation of soft coral shows the principle disadvantages. The larger fragments consist of parts of fragile coral formation and partially

GRAIN SIZE DISTRIBUTION

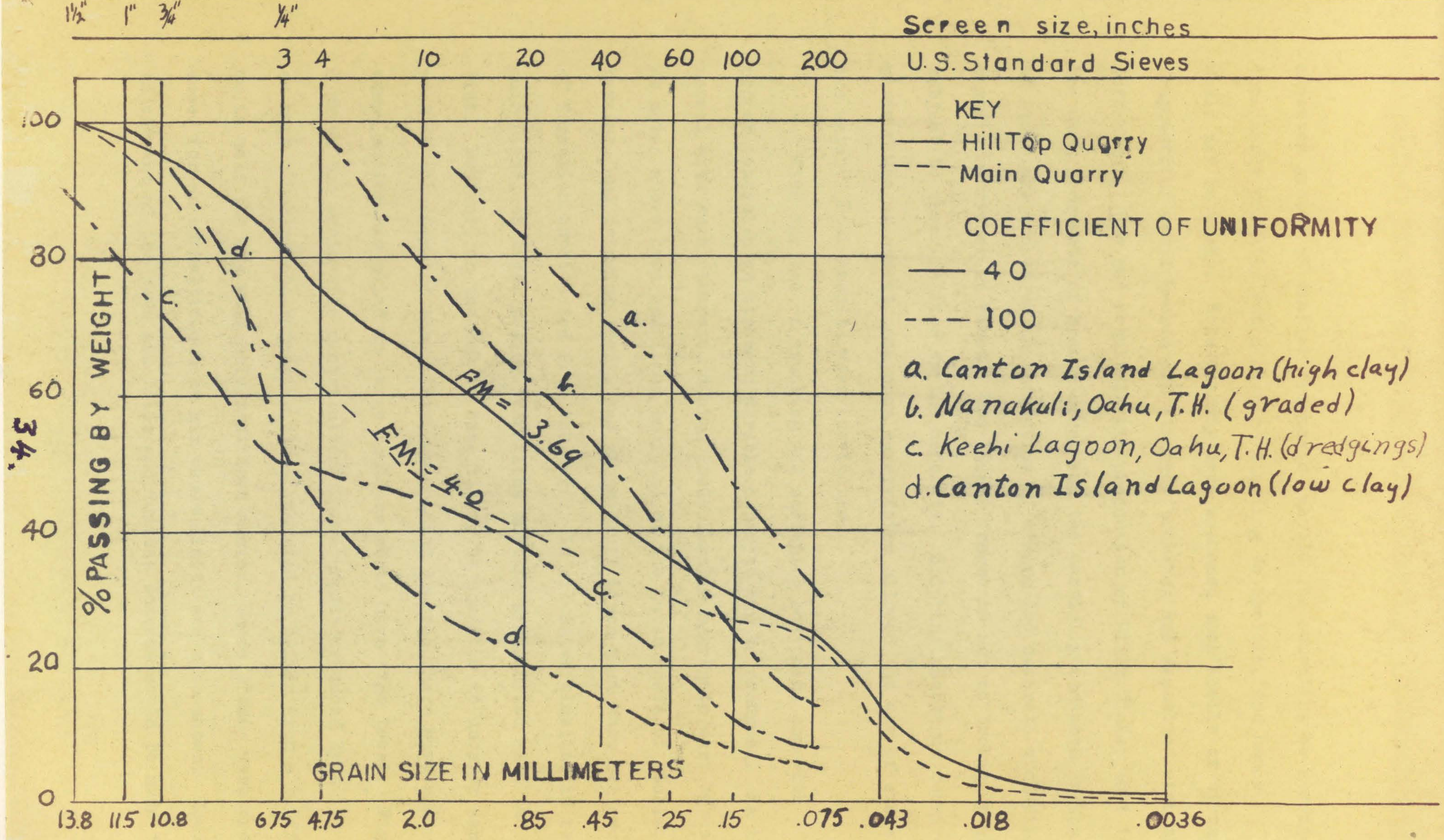


Figure 5

cemented groups of smaller fragments (should the cementing be strong the quarry probably would require blasting to operate, and hence would not be used). Solution may have weakened such shells or stronger fragments of coral broken off stronger branches and deposited with the soft coral. The net result is the production of Mixer fines; that is the weak fragments of branch coral and the partially cemented groups of fines are broken up in the action of mixing the concrete producing a mix even richer in fines. The larger fragments not so broken up are subject to shear failure to the concrete. Shipping shortages required minimum use of cement, and poor supervision allowed the use of excessive water. Poor results were inevitable.

With the use of crushing and screening equipment and with proper control high strength durable concrete can be produced. As is normal with such concrete, a high grade durable aggregate must be used. As noted above hard coral may be found on the outer reefs of atolls, barrier, and fringing reefs, and along bluff lines that show evidence of formation unprotected from the surf. In all cases blasting is required,and, on tidal reefs, operations must be sychronized with the tide. However, in the latter case it may be possible to uncover sand rock on the edges of the islets, or to find an area where wave and storm action has piled up large boulders above high tide level. Figure 6 shows the grain size distribution of two grades produced by a 150 ton an hour crushing and screening plant quarried on Saipan from a bluff quite near the dry well hole mentioned above. These grades were produced for an asphaltic cement mix whose limits are also shown. However, adjustment of the jaws and rolls and various screens could be made to

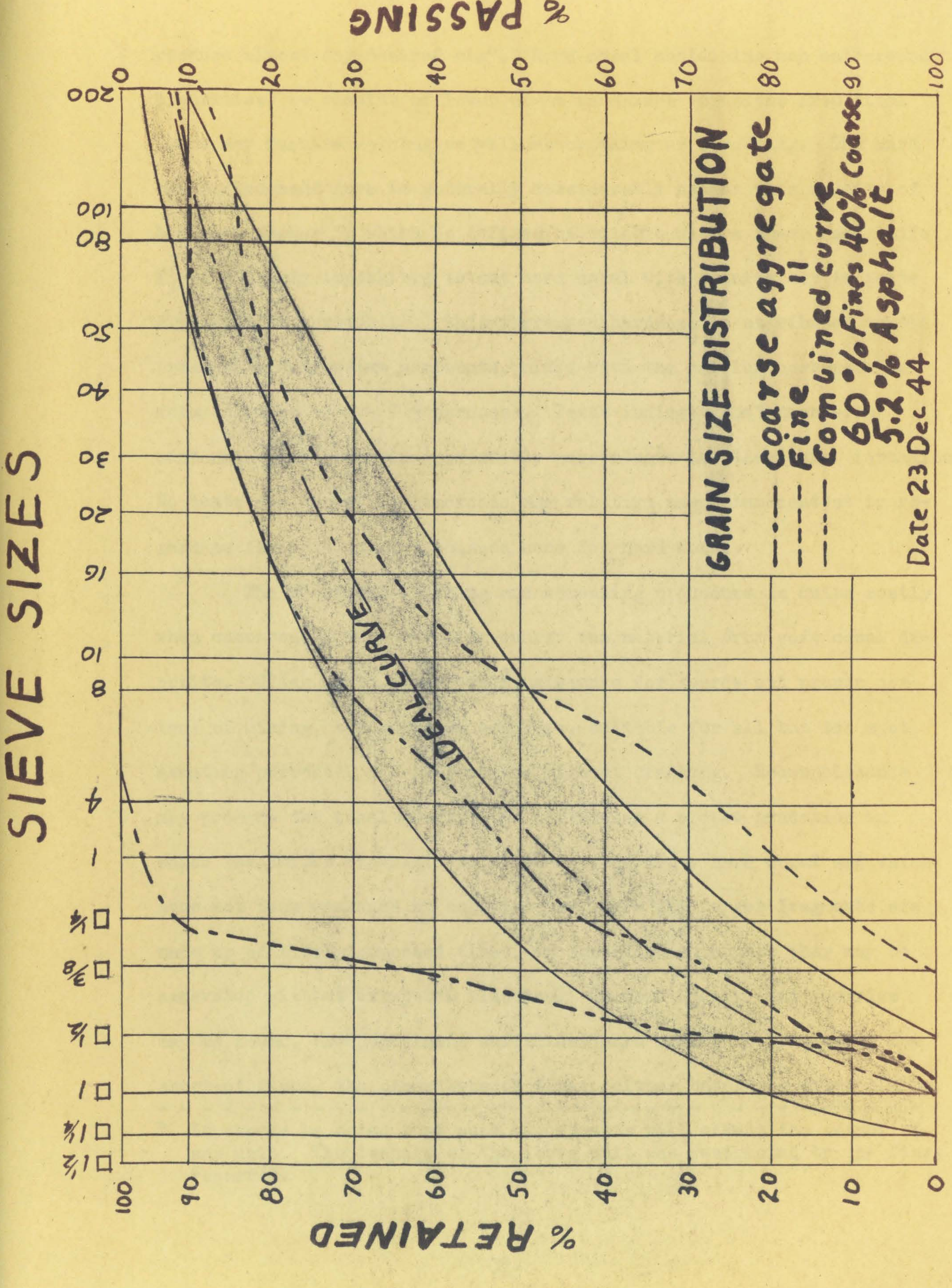

SIEVE SIZES
% PASSING
% RETAINED
200
100
80
50
40
30
20
16
10
8
4
1
¼ □
⅜ □
½ □
1 □
1¼ □
1½ □
0
10
20
30
40
50
60
70
80
90
100
IDEAL CURVE
GRAIN SIZE DISTRIBUTION
Coarse aggregate
Fine "
Combined curve
60% Fines 40% Coarse
5.2% Asphalt
Date 23 Dec 44

Figure 6

produce almost any desired mix*. Hard coral containing non calcareous impurities, or remains of lower plant an animal organisms from tidal reefs may require washing as well as crushing or screening. The hard coral discussed here is generally considerably harder than calcite of hardness Number 3, which is defined as cutable with a sharp hard knife. It is not only impossible to cut hard coral with a knife, it is quite difficult to scratch it. This increased hardness is attributed to the presence of magnesium carbonate, mixed with the calcium carbonate to form dolomite of 4 - 4.5 hardness. Tests indicate that magnesium carbonate is present in appreciably percentages in older coral formations. No tests are known that indicate the relative magnesium content in regard to the density as discussed here for hard coral.

The blasting, crushing and screening procedure is quite costly when compared to that of using quarry run material from soft coral deposits. Often, with proper reconnaissance for source and proper control of mixing, a good grade concrete, suitable for all but the most exacting purposes, can be produced without crushing. Reconnaissance may produce the ideal quarry, one containing a proper gradation in which the larger fragments were broken from dense hard coral and which have not been weakened by solution, or where the larger fragments are made up of firmly cemented fines, in condition such that they may be excavated without extensive blasting. Or more likely, two quarries may be found, one containing sufficient hard nodules or fragments but short of fines, the other long on fines, either before or after mixing,

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* It should be noted that such adjustments will effect the output of any unit. The tonnage of the above unit was restricted by the fines required.

which can be mixed together to make good aggregate. Beach sand, generally always available may be used to balance material from a coarse quarry; however, this method is not as good as getting the fines from a softer quarry. Coral beach sand, as shown in Table I, is alarmingly uniform, practically all passing through one sieve and being retained on the next, while the fines of a soft quarry are better graded (See Figure 5). Occasionally finger coral can be found to increase the coarse aggregate of a soft coral pit. Finger coral defines the coral often found in banks that consist of broken branches about the thickness of and generally no longer than one's finger, from which all fines have been washed. It is not often usable as it usually has been subject to solution and is light and fragile.

TABLE I

Typical Coral Sands of the Hawaiian Islands
(Figures indicated % passing a given sieve size)

Sieve Sizes	Bellows Beach	Kahuku Beach	Kaneohe Dunes	Waianae Beach	Waimea Beach	Makua Beach	Kahuku Dune	Barking Sands Dune
200	0	0	0	0	0	0	0	
100	1	0	0	0	0	0	1	0
50	17	0	10	1	0	1	2	5
30	85	32	79	38	33	55	89	83
16	100	93	100	92	92	95	100	100
8		99		99	100	99		
4		100		100		100		

When none of the above combinations can provide a good graded aggregate it is possible to open up a quarry that produces coral intermediate between soft and hard. Such a quarry will require some blasting and heavy dozing and rooting, and the product must be screened by a grizzly, or run through a jaw crusher and used as crusher run. In this manner a good aggregate can be produced at lesser cost than establishing a full scale plant in hard coral.

It is obvious when using coral that more care must be devoted to the selection of aggregate and to the control of the mix than normally. However, with such care good concrete can be produced without expensive blasting and crushing procedure. Table II shows the results of tests on various batches of coral aggregate made by the Navy Material Testing Laboratory at Pearl Harbor*.

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* From Aug. 9, 1945 Eng. News Record "Coral, A Good Aggregate for Concrete" by J. R. Perry.

TABLE II

Compressive Strengths, 7 Day and 28 Days Using Coral Aggregate

% Fines In Aggregate	Mix	Cement Sacs/yd	W-C Ratio gal/sac	Slump Inches	7·Day #/ in^2	28 Day #/in^2
	1:3	10.43	4	3.5	3855	3937
	1:3	9.88	5	6.5	3520	3970
	1:4	8.36	4.8	2.75	2910	3440
81%	1:4	8.12	5.5	6.	2632	3267
	1:5	6.92	5.88	3.5	2244	2799
	1:5	6.78	6.48	6.5	2064	2533
	1:6	5.95	6.71	3.	1724	2136
	1:6	5.77	7.81	6.25	1545	1975
	1:3	9.22	5.28	3.	4152	4250
	1:3	8.88	6.12	7.25	3833	4074
	1:4	7.45	6.12	3.25	3740	3955
50%	1:4	7.13	6.96	6.5	3014	3598
	1:5	6.19	7.31	3.	2096	3274
	1:5	6.08	7.90	6.	2576	3060
	1:6	4.91	11.39	2.25	2129	2448
	1:6	4.72	13.09	7	1455	1862
	1:3	8.97	6.12	3	3337	3935
	1:3	8.64	6.96	7	2994	3322
	1:4	7.06	7.92	3	2043	3419
30%	1:4	6.95	8.40	7	2296	2580
	1:5	5.85	9.60	4.5	2015	2573
	1:5	5.71	10.45	7.25	1724	2049
	1:6	4.98	11.76	3.5	1766	2408
	1:6	4.88	12.24	7	1300	1510

The coral used in these tests was selected to show the range from different type quarries. Most soft corals will run over 80% fines after mixing. Where deposits can be found with a high percentage of coarse aggregate not subject to breaking up they are generally short of fines. The value of mixing such corals is clearly evident in the Table. With selected material 3000# concrete can be produced with a six sac mix. 4000# concrete can be made with rich mixes up to nine sacs, however, the durability of such concrete is decreased by the added volume of past. Reduction of the water cement ration allowed by air entrainers or Pozzolith will further increase strength.

Type Coral Needed for Asphaltic Concrete Aggregate

In soft coral deposits the individual coral particles are generally coated with calcareous clay, not too firmly cemented. Asphaltic mixes, whether road mix, penetration or hot central mix, merely wrap a layer of asphalt around such particles without penetrating into them. Larger particles may be easily removed from the compacted concrete with a pen knife, and the asphalt peeled from the particle with one's fingers. Such asphaltic concretes generally have spongy surfaces of poor wearing ability. This is somewhat less true with hot mixes of material selected in the manner outlined for portland cement from soft corals.

If a hard grade coral is used, crushed and graded, good asphaltic concrete can be made by any of the normal methods.

Use of Water Bound Coral for Base Coarses and Wearing Surfaces

The greatest and by far most successful use of coral during the recent war has been for base coarses for runways and roads of the military bases in the Pacific. Very simple rules were followed -- generally it was quarried at the nearest location that did not require blasting, laid down 6 inches deep for light traffic and 12 inches for heavy, and compacted with such water as could be distributed with the equipment available. However, the reasons why such a procedure almost always was satisfactory; along with the conditions that made it satisfactory, and why it sometimes failed were not generally understood by those who did the construction.

Almost everyone who used coral noticed that at times the coral, after quarrying and hauling and spreading, would set up almost like concrete. This setting up phenomena was much discussed, and many hours of reconnaissance time was spent in exploring for coral sources that would produce of coral that set up.

The first requirement for roads and airfields is generally a source of adequate material near at hand that can produce the yardage rapidly at low cost. This condition generally precludes blasting and crushing the material, hence requiring a source in which the material can be broken out by use of modern heavy equipment, power shovels and dozers. As we have seen in Section II such sites exist as the inner reef shelf of atolls and barrier reefs; as the talus slopes of bluff lines particularly where such slopes give evidence of having been protected from the surf; as rubble mounds of reefs that have been torn down by wave action; as elevated benches, once interior reef flats; and even bluff lines themselves where they were protected during formation and have been subjected to weakening leaching action. The discussion of the natural cementing process in Section II should make it evident that a quarry that satisfies one of the above conditions is not always workable without blasting. Organic impurities with loam silt and clay may also nullify the value of a particular quarry; however the acceptable percentages are considerably greater than with concrete aggregate, running as high as 20% in dry weather. Nevertheless practically all good quarries developed satisfy one of the above conditions. As example, a few of the good quarries the author has personal knowledge of will be cited.

Typical Sources of Soft Coral

It was noted in Section II that calcerous clay deposits might be found in the interior of large shallow lagoons. Such deposits are present in Christmas and Canton atolls. In spite of the general concept that 20% clay will nullify the value of an aggregate, large volumes of almost pure clay were excavated with drag lines and carry-all scrapers and were successfully used, unmixed, for the airports on those atolls. Successful use of this material was probably due to the dry climate. These islands are in the group known as the dry islands and are quite barren.

The lagoon reef flat' in the Ellice and Gilbert Island' were almost always bare on low tide. The material on those flats nearest the airport sites was excavated by scrapers, working continually except during high spring tides, and by drag lines. For roads running along the narrow Islets coral was quarried wherever convenient access to the road made it desirable. The material was universally satisfactory. On Makin atoll the material from the lagoon shelf ran as high as 50% sand. Though sand has adequate bearing power, it forms a loose surface. This particular material had sufficient calcareous clay and larger shells or coral fragments to make it satisfactory as a wearing surface in spite of the large sand content.

In the Marshall Island the lagoon shelf was often underwater at such a depth to preclude excavation by tractor and scrapper. At Eniwetok drag lines were used; however, at Kawajeline drag lines were not available. Soft coral was obtained by removing the sandy top soil of the islet proper down to the coral base, which was found to be similar to that of a lagoon shelf. This coral was then excavated by scrapers as deep as the water table would allow and the hole backfilled. This procedure is not recommended as available space on Islets is limited and such excavation amounts to pulling an island out from under itself.

One quarry on Saipan has already been discussed. Other larger and better quarries were located in protected talus slopes and one large one was located in the rubble of a reef almost entirely torn down by wave action. Figure 7 shows a quarry of the first type from which over 2,500,000 yards were eventually excavated. Figures 8 and 9 show the latter quarry. These quarries required extremely little blasting to remove local cemented areas that interfered with uniform development. The shelf coral on Saipan, between bluff lines, was usually quite hard, requiring blasting for grading operations, or became quite hard after a few feet had been excavated, depending on the extent the shelf had been protected from the open sea in formation. In the latter case the top layers of coral had apparently been softened by leaching.

On Guam the shelves were generally extremely broad, and were therefore less subject to surf action. Roads were constructed by opening quarries where convenient along the right of way. One major airfield was surfaced largely with soft coral excavated in the grading process. However two others had sufficient hard coral present that blasting was necessary. As such coral would have to be crushed for use as base, soft coral quarries were located nearby, in one case along a protected bluff line and in the other on protected shelves.

On Ie Shima the northern coast, as mentioned above was extremely hard and precipitus, while the southern coast rose in a series of bluffs and shelves to the central plateau. One of the best soft

Figure 7: Main Air Base Quarry, Saipan

Figure 8: Auxiliary Quarry, Saipan

Figure 9: Auxiliary Quarry, Saipan

quarries in the Pacific was developed in one of these bluffs, starting at the base and eventually crossing the entire high shelf. Also several good quarries were located on the plateau shelf itself, as on the broad shelves of Guam.

An excellent quarry for Yontan Airport, Okinawa was developed in the south face of a bluff protected on the west by a hard reef line and on the north and east by hilly terrain. The coral of Yontan plateau shelf was covered with too much overburden to obtain without disrupting the needs of the Airport for space.

Before continuing to an analysis of the material typical of these quarries it is well to point out again that the above examples are merely guides as to what is likely to be encountered and not as examples of what is always encountered. Contradictory conditions will be found, as the bluff quarry at Ie Shima which was entirely open to the sea from the south, yet had a rounded appearance and a talus slope of a soft quarry.

The Analysis of a Typical Soft Coral

It must be borne in mind that no two quarries produce identical coral, but that most soft coral quarries are similar as the effect of leaching or cementing action on the original mass is limited to approximately the same range by the requirement that they be capable of excavation by modern heavy equipment without material blasting. Though each different quarry coral may have different sieve analysis, different densities and different optimum moisture contents, requiring different methods of processing them for base and wearing surfaces, these different methods are merely modifications of a general method, suitable to all conditions, to meet local conditions. The primary method of processing coral, the characteristic advantages and disadvantages of the result, and the conditions necessary for successful use are basically the same for all soft coral.

This analysis of coral from the quarry on Saipan shown in Figure 7, has been selected because it is quite typical, and because it is the most complete analysis available. The grain size distribution is shown in dotted lines on Figure 5.

Compaction Tests

a. Samples of coral taken directly, from the pit were compacted in the Proctor Mold using the Modified Rammer (10 lb. hammer 18" stroke). The degree of compaction was varied by changing the number of lifts and the blows used to compact each lift. For each compaction method the water content was varied from 5% to 15% and dry density was plotted against water content (Figure 10).

b. Optimum moisture was determined as 11% at which a dry density of 122.5 lbs. per cu. ft. was obtained. Field density test indicated that a greater density was being reached in the field and a curve was plotted for 7 lifts with 25 blows per lift. This curve closely approximated field compaction and a density of 125.5 lbs. per cu. ft. was reached at a moisture content of 11%. The curves indicate that practically no increase in density can be achieved when the moisture content is 14%--15% or greater. It was also determined that the coral lost all stability when the moisture content reached 14% - 15%.

c. Figure 11 shows the relationship of the three moisture density curves. Curve A, Figure 11 indicates what compaction was anticipated and

MOISTURE DENSITY CURVE

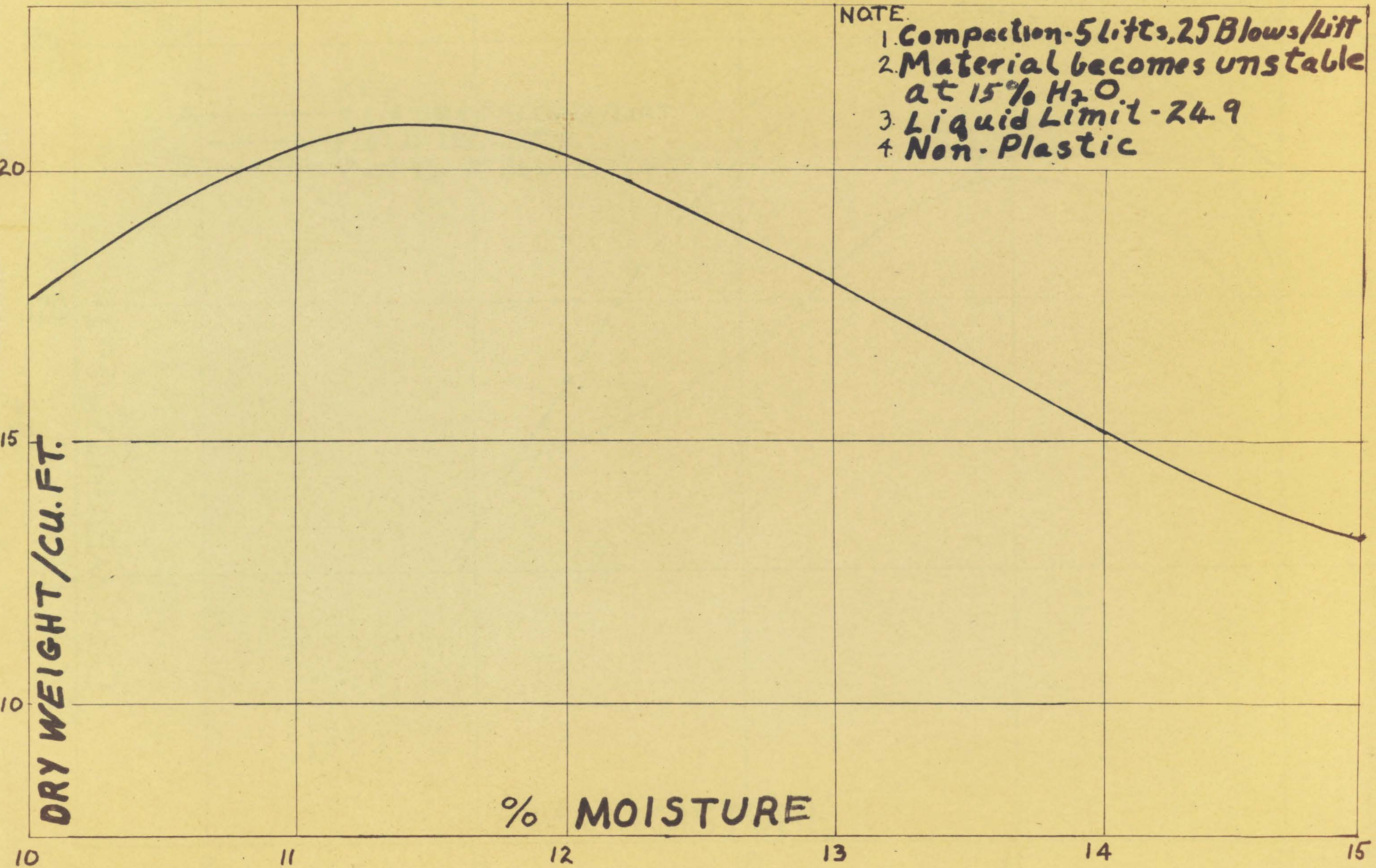

Figure 10

FIELD DENSITY CURVE

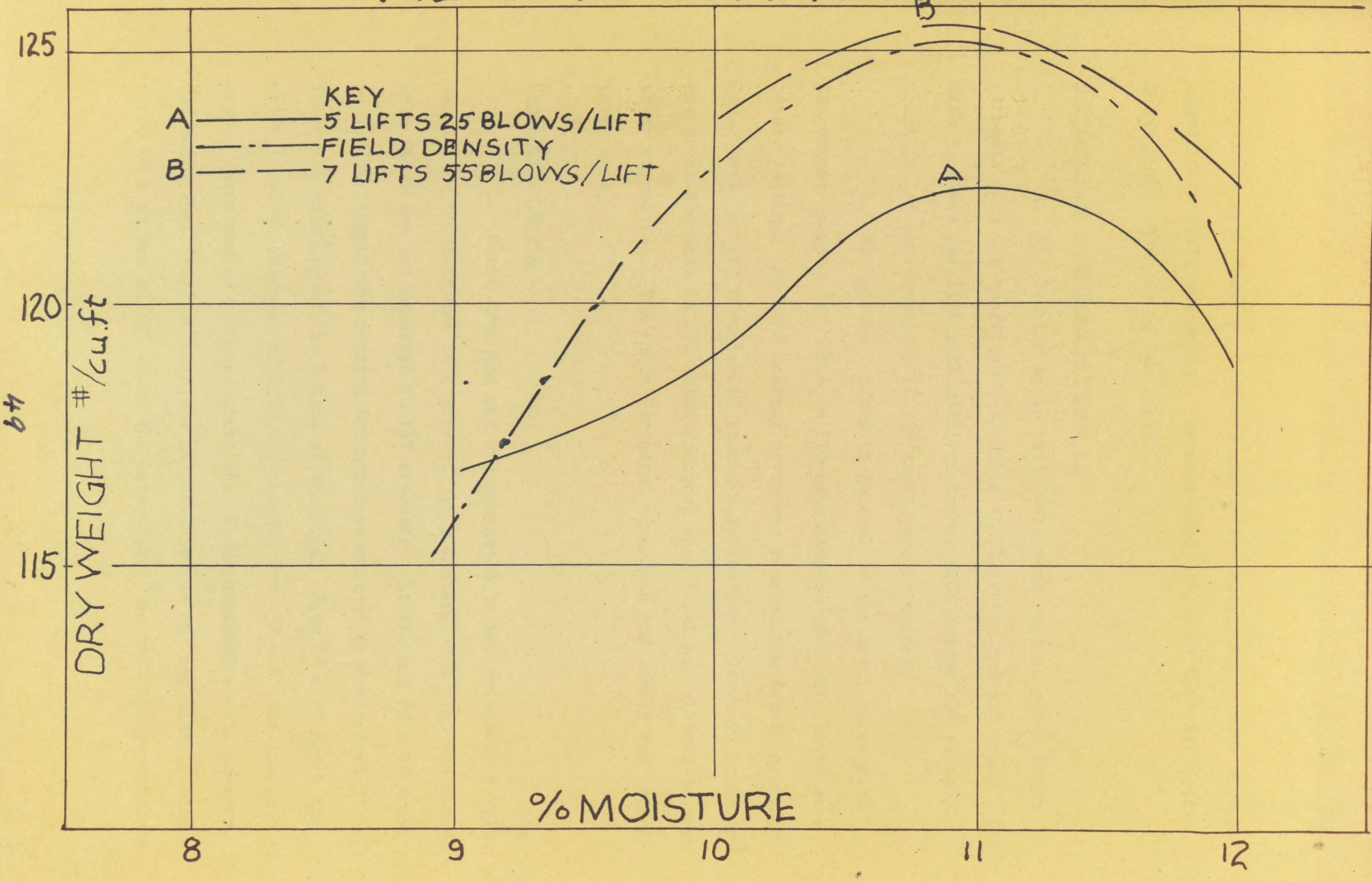

Figure 11

considered satisfactory. Curve B was later determined to more closely approximate field compaction. Approximately 94.5% of Zero Air Voids Density was obtained in the field.

California Bearing Ratio - Figure 12

a. All bearing ratio tests were performed on coral taken directly from the quarry and compacted at 11% water content using 5 lifts with 55 blows per lift with modified rammer (10# hammer 18" stroke). Densities of approximately 122.5#/cu.ft. were obtained.

b. The curves conform in general to the ideal curve with CBR values ranging from 86.6 to 120 depending on time allowed to cure before testing. Maximum bearing power was reached the fourth or fifth day. Tests showed no material increase thereafter. Curve #7 indicates the great decrease in CBR which occurred when coral was allowed to soak after compaction. CBR value for coral compacted and soaked was approximately 25.

Capillarity Tests

1. Coral from the pit was compacted to approximately 117 lb. per cu. ft. at 11% moisture in a pipe of $3\frac{1}{2}$" diameter. The pipe was placed with the lower end immersed in $1\frac{1}{2}$" of water. At the end of a 48 hour period the sample was removed and moisture content determined at 3" intervals starting at the bottom of the pipe. From 0" - 3" above the water level an increase of 2.2% was noted. From 3" - 6" the increase was 0.3%. There was no increase above 6". In uncompacted coral, however, it was found that definite increase in moisture due to capillarity took place to a height of 12" above the water level the test being performed

CALIFORNIA BEARING RATIO CURVES

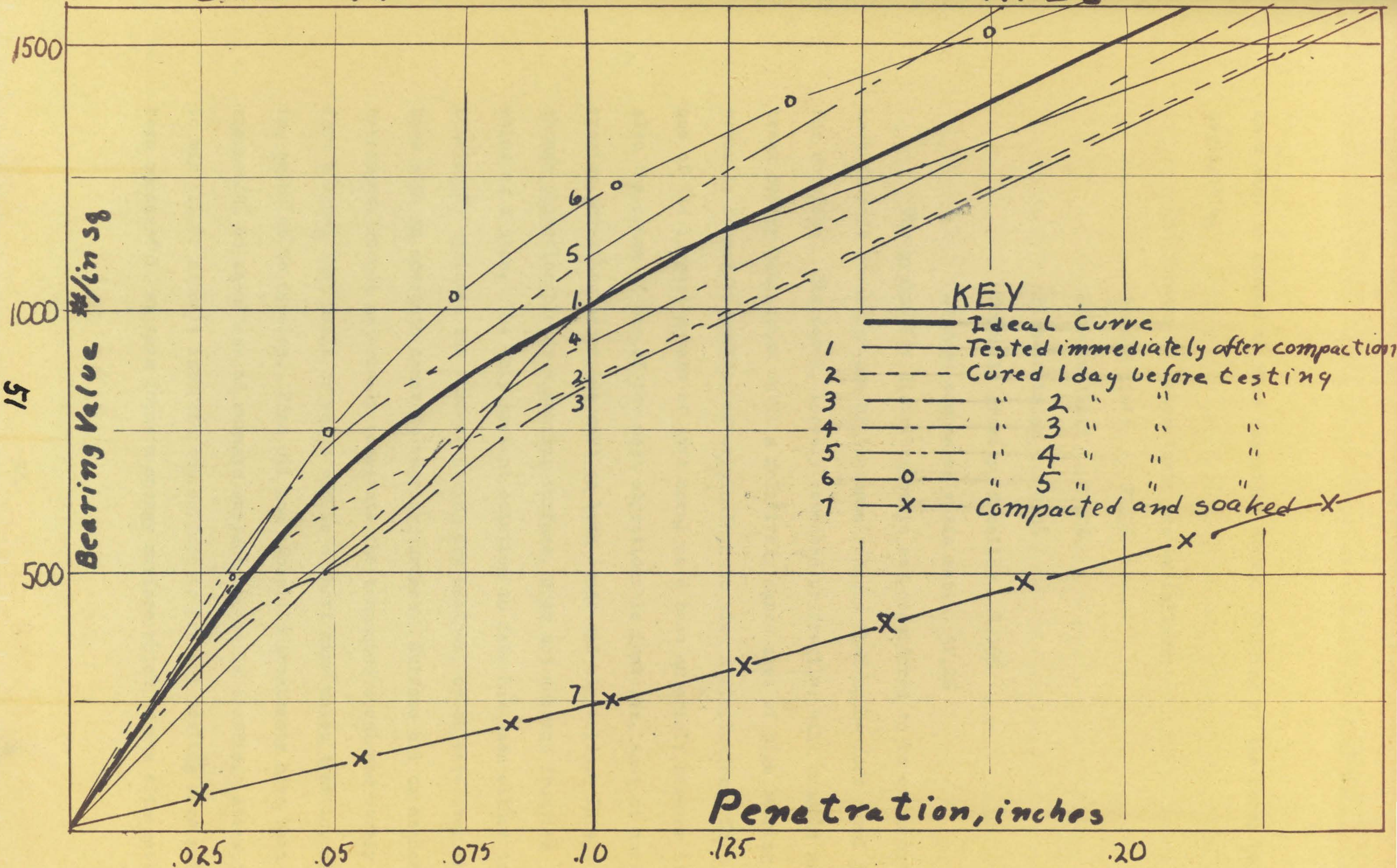

Figure 12

in a similar manner to that described above. Bulking of the coral was negligible.

The results of other tests are as follows:

Liquid limit	27.2%
Plastic limit	23.2%
Plastic index	4.0%
Specific gravity of solids	2.76%
Average compacted voids ratio	32.2%

The grain size distribution is not considered to be of importance in soft coral for one of the same reasons that makes soft coral poor for concrete. The coral, loosely cemented or fragile, will crumble and break during compaction until a relatively dense mass of high bearing power is formed regardless of original grain size distribution. This is one of the largest assets of soft coral as a base material; however it is also the cause of one of the most objectionable features, that of surface erosion, creating excessive dust on both roads and airfields. This, though objectionable as a wearing surface, does not detract from its value as a base. The only present solution to date has been either to constantly sprinkle the surface during dry weather, or to pave over the base with an adequate concrete wearing surface. Surface oil or asphaltic treatments do not materially penetrate the compacted coral and merely form a crust that peels or wears off in a short time under traffic, allowing potholes to develop. Road oil and asphaltic treatments have been successful on shoulders of runways subject to little traffic. Attempts to mix oil or asphalt into the top surface to prevent peeling have not been successful, as this forms a spongy surface which, while eliminating dust, ravels badly.

Most California Bearing Tests of coral indicate a high CBR, such as the one of 120 for the above example. It will be noted however that this CBR is taken after compaction but not after saturation, and that the saturated CBR for the example is 25. Attention is called to the slow absorption of water by capillary action. In the test given it took the bottom 3 inches 48 hours to approach saturation. Had the test lasted longer there is little doubt that the coral would have become saturated considerably higher. The slow rate of initial saturation plus the fine and dense state of the material, producing small pores, both support this conclusion. Unfortunately this reported capillary test is the only one available.

A material with a saturated CBR of 25 is not considered a good base as it is likely that a sub-base will become saturated, thereby providing water to saturate the base. This is of little consequence to coral as the sub-base is almost invariably extremely porous and incapable of drawing up water, or the water table is well below the depth of capillary action. In the vast majority of cases coral bases are laid either on a subgrade of undistributed coral or on banks of coral sand, both of which are extremely porous. On Makin one shoulder of the runway on a sand sub-base subject to vehicular traffic was actually flooded during spring high tides. However, such tides were of such short duration, and the mean water table was sufficiently below the base that there was insufficient time to saturate the compacted coral. The only failure was minor surface raveling caused by vehicles traveling through the water. Tropical rain fall has little effect as the compacted coral sheds the water rapidly. Minor imperfections of grade causing ponding are not dangerous providing they are not subject to traffic, as the water will generally evaporate before it has had sufficient time to saturate much coral. However, under traffic, raveling sets in rapidly, increasing the ponding. For this reason a 1½% crown slope is considered necessary to minimize ponding in grade imperfections.

Other than on native coral or sand, coral bases are laid on either tidal marshes or on non calcareous earth in the hilly land of elevated coral islands where the base foundation is exposed through or above the coral zone. In the first case extremely thick bases are necessary unless an adequately drained sand blanket is first laid down. The extension of B runway, Hickam Field, Oahu, was made over the Hickam mud flats with a 48" base of coral (though 60" was indicated by CBR tables) without a sand blanket and appears satisfactory. In the latter case adequate surface drainage will prevent failure with the normal thickness of coral base, as the water table is generally far below the possible capillary rise. Ponding along side of fills has caused failure and must be prevented. Similarly caution must be used in the rare valleys with stream flow or near springs. The foundation material that is exposed through the coral zone is normally hilly, precluding airport construction. Proper road drainage can generally preclude the saturation of the sub-base. The only major airport built on such material with coral, Wheeler Field, Oahu, had a base made up of crushed, porous, igneous rock in the lower layer with compacted coral on top.

Failures have also been caused by laying coral bases on saturated sub-base fills of non calcareous material. In one case the dirt fills were compacted in dry weather, but imperfectly graded. Rain ponded on them; then coral base was laid in two lifts. Faulty supervision allowed the placing of the second left before the first was adequately compacted. Had it been compacted failure would likely have occurred in the process. The second lift was thoroughly compacted, and the surface used by light planes and vehicles for several weeks before failures occurred under heavy planes. Adequate grading of the sub-base prevented subsequent like failures.

It is therefore, both safe and proper to design coral base courses with optimum rather than saturated CBR's wherever sub-base conditions are such as to or can be made to prevent saturation. Under these conditions, prevalent throughout the Pacific, twelve inches of good coral base is all that is required for present day maximum loads.

It should be noticed, in the typical analysis above, that while the optimum moisture content is 11%, the material loses all stability of 15% moisture content. This is a characteristic of most soft corals, that is, though the optimum moisture content may vary from 10% to 15% an addition from four to five percent moisture over optimum will cause the loose material to lose all stability. It should be further noticed that approximately 94.5% of zero air voids density was obtained in the field, and that bulking of the coral was negligible. If bulking were actually zero the compacted coral could take up only 0.66% additional moisture to become 100% of zero air voids density. Such saturation would have little effect on the bearing strength of coral. However, the capillarity tests indicate that bulking must occur, enough to allow an additional 2.2% moisture in the forty-eight hours. This would bring the total moisture content up to 13.2% and seriously effect the bearing strength, as was noted by the low CBR after saturation. This moisture content is still short of that in which the coral loses stability, hence it may still be worked by modern grading equipment. Knowledge of the above factors enables well trained construction workers to proceed only slightly less efficiently during rainy season. The porous nature of undisturbed coral in the quarries prevents this coral from having higher moisture content than 10 or 11 (in case of the above example). Such coral may be trucked to the place of deposit in all but the heaviest rainfalls without going up to the dangerous 15% moisture content. However, it must be immediately compacted. In dense rainfalls it is sometimes necessary to roll the coral immediately with a smooth wheel roller, after a dozer has struck off the dumped pile, in order to compact a surface crust. Though the crust is irregular and will collect water, it protects the coral beneath from becoming saturated. After the rainfall lets up some, the crust must be broken and the coral properly compacted as described later. Of course in such cases it is vital to have a well drained sub-base.

Grading and Compacting the Base Course

As has been noted above, over a suitable sub-base 12 inches of coral is satisfactory for all present day loads. Such a depth should be laid down in two lifts of 7 to 8 inches loose, each, compacted to six inches. This allows 4 to 5 inches cemented "stones" to be present without seriously impairing grading operations. The quarry selected should not produce an appreciable percentage of larger size than this. (If such a quarry is not available a grizzly can be constructed and used at some cost to efficiency of the quarry operation.) Oversize rocks are dumped along with the rest of the coral. A dozer should be available to spread dump piles in approximately the right depth (unless dump spreading is done, a process which slows down round trip time of the truck and often increases truck maintenance). This dozer can rake out the larger of the oversize rocks, while trucks spotters and grade foreman can generally remove the rock from 6 to 12 inches in size. Compaction should commence immediately by **sprinkling** and rolling with sheepsfoot rollers. With coral quarried above the water table, and with a water source adjacent to the construction area one 1500 gallon motorized water distributor and one tractor with four drums of standard sheepsfoot rollers are the maximum needed for each 1000 yards of coral placed each day to maintain optimum moisture and maximum compaction during dry weather. Rain and tide water quarries will naturally reduce the necessity for water distributed but not for sheepsfoot rollers. There has been some discussion as to the relative merits of the sheepsfoot roller and the rubber-tired roller for compaction. Up to optimum moisture the sheepsfoot is superior for two reasons.

a. The sheepsfoot starts compacting from the bottom of the lift by digging down through the loose top coral. Yet, at or near optimum moisture content it will actually "walk out" compacting all the way up. (See Figure 13 and 14). However the rubber-tired roller tends to knead the top two or three inches together without digging into loose material.

Figure 13: Imprint of Sheepsfoot Roller on Coral at Optimum Moisture Content

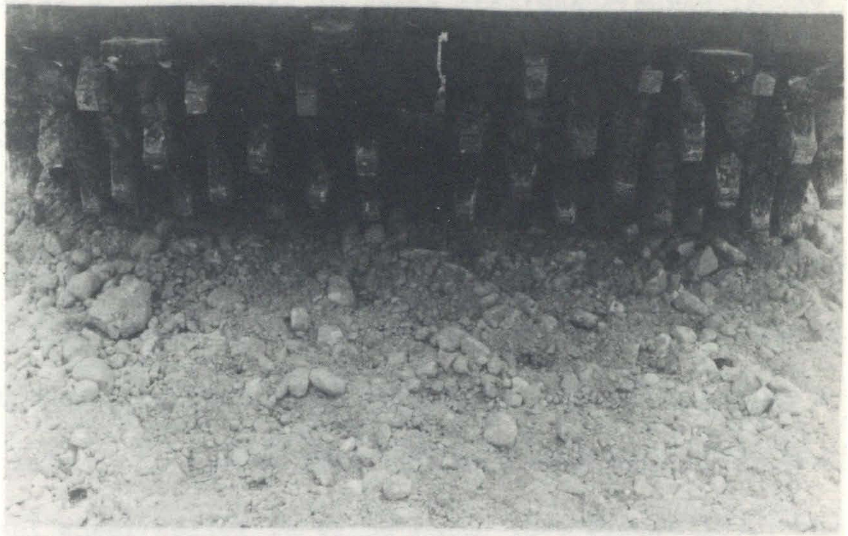

Figure 14: Sheepsfoot Roller on Dry Coral

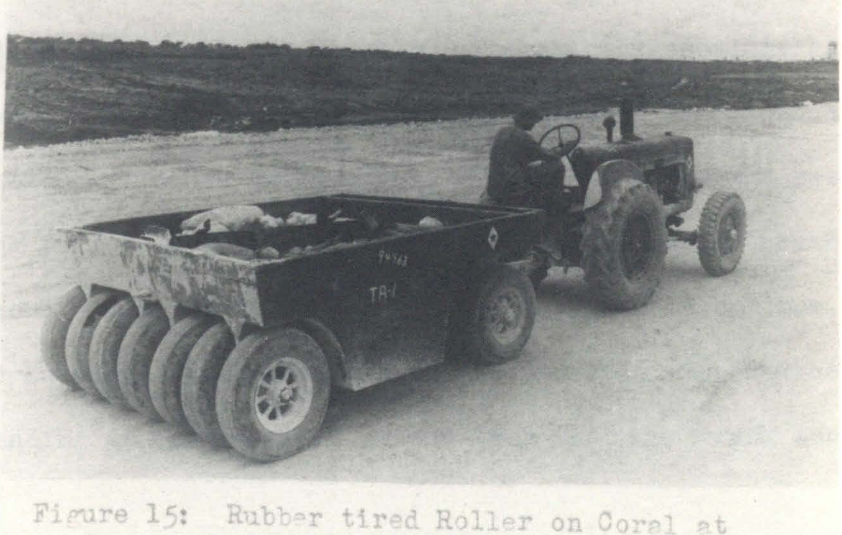

Figure 15: Rubber tired Roller on Coral at Optimum Moisture Content (Final Rolling)

This compacts the top of the lift satisfactorily but not the bottom.

b. Sharp edges of dry coral cause excessive maintenance of rubber tires. (See Figure 14 for nature of such coral).

When coral is at optimum moisture there is little choice between the two (See Figures 13 and 15).

When coral is over optimum moisture content the sheepsfoot tend to keep the top layer stirred up, while the rubber wheeled roller, far superior, tend to knead and force the surplus moisture out to the surface where it may evaporate or drain off (See Figures 16, 17, 18).

Normally the first lift is just rough graded and compacted with sheepsfoot (or rubber-tired) roller and the second lift placed over it. As the compaction of the second lift nears completion motor patrol graders are used to distribute the top material to the final grade after which it is rolled with smooth steel wheel rollers. Again moisture content should be controlled carefully. If the material is over optimum and left as in Figure 18 by the rubber-tired roller, rolling with the steel wheel roller is of no value (See Figure 19). The surface slush must be allowed to dry out some by evaporation and be touched up with a grader before final rolling, or the slush may be graded off and then final rolled. However, if the truck spotters have done their work accurately this may leave that portion of the field one-half to one and one-half inches below grade. Figure 20 shows the result of final rolling of too dry material. High points are merely crushed. Figure 21 shows the final appearance of coral rolled at optimum.

There has been some criticism of the use of a smooth wheel roller as tending to form a crust on the base that may break loose.

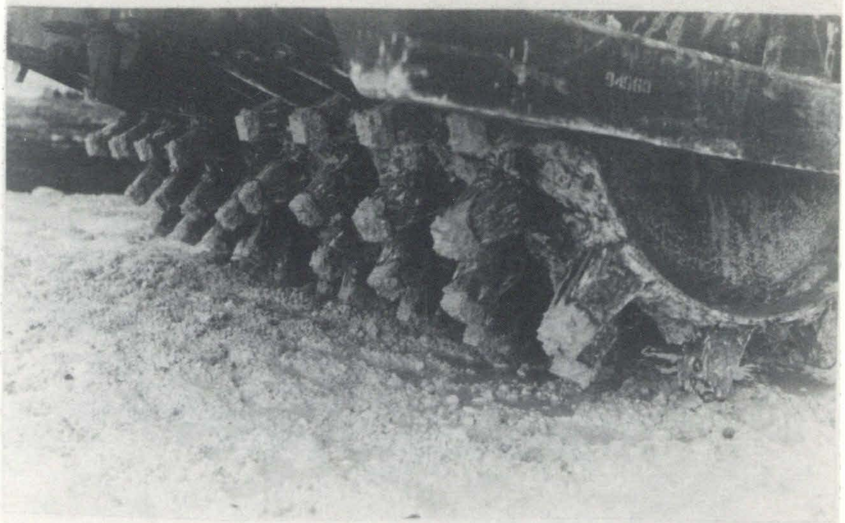

Figure 16: Sheepsfoot Roller on Saturated Coral

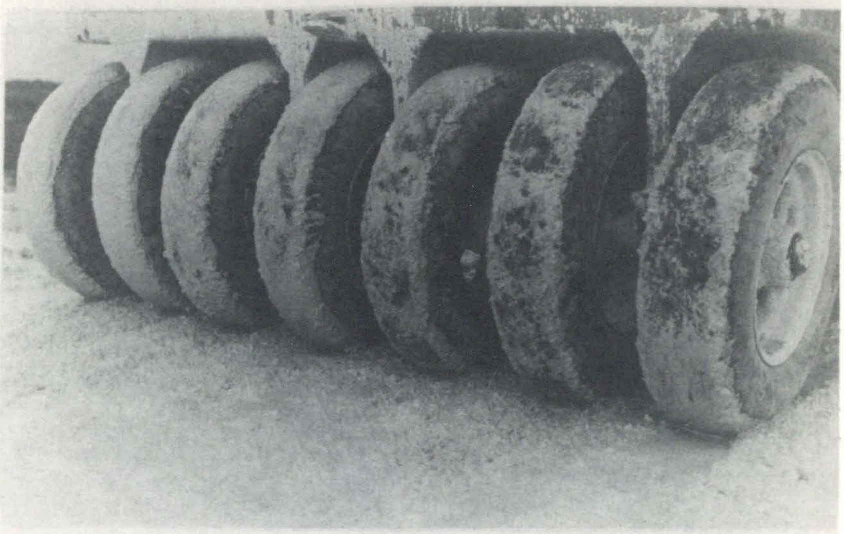

Figure 17: Rubber-tired Roller on Saturated Coral

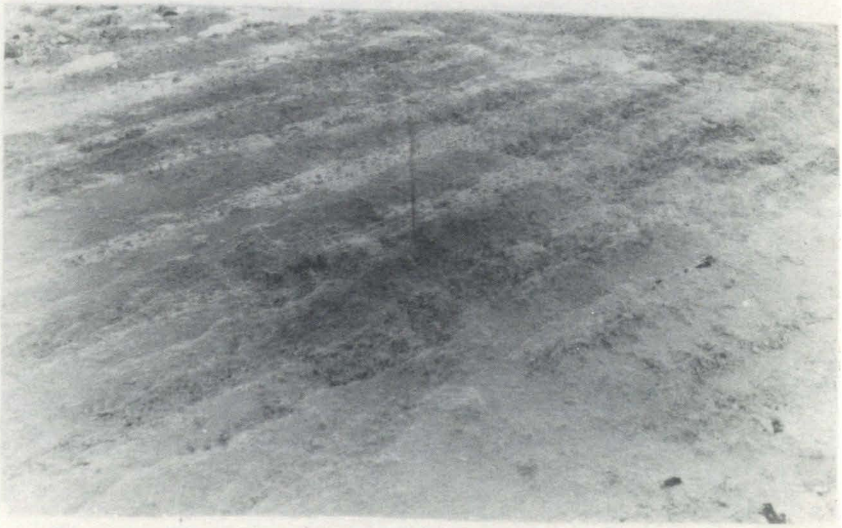

Figure 18: Saturated Coral After Rolling With
Rubber-tired Roller

Figure 19: Attempting to Smooth Roll Coral In Figure 18

Figure 20: Dry Coral Smooth Rolled

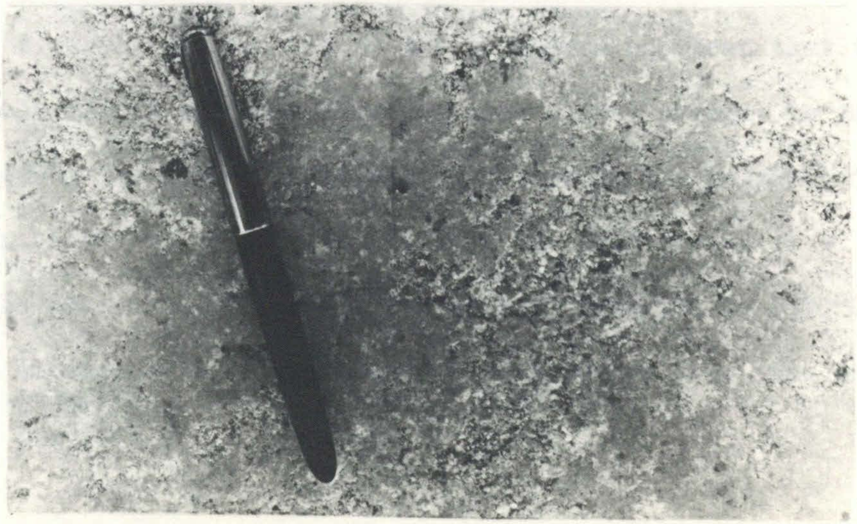

Figure 21: Coral at Optimum Water Content After One Pass With a Smooth Roller

Where proper moisture and compaction have been maintained there is no such danger, and this final roll does give a somewhat harder more durable surface. However, to maintain the dense hard surface noticed in the middle of Figure 21 continual maintenance rolling is necessary, plus sprinkling during dry weather.

To bring low spots up to proper final grade a thin film may be cut from neighboring high spots and moved in with a grader, or a small amount of coral may be sieved to eliminate one inch size rock and over and this used for such purposes. Generally it is desirable to scarify slightly the rolled surface before adding more material, but no failures have been noticed when this is not done. The added material, at optimum moisture content, need merely be graded into place and rolled with a steel wheel roller.

The "Setting Up" Phenomena

The action of coral sometimes "setting up" in the manner of concrete, after placing has been much discussed by those who have observed the use of soft coral. Such coral is often much searched for, but from the observations of the author it has been most prevalent on atolls.

A common explanation of the phenomena has been that there is a certain amount of quick lime (calcium oxide) present in the coral. Considering the nature of formation of coral, the precipitation of calcium carbonate of the sea, through the life processes of the polyp, plus the fact that it takes a temperature from 900 to 1000°C to drive carbon dioxide from the carbonate leaving quick lime, the presence of free lime seems highly improbable. Further, the readiness of free lime to react with water and carbon dioxide, present in both fresh and salt water exposed to the atmosphere, leaves little doubt that all quick lime, if present, would be converted into limestone in the generally extremely porous coral formation, during the 10 to 40,000 years of existence of the youngest coral used in the Pacific. A milky appearance of the water used in moistened coral is taken to be milk, or slaked, lime, to help establish the lime theory. Practically this milkiness is due to calcareous clay of colloidal size. All good soft coral contain some calcareous clay which on saturation tends to cause surplus water to be milky.

The explanation more probably lies in the characteristics of losing all stability at four percent over optimum moisture. Coral excavated from the inner reefs of lagoons is generally taken from below the water table, even on low tide. Scrapers often come up to the field dripping milky water draining from the coral. Such coral is naturally super saturated with water and is quite unworkable. However, after being spread on a porous sand sub-base in a layer say 6 inches thick, in the hot tropical sun, this coral will set up in a few minutes; that is, water will drain out of it until it reaches a moisture content at which it rapidly regains stability. Under adverse conditions of an impermeable sub-base and continued rainy weather the setting up may be delayed for sometime. On Saipan approximately 5,000 yards of coral became supersaturated, due to mishandling during a heavy rain storm. This material was dozed to one side where the naturally porous sub-bases was covered by a thin layer of relatively impervious top soil. The rainy season lasted another month and a half, keeping this mass constantly supersaturated. It was not until after two weeks of good weather that this coral set up. Then it was picked up and reused. A most dramatic evidence of setting up occurred on Makin. The natives had dug large pits down to the water table (3 to 5 feet) in the airfield area to grow "Bobai", a starchy root plant which made up an important element of their diet. It was necessary to fill these pits and for such purpose coral hauled from the nearby lagoon reef was dozed into the pit to a depth of about four feet before compaction was started, (final grade being considerably higher). A tractor with a sheepsfoot roller attempted to compact the mass and became hopelessly stuck, below the level of the top of his tracks. Other tractors were able to pull out the sheepsfoot roller, but merely broke cables in attempting to pull out the tractor. A tractor drawn rubber-tired crane was called to lift the tractor out. It took about an hour to get the crane and rig the slings. By this time the coral in the Bobai pit, draining only out the side and top, had set up to such an extent that it not only supported the two tires of the crane next to the stuck tractor but also the entire weight of the tractor and crane plus the resistance to being pulled out on those tires.

While the above discussion explains adequately the visible "setting up" phenomena there is still possibility that some other setting up action playing a part. It will be noticed in Figure 12 that the bearing of coral compacted at optimum density decreased from 1000 lb./sq.in to 860 lb./sq.in.in two days curing, and thereafter rose to 1200 lbs./sq.in. in the next three days. **This** is a gross increase of 39.5% and a net increase of 20%. The initial decrease may be attributed to elastic readjustment following over compaction. If so, the entire gross increase is due to some additional phenomena.

There are two possible causes for this action:

a. As the cylinders dry out the moisture in the small pores receed from the surface, setting up the same surface tension forces present in shrinking clay. In the same manner that concrete test cylinders show an increased compressive strength when dry over when wet, the coral should show a higher bearing value. The additional compressive strength of dry concrete cylinders over saturated is attributed to the contraction of the cement paste which set up tensile forces that must be overcome by initial compression, and due to the development of hydrostatic pressure in the saturated cylinders. The first condition, as such, is not present in coral. However the forces set up by surface tension of water in the pores sets up a similar internal tension tending to compress the sample further. This force would be relieved if the sample is completely dried of unbound water, or brought up to optimum moisture again. In any event the effect would appear to be less than that of concrete. In concrete the increase varies from 18 to 25%*. The gross increase shown in Figure 11 is 34.5%, indicating that there may well be other elements to consider.

b. In the field it has been noticed that salt water produced better results than fresh water when used to maintain optimum moisture. The most obvious reason for this is that the salt so deposited is deliquescent and tends to maintain the presence of moisture. For

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* Figure 10, The Making and Testing of Plain Concrete, Troxel and Davis.

consistency, salt water was used in compaction test. Now, though the advantage of deliquescence to maintain moisture content is obvious, such maintenance of moisture would not cause increase of in bearing strength. Sea water contains approximately 3.3% soluble salts by weight. The volume of such salts in solid form is about 1/2 that percentage because of their specific gravity. On drying out of the sample the voids would be reduced by approximately 1.6%. Natural surface tension within the void spaces tends to concentrate moisture between the closest faces as it evaporates. Hence more salts will be deposited in these spaces, where they will have the most effect in cementing particles. This effect possibly contributes to the increased bearing values.

It should be noticed that the testsshown in Figure 11 are the only tests that the author knows that have been performed in effort to prove definitely the presence of a setting action other than that caused by draining of saturated material. It is his opinion that other soft coral will act similarly, if the reasons given above are true, but this has not been established by actual test.

If such be true, and if the second reason plays an appreciable part an interesting possibility is raised. Granted that the great bulk of crystals filling the 1.6% of void space are soluble and are subject to rapid leaching; still approximately 0.00656% is relatively insoluble limestone. Is it possible by chemical precipitation to greatly increase the amount of limestone precipitated in the voids, thereby accelerating the natural cementing process discussed in

Section II? Such a process would be highly desirable if by that means a hard, securely bonded crust of calcite could be produced on the surface of a coral base, thereby eliminating its greatest disadvantage, erosion produced dust, and eliminating the need for an additional concrete wearing course.

SECTION IV

CONCLUSION

It is seen that coral, as normally used, is a poor concrete aggregate because of its softness, and that, with low saturated CBR's, it is a poor base material. Nevertheless, with good control and proper conditions, excellent results may be obtained with coral both as concrete and for bases. It is fortunate indeed that the proper conditions for the use of coral exist on practically all the islands of the Pacific where it is available, thereby providing a reliable aggregate for large areas of the world without other possible sources.

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11. Correspondence with:

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    b. Dr. H. T. Stearns, formerly Geologist, Pacific Ocean Areas, U. S. Geodetic Survey.

    c. United States Engineer District, U. S. Army, Honolulu, T.H.

The date given in the analysis of a typical soft coral was taken from the "Airbase Construction Report, Saipan, Marianas", prepared by the author. The remaining data used was taken from "The Oceans".

PART II

CHEMICAL STABILIZATION OF CORAL SURFACES

Introduction

It has been noted that the greatest disadvantage of the use of coral, as a surfacing material for roads and runways, is the manner in which it erodes, creating a tremendous dust hazard unless elaborate precautions are taken to keep the surface moist and rolled. Furthermore, in a relatively short geological time and under the right chemical conditions loose coral particles and porous coral formations in their natural state may be so cemented by precipitation of calcium carbonate as to form solid relatively impervious limestone rock. The manner in which this natural precipitation may be accelerated to provide a tight dust proof wearing surface, requiring little maintenance will be developed.

Basic Considerations and Assumptions

Coral limestone is almost pure calcium carbonate, the principle impurity being magnesium carbonate. For the purpose of simplification it will be treated as pure calcium carbonate and the effect of the magnesium carbonate on the reactions involved will be discussed later. Saipan coral again will be used as typical. Compacted at optimum moisture it has a density of 125 pounds per cubic foot. The specific gravity of the solids is 2.76; therefore solid coral limestone without voids, would weigh 172.5 pounds per cubic foot. For convenience of calculation weights of limestone to fill the voids present in one compacted cubic foot of coral will be used rather than voids ratio. 47.5 pounds are required to fill all the voids. Initial chemical precipitation of calcium carbonate from the water in pore space will be uniform; however, as the water evaporates surface tension will draw it toward the point of contact of the coral particles. As more water evaporates additional calcium carbonate will be precipitated around the point of contact where it will be of greatest value in cementing those particles. Considering the above a reasonable estimate of the amount of precipitated limestone needed to cement the coral particles is 12 pounds (reducing the voids ratio from 27.5 to 20.3). Dense cemented coral limestone in natural state generally have voids ratios higher than 10%, therefore as a maximum figure it will be assumed that 36 pounds of calcium carbonate (reducing the voids ratio to 6.65) will guarantee cementing.

Only a thin crust of cemented coral on the surface is needed to prevent dust, but such a crust would tend to break or peel off. To prevent this it will be necessary to cement a strata several inches thick, varying from maximum cementing at the top to none at the bottom. It is estimated that 4 inches is sufficient, varying uniformily. To obtain 12 pounds and 36 pounds additional limestone on the surface will therefore require 2 and 6 pounds of calcium carbonate respectively per square foot of surface area. The word respectively will henceforth be used to denote calculations based on these two figures.

There are several ways that this precipitation can be accomplished. The equations involved are given on page 84.

a. An acid may be added to water in contact with solid base calcium carbonate (Equation 1) and the resulting solution distributed during and after compaction of the top layer. On evaporation calcium carbonate and the calcium salt of the acid added will be precipitated. The latter of the normal acids, chloride, sulphate or nitrate will be relatively soluble and will leach out rapidly with rain, hence only half of the calcium so applied will be effective. Further, the process will require large quantities of expensive acids.

b. Calcium carbonate may be burned in a kiln, producing quick lime (equation 2) which may be distributed dry as a powder and slaked (equation 3) by distributing water on it, or may be slaked initially and distributed in solution. The former process is undesirable because of the large bulking that takes place on slaking, disrupting the compaction procedure, and because of the practical difficulties of obtaining uniform decreasing distribution of the lime in the top layer of coral. Calcium hydroxide, relatively insoluble, can be handled by distributors by forming what is known as lime milk. If only a slight amount of water more than that required by equation 3 be added the product becomes pasty rather than a dry powder. As more water is added the viscosity of the paste is reduced, resulting in a colloidal solution of calcium hydroxide with only a small percentage actually in true solution. A ten to twenty percent solution can thus be readily handled by normal water distributors. In both methods the carbon dioxide in the air will turn the calcium hydroxide to limestone. (equation 4). This reaction is very slow because the carbon dioxide content of the air is low and because diffusion must be depended on for penetration to depth.

c. A weak acid may be made by bubbling carbon dioxide through water, forming carbonic acid. If this acid be used in the method described in (a) the expense will be reduced and all the calcium in solution will be effective (equation 5, 6 and 7).

d. A combination of method b. and c. may be used causing chemical precipitation (equation 8) as well as precipitation by evaporation, and also eliminating the need of equation 4 in the b. method, a slow reaction because of the small concentration of carbon dioxide in the air.

Precipitation by Chemical Reaction

Several other methods are possible, modifications of the above. It is believed that method (d) is most practical and it will be discussed in detail. Proportional weights necessary for the precipitation of 2 and 6 pounds of calcium carbonate respectively are shown on page 84 for equation 2a, 3a, 5a and 8.

Production of slaked lime and milk lime is a standard commercial process that involves no difficulty where limestone is available. It is seen from equation 2a that 1 and 3 pounds of limestone respectively must be burned to produce sufficient lime for one square foot of surface. For a runway 6000 feet by 200 feet this would require 600 and 1,800 tons respectively. As a comparison 14,800 tons of rock would have to be heated to about one half the temperature for a hot mix pavement, requiring a considerable larger kiln plant. (Burning limestone requires a heat of about 900°C against 450°C for a hot mix). One application of a 20% lime water solution at the rate 4 gallons per square yard will cause the final precipitation of 2.06 pounds of limestone per square foot slightly more than the 2 pound value needed. (Assuming density of solution is 64 lbs. per cu. ft. well under actual). For the maximum 6 pound value three applications are needed, allowing the surface to dry out between applications, unless it proves feasible to distribute a higher percentage than 20%.

Production of the calcium bicarbonate solution needed again follows standard commercial process, that of recarbonation of lime softened waters; however the process must be carried to a point considerably further than in the normal softening process in order to reach practical concentrations. The plant, relatively simple, is described in most water supply and treatment manuals. It consists of passing carbon dioxide through a tank of water containing limestone in the solid phase, that limestone going into solution as bicarbonate, (equation 5). A ready source of carbon dioxide is available in the flue gases of the kiln used to burn the limestone. By comparing equations 2a and 5a it is seen that the exact amount of carbon dioxide required in equation 5a is provided in 2a. Naturally it is not practical or possible to use this exact amount, however a large surplus will exist in the flue gases due to the combustion of the fuel used to heat the kiln.

It is now necessary to approximate the possible concentrations of calcium carbonate that can be dissolved by the above method, in order to determine if sufficient amount can be distributed to be practical. This involves a study of the carbonate-bicarbonate mass law equations; a subject in which there is still considerable divergence between strict theoretical analyses and the results of various investigators (Ref. 2).

On this Langlier (Ref. 5) states "A survey of . . . . . . literature has failed to reveal an adequate and practical formulation of the chemical mechanism of the carbonate film theory". Considerable effort has been devoted to this study as it has a direct bearing on the corrosive or depositing action of waters on pipes. From the literature on the subject it has been possible to derive a method of approach for this cementing problem. Within the range of the experiments which have been performed the method checks accurately, however in an effort to obtain high concentrations the method has been carried beyond the presently established limits, with possible progressively large errors.

Page 85 gives five well known mass equations and one stoichiometric equation. From these the basic working equation No.16a has been derived algebraically. Langlier has used equation 16b in Ph ranges of 4.5 to 10.3, and equation 16c in ranges 6.5 to 9.5. The Ph range of this problem is 5.8 to 10.14. In the lower end of the range equation 16c is still amply accurate because of the higher alkalinity*. (Alkalinity being defined as the titratable equivalent of base per liter, in this case is equivalent to the calcium ion concentration under the assumption made above. Actually it will be somewhat higher than the calcium ion concentration, a condition which is beneficial to the process). In the upper end of the range slight errors are introduced by using 16c. These values have therefore been derived by using a simpler form for calculations of equation 16a, equation 17. This equation was

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*Taking the Ph of 6 beyond Langlier's limit for equation 16c
$P(alk) \triangleq 1$ (See Pg.89) while $(H+) - \frac{Kw}{(H)} = 10^{-6} - \frac{10^{-13.88}}{10^{-6}} =$

$10^{-6} - 10^{-7.88}$. (An infinitismal compared to 1).

derived from equation 16c and 12. Page 87 gives various empirical formulas for equilibrium constants needed. K stands for the true disassociation constant K' for the apparent disassociation constant. K_1 is the first disassociation constant of H_2CO_3 and K_2 is the second. Kw and Kca are the disassociation constants of water and limestone respectively. μ is the ionic strength defined as the sum of the various ion concentrations of a solution times the square of their valance divided by two. Equation 22 is an empirical expression for sea water. Cl representing the chlorinity in parts per thousand. P indicates the negative logarithm of the particular ions molecular concentration in mols per liter.

Table 1, page 88, evaluates the various constants needed for the range of calcium ion concentration being investigated. Column 6 was derived from equation 19. However, this equation has been proven inaccurate at ionic strength greater than 0.02. The value of PK'ca for sea water (Cl = 19 $\frac{0}{00}$) has been established as 5.57 (Ref. 2). Equation 22 establishes μ = 0.7 for sea water Cl = 19‰. Using this value Column 6a was determined by graphical interpolation, Page 91.

Table II, page 89 determines the Ph corresponding to the various calcium ion concentrations, using the values of Table I and equation 16c. Page 90 gives a typical solution of equation 17, the results of which for the upper range of Phs have also been posted on Table II.

Both of the solutions developed in each case with equation 17 are correct, indicating that limestone has a minimum solubility between Ph of 9.44 and 10.14. The actual minimum value can be established by additional trials between PCa = 3.6 and PCa = 3.9, however the only value here of this calculation is to indicate the correctness of this method, as the study is to develop high concentration of calcium at the lower range of Ph's. Actual experiments indicate the minimum value is in this range.

Equation 23, pg. 87 has been developed from equation 12b, the results of evaluating equation 23 using values from Tables 1 and 2 are given in Table 3.

As $K = CP_{co_2}$ (Equation 1), the partial pressure of carbon dioxide necessary to develop the arbitrary calcium ion concentration of Table 1 can be calculated. The range of values for C is given under Equation 1, except between $\mu = 0$ and $\mu = .4$ for which the value of .3 is used. The error so introduced is not important as it is in concentration below those needed. The partial pressures have been recorded in Table 3.

The parts per million of calcium carbonate that can be dissolved with the various partial pressures of carbon dioxide are also posted in Table 3. These, and the above, values have been plotted against ionic strength on page 91.

Both the inaccuracies of PK'ca and a study of Table 3 indicate that this table is not reliable beyond $\mu = .7$. However, it does indicate that there is a strong possibility of dissolving approximately 5000 PPM calcium carbonate with a partial pressure of .50 atmosphere. Flue gases should run about this high. Since in the normal process of recarbonation the flue gases are led into the bottom of a tank under a head of five to ten feet, with a consequent increase of partial pressure at the bottom of the tank decreasing to .50 at the top, the use of this figure is conservative.

On the basis of 5000 P.P.M. calcium carbonate (in form of bicarbonate) a four gallon per square yard distribution of the solution will cause the final precipitation of .03 pounds per square foot. To achieve the estimated 2 pounds required will take approximately 70 applications. For the maximum amount of 6 pounds 200 applications are required. See Page 90 for calculations of these amounts. Both of these conditions are possible, even at the reduced rates of applications that will be necessitated as the surface becomes less pervious. However it will be necessary to carry on the distribution for a considerable time after the surface is otherwise completed.

Tentative Field Procedure

A tentative procedure for carrying out this cementing process is as follows. The last lift of coral laid down is generally about six inches. Compaction of this lift should commence as normally done, that is distributing water to obtain optimum moisture content and compacting with a sheepsfoot roller. This process should be stopped when about half complete, that is, when the bottom half of the lift has been fairly well compacted, yet the top half is still loose. Normally one application of water and about four passes with the sheepsfoot will be sufficient, but field experiments can best determine this. The surface should then be allowed to dry for a day or two, depending on the weather, to allow a maximum application of milk lime by distribution. (It is not believed possible to accomplish the control necessary during rainy weather). If field experience indicates more than one application is needed it will be necessary to allow the surface to dry after each one, but the last. There is no way to control uniform gradation of lime from maximum at the top to nothing four inches down, but the tendency will be in this direction as top layer will tend to filter the colloidal lime out. After the last application compaction with sheepsfoot rollers is continued until of no more value. By this time the surface will have dried out sufficiently for the first application of the bicarbonate solution. All applications should be as heavy as the surface can take without run-off. Final grading and smooth rolling can proceed alternately with applications of the bicarbonate solution. As precipitation by chemical reaction and partial evaporation takes place the surface will become less pervious upward until finally a tight cemented top surface is made that is practically impervious. The rate of distribution of the bicarbonate will necessarily decrease steadily to prevent run-off of the solution. This may well leave some calcium hydroxide unreacted deeper down, but as it has a cementing value of its own this is not disadvantages and the desired result has been accomplished. The results of this analytical study indicate that the distribution of the bicarbonate will continue from two months to a year after the final rolling at rates probably considerably less than required as a dust pallative on untreated surfaces. Fresh water should be used for the bicarbonate solution rather than sea water, even though sea water initially has a considerably higher bicarbonate concentration. The large quantity of soluble salts, 3.3% in sea water, when precipitated by evaporation, would occupy space desired for the less soluble limestone.

Analysis of Assumptions

Certain inaccuracies are present in this development:

(a) As pointed out above the theory of the carbonate-bicarbonate equilibrium reaction is still quite indefinite. Results of various different researchers agree only generally and much remains to be solved in this line. Though this may considerably alter the above development, the theory is nevertheless accurate enough to show the general trend of these reactions and this trend definitely indicates the possibility of accelerating this natural geological process to the point where it may be practically employed.

(b) No mention has been made of the time necessary for these equilibria reactions, and the time has not been recorded in the published results of the various researchers, other than increased temperature increases the speed of reaction. Unfortunately, this can not be used to advantage, as increased temperature also decreases the solubility of carbon dioxide, and hence the amount of calcium carbonate that can be dissolved.

(c) The quantitive development of the milk lime solution was based on 100% pure limestone and 100% complete burning. Neither will be achieved in practice, resulting in the necessity of distributing greater amounts of milk lime solution.

(d) Uniform horizontal distribution of the two solutions can be readily achieved, but uniform distribution from maximum at the top to none four inches down, vertically, is impossible. The greatest danger is the development of a strata not well cemented to a lower one, but is is believed that experience in following the procedure outlined above will adequately solve this point.

(e) The broad range of the quantity needed for cementing calculated above will adequately cover the amount actually needed. It is believed that only 2 to 3 pounds will be required.

Necessary Experimental Work

This development has been entirely analytical. A large amount of experimentation both in the laboratory and in the field will be necessary not only to prove the practicability of the process but the necessary methods of control. Some of these experiments are as follows:

(a) The amount of colloidal calcium hydroxide that can be handled in solution with normal distributions, by both laboratory viscosity tests and experiments with a distributor.

(b) Percentage of carbon dioxide in flue gases by laboratory and plant tests.

(c) Concentration of calcium bicarbonate that can be attained with that percentage of carbon dioxide, by laboratory and plant tests.

(d) Time required to attain the above concentration by both laboratory and plant tests.

(e) Time of reversal of the bicarbonate equilibrium, when no longer in the presence of carbon dioxide, by laboratory and plant test. (Important as the value of a distributor may soon be nullified by carrying the super saturated bicarbonate solution in presence of normal atmosphere. The distributor pipe system could rapidly be clogged with limestone handling these high concentrations. If this is serious it may be partially nullified by pumping flue gases in the tank of the distributor prior to filling, thereby maintaining the high carbon dioxide partial pressure during the filling and for a reasonable time thereafter, until atmospheric air is brought in during the emptying.)

(f) Percentage of voids to be filled to obtain adequate cementing, by laboratory and field test.

(g) Depth that treatment must go to, to prevent peeling, by field test.

(h) Control necessary and progressive rates of applications of solutions, by field tests.

Effect of Magnesium Carbonate

The presence of magnesium carbonate in small percentages was mentioned above. Actually magnesium carbonate, bicarbonate and hydroxide have similar properties to the same calcium compounds. In the equations presented magnesium can replace calcium and they will still hold, by changing the molecular weights and adjusting the constants. Magnesium oxide and hydroxide will be produced in the same manner as discussed above and will not alter the milk lime solution materially. In the range of Ph used magnesium carbonate is slightly more soluble than calcium carbonate, hence a proportionally greater amount of it will go into solution in the recarbonation tank. Similarly the precipitate on the field will have a greater amount of magnesium. An equal mixture of magnesium and calcium carbonate is called dolomite and has a hardness number of 4 to 4.5, compared to that of 3 for calcite (hardness base talc 1 to diamond 10). Hence the presence of the magnesium in larger percentages than in coral will tend to produce a harder surface.

Conclusion

It should be noted that a surface hardness of 3 to 3.5 is the best that can be obtained. Such a surface will resist wind and water erosion well, but will still wear under heavy traffic, and such material that does wear off is, again, a dust hazard. For this reason, if successful, the process will have greatest application on airfields where the density of traffic is low, and less value on roads. The application of the process should be completely adequate for all except the most heavily used airport, and of some value on roads, particularly secondary roads. It will be considerably more economical than the normal surface paving placed on coral bases. It has possibilities of much wider application than the coral islands of the Pacific, as it may be used wherever limestone, not necessarily of coral origin is used, or available for base material.

It is possible that an artifically hardened surface might provide a satisfactory bond for some of the less expensive types of bituminous surface treatments. Practice to date has been unsatisfactory since natural coral does not provide sufficient bond to prevent flaking of the surface treatment material.

Basic Chemical Equations

1. $2\,CaCO_3 + 2H^+ \rightarrow Ca^{++} + Ca(HCO_3)_2$

2. $CaCO_3 \rightleftarrows CaO + CO_2$ (equilibrium at 910°C)

3. $CaO + H_2O \rightarrow Ca(OH_2)\downarrow$

4. $Ca(OH)_2 + CO_2 \rightarrow CaCO_3\downarrow + H_2O$

5. $Ca(OH)_2 + H_2O + CO_2 \rightleftarrows Ca(HCO_3)_2$

6. $CO_2 + H_2O \rightleftarrows H_2CO_3 \rightleftarrows H^+ + HCO_3^- \rightleftarrows 2H^+ + CO_3^=$

7. $CaCO_3 + H_2CO_3 \rightarrow Ca(HCO_3)_2$

8. $Ca(HCO_3)_2 + Ca(OH)_2 \rightarrow 2\,CaCO_3\downarrow + 2H_2O$

154	74	2×100	2×18
1.54	0.74	2	0.36
4.6	2.2	6	1.08

3a. $CaO + H_2O \rightarrow Ca(OH)_2$

56	18	74
0.56	0.18	0.74
1.66	0.54	2.2

5a. $CaCO_3 + H_2O + CO_2 \rightleftarrows Ca(HCO_3)_2$

100	18	44	154
1	0.18	0.44	1.54
3	0.5	1.69	4.6

2a. $CaCO_3 \rightleftarrows CaO + CO_2$

100	56	44
1	056	0.44
3	1.66	1.68

Stoichometrical Mass Equilibrium Laws

9. $(H_2CO_3) = C\,p_{CO_2} = K$

values of C						
	$\mu = 0$	0.4	0.8	1.2	2.0	4.0
	$C = 0.033$	0.329	0.311	0.314	0.30	0.27

10. $\frac{(H^+)(HCO_3^-)}{(H_2CO_3)} = K_1'$

a. $Ph + PHCO_3 = PK_1' + PH_2CO_3$

b. $(HCO_3^-) = \frac{KK_1'}{(H^+)}$

11. $\frac{(H^+)(CO_3^=)}{(HCO_3^-)} = K_2'$

a. $Ph + PCO_3 = PK_2' + PHCO_3$

b. $(CO_3^=) = \frac{KK_1'K_2'}{(H^+)^2}$

12. $(Ca^{++})(CO_3^=) = K_{Ca}'$

a. $\frac{(Ca^{++})(HCO_3^=)}{(H^+)} = \frac{K_{Ca}'}{K_2'}$

b. $(Ca^{++}) = \frac{K_{Ca}'(H^+)^2}{KK_1'K_2'}$

13. $(H^+)(OH^-) = K_w'$

a. $Ph + POH = PK_w'$

14. $(Alk) + (H^+) = 2(CO_3^=) + (HCO_3^-) + (OH^-)$

a $(Alk) = (Ca^{++}) \cong 2(CO_3^=) + (HCO_3^-)$

Developement of Working Equations

15. $(CO_3^=) = \frac{K_2'(HCO_3^-)}{(H^+)} = \frac{(Alk.) - (HCO_3^-)}{2}$; (Eq. 14a. and 11)

a. $PHCO_3 = P(Alk) - P\left[1 + \frac{2K_2'}{(H^+)}\right]$

b. $PHCO_3 = P\left[(Alk.) + (H^+) - \frac{K_w'}{(H^+)}\right] - P\left[1 + \frac{2K_2'}{(H^+)}\right]$; (Eq. 14 and 11)

16. Eq. 12a: $PCa + PHCO_3 = PK_{ca}' - PK_2' + PH$, and Eq. 15

a. $Ph = PK_2' - PK_{ca}' + PCa + P\left[(Alk) + (H^+) - \frac{K_w'}{(H^+)}\right] - P\left[1 + \frac{2K_2'}{(H^+)}\right]$

Complete range of Ph

b. $Ph = PK_2' - PK_{ca}' + PCa + P(Alk) - P\left[1 + \frac{2K_2'}{(H^+)}\right]$

Ph range 4.5 to 10.3 (Ref. 5)

c. $Ph = PK_2' - PK_{ca}' + PCa + P(Alk.)$

Ph range 6.5 to 9.5 (Ref. 5)

17. Eq. 16a and 12; $(H^+) = X$

$$X^2 + \frac{2K_2'(CO_3^=) - K_2'(Alk.)}{(CO_3^=) - K_2'} X + \frac{K_2' K_w'}{(CO_3^=) - K_2'} = 0$$

Empirical Equations for Various Constants

18. $PK'_{ca} = PK_{ca} - 4\sqrt{\mu}$; $\mu \overset{=}{<} 0.02$

a. $PK_{ca} = 8.32$

19. $PK'_w = 14.17 - 0.1517\sqrt[3]{\mu} + 0.0083\mu$, 20°C

a. $PK'_w = PK'_w(20^\circ) - 0.035T$

20. $PK'_1 = 6.47 - 0.188\sqrt[3]{\mu}$, 20°C

a. $PK'_1 = PK'_1(20^\circ) - 0.006T$

21. $PK'_2 = 10.288 - 0.443\sqrt[3]{\mu} - 0.0046\mu$, 20°C

a $PK'_2 = PK'_2(20^\circ) - 0.011T$

22 $\mu = 0.00147 + 0.03592\,Cl + 0.000068\,Cl^2$,

For Sea Water, Cl in ‰ = 19, $\mu = 0.7$

Determination of K, Eq. 9, 10, + 12

23. $K = (H_2CO_3) = \frac{(HCO_3^-)(H^+)}{K'_1} = \frac{(H^+)^2(CO_3^=)}{K'_1K'_2} = \frac{(H^+)^2K'_{ca}}{(Ca^{++})K'_1K'_2}$

a. $(CO_3^=) = \frac{K'_{ca}}{(Ca^{++})}$

TABLE I

Values of Various Constants with Assumed Values of Calcium Ion Concentration

1.	2.	3.	4.	5.	6.	6a.	7.
(Ca^{++})	μ	PK'w	PK'_1	PK'_2	PK'ca		PK'_2 - PK'ca
0.	0.	13.985	6.43	10.26	8.32		1.94
0.000125	0.0005	13.98	6.42	10.26	8.23		2.03
0.00025	0.001	13.97	6.41	10.26	8.19		2.07
0.0005	0.002	13.97	6.41	10.25	8.14		2.11
0.00075	0.003	13.96	6.40	10.25	8.10		2.15
0.001	0.004	13.96	6.40	10.24	8.07		2.17
0.00125	0.005	13.96	6.40	10.24	8.04		2.20
0.0025	0.01	13.95	6.39	10.22	7.92		2.30
0.0037	0.015	13.94	6.38	10.20	7.83		2.37
0.005	0.02	13.94	6.38	10.18	7.76		2.42
0.01	0.04	13.93	6.37	10.082	7.52	7.55	2.53
0.025	0.1	13.91	6.34	10.027	7.04	7.10	2.93
0.1	0.4	13.88	6.30	9.906	5.80	6.1	3.8
0.175	0.7	13.86	6.27	9.837	5.06	5.57	4.26
0.25	1.0	13.84	6.24	9.786	4.32	5.1	4.68
0.5	2.0	13.81	6.19	9.670	2.68	3.8	5.87
1.0	4.0	13.78	6.13	9.522	0.32	?	?

a. $\mu = 4 \times (Ca^{++})$. (See definition of ionic strength.)

b. PK'w, equation 19 and 19a, corrected to 25°C.

c. PK'_1, equation 20 and 20a, corrected to 25°C.

d. PK'_2, equation 21 and 21a, corrected to 25°C, $\mu = 7.02$

e. Boxed values from reference 5.

f. PK'ca, Col. 6, equation 18.

g. PK'ca, Col. 6a, Graph, page 91

TABLE II

Determination of Ph for Various Calcium Ion Concentrations

Equation 16c: $Ph = PK'_2 - PK'ca \quad 2PCa$; $(Ca^{++}) = (Alk)$

1. (Ca^{++})	2. $PK'_2 - PK'ca$	3. 2PCa	4. Ph	5. Ph'	
0.000125	2.03	7.8	9.83	imaginery	
0.00025	2.07	7.2	9.27	9.44	10.19
0.0005	2.11	6.6	8.71	8.73	10.88
0.00075	2.15	6.25	8.40		
0.001	2.17	6.0	8.17		
0.00125	2.26	5.8	8.00		
0.0025	2.30	5.2	7.50		
0.0037	2.37	4.86	7.23		
0.005	2.42	4.6	7.02		
0.01	2.53	4.0	6.53		
0.025	2.93	3.2	6.13		
0.1	3.8	2.0	5.8		
0.175	4.26	1.52	5.78		
0.25	4.68	1.2	5.88		
0.5	5.87	.6	6.47		
1.0	-	0	-		

Col. 4, Equation 16, Col. 5, Equation 17.

* * * * * * * * *

TABLE III

Determination of Partial Pressure of Carbon Dioxide for Various Calcium Ion Concentrations, and Recap of Principle Values

PCa	3	2.6	2.3	2	1.6	1	.76	.6	.3
μ	0.004	0.01	0.02	0.04	0.1	0.4	0.7	1.	2.
Ph	8.17	7.5	7.02	6.53	6.13	5.8	5.78	5.8	6.47
PK	5.25	3.71	2.42	2.16	1.4	0.5	0.27	0.24	0.48
$PpCO_2$	4.75	3.71	2.94	1.70	0.92	0.0	-0.22	-0.26	0.0
P.P.M. $CaCO_3$	100	200	500	1000	2500	10,000	17,000	25,000	50,000

Solution of Typical Equations

Equation 17.

a. $(Ca^{++}) = 10^{-3.6}$, $K'_{Ca} = 10^{-8.19}$, $K'_2 = 10^{-10.26}$, $K'_w = 10^{-13.97}$, $(CO_3^{=}) = 10^{-14.59}$

$$X^2 + \frac{10^{.3-4.59-10.26} - 10^{-10.26-3.6}}{10^{-4.59} \cancel{- 10^{-10.26}}} X + \frac{10^{-10.26-13.97}}{10^{-4.59} \cancel{- 10^{-10.26}}} = 0$$

$$X^2 + \frac{10^{-14.55} - 10^{-13.86}}{10^{-4.59}} + \frac{10^{-24.23}}{10^{-4.59}} = 0$$

$$10^{-14.55} - 10^{-13.86} = -10^{-13.96}$$

$$X^2 - 10^{-9.37} X + 10^{-19.64} = 0$$

$$X = \frac{10^{-9.37} \pm \sqrt{10^{-18.74} - 10^{.6-19.64}}}{2}$$

$$= \frac{10^{-9.37} \pm 10^{-9.52}}{2} = \underline{10^{-9.44}}, \underline{10^{-10.19}}$$

b. $(Ca^{++}) = 10^{-3.9}$, $K'_{Ca} = 10^{-8.32}$, $K'_2 = 10^{-10.26}$, $K'_w = 10^{-13.98}$, $(CO_3^{=}) = 10^{-4.42}$

$$X^2 + \frac{10^{.3-10.26-4.42} - 10^{-10.26-3.9}}{10^{-4.42} \cancel{- 10^{-10.26}}} X + \frac{10^{-10.26-13.98}}{10^{-4.42} \cancel{- 10^{-10.26}}} = 0$$

$$X^2 - 10^{-10.04} X + 10^{-19.82} = 0$$

$$X = \frac{10^{-10.04} \pm \sqrt{10^{-20.08} - 10^{-19.22}}}{2} = \underline{a \pm bi}$$

Amount of $CaCO_3$ Finally Precipitated by Distributing:

a. 20% Solution of $Ca(OH)_2$ at rate of 4 gal/yd^2, or .455 gal/ft^2

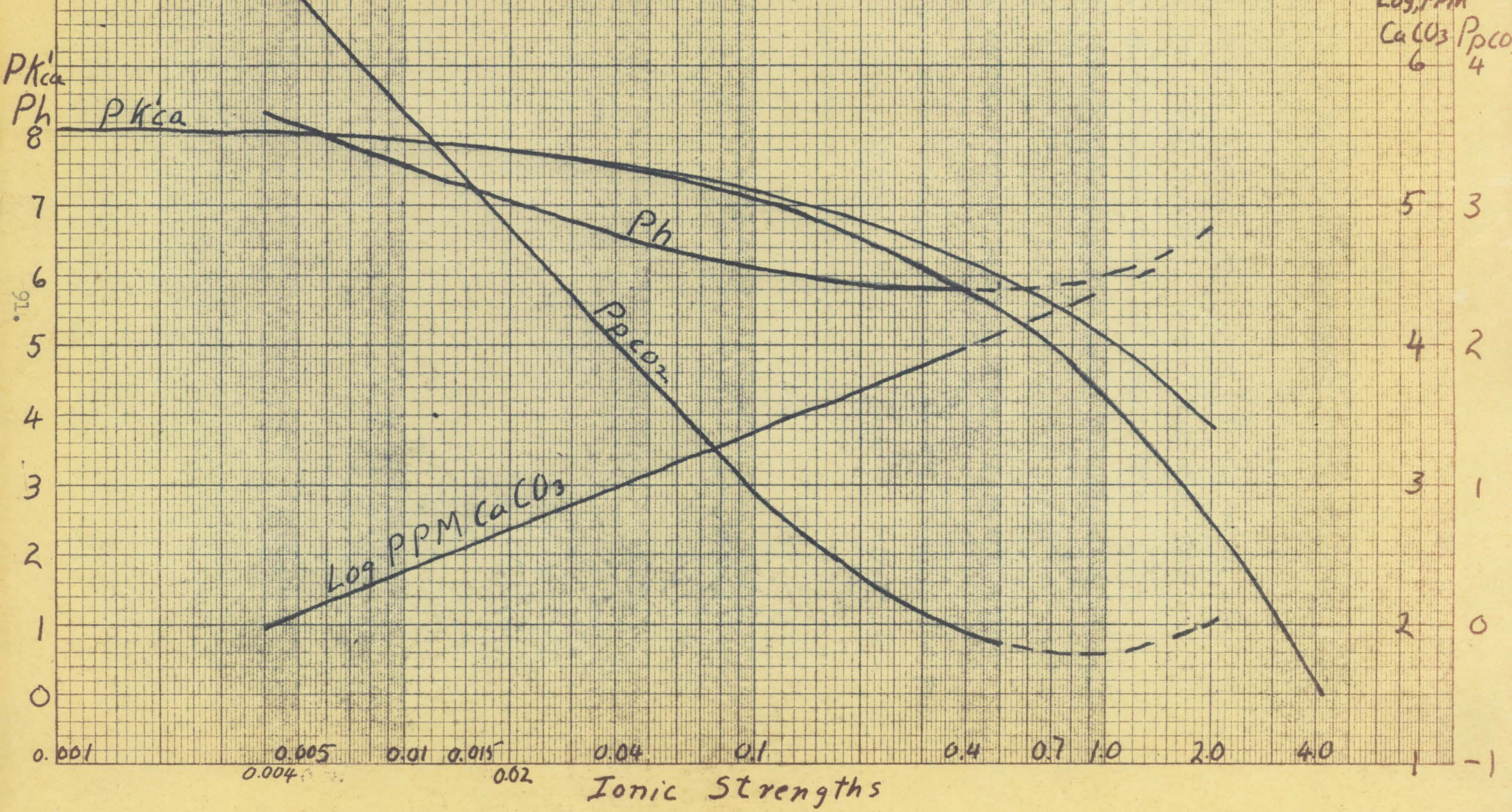
Eq. 3a + 8a, 0.74# $Ca(OH)_2$ will precipitate 2# $CaCO_3$
assuming density of solution =64#/ft^3, or 8.55 #/gal

$$X = .445 \times 8.55 \times 0.2 \times \frac{2}{.74} = \underline{2.06\ \#/ft^2}$$

b. Similarly 5000 PPM $CaCO_3$, as $Ca(HCO_3)_2$, at 4 gal/yd^2

$$X = .445 \times 8.55 \times 0.005 \times \frac{2}{1.26} = \underline{0.03\ \#/ft^2}$$

PK'ca, Ph, Ppco₂, Log PPM CaCO₃ plotted against μ



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Note: These references adequately cover the material discussed, and contain all formula used. They have been culled from a larger group of references examined.