Richardson C (1897) Lime, Hydraulic Cement, Mortar and Concrete. Part I. The Brickbuilder Vol 6 April. Rogers and Manson Boston.

The Foundation of Cements.

The foundation of all cements, except those of a bituminous nature, which are used for binding together materials in masonry and concrete, is lime, the oxide of the metal calcium, which, although never found in the free state, is, in its various combinations, so widely diffused in nature.

Occurrence.
It occurs as carbonate in marble, in limestone, in chalk, in marl, and in shells, as sulphate in gypsum, as silicate in many minerals and rocks, and as phosphate in a few.

Forms of Importance.
Carbonate of lime in its purer forms and, when mixed with clay, in argillaceous or hydraulic limestones and some concretions, is of the greatest importance to the engineer and builder. From those forms in which there is but a small admixture of other substances lime is made. From those which contain clay or from a mixture of the pure carbonate with clay, hydraulic lime and cement are made.

CAUSTIC OR QUICK LIME.

The product of the expulsion of carbonic acid from the purer forms of carbonate of lime at a red heat is caustic or quick lime. It is the more or less pure oxide of the metal calcium, of which it contains about 95 per cent, when of the best quality. The process of making lime in this way is called lime burning. It is conducted in kilns of various forms in which a suitable temperature can be maintained.

Lime Kilns.
The kilns in use in lime burning are of both the intermittent and continuous types, and these again may each be divided into two classes, one in which the fuel is mixed with the limestone, the other where the combustion is carried on in a separate chamber or furnace, apart from the stone.
Whatever the method of burning, the product is much the same, the advantage of one form over another being purely one of economy of fuel and completeness and regularity of burning. In the United States almost all the lime burning is done in kilns of the continuous type, with the fuel, either coal or wood, mixed with the stone. Wood is supposed to produce a better lime, as the ash is smaller in amount and not so siliceous. Where fuel oil, or gas is available, one of these sources of heat is the most satisfactory for lime burning.

Lime Burning.
Lime burning consists of raising limestone to that temperature at which it will lose its carbonic acid. It is usually carried on at a bright-red heat or about 1,700 degs. Fahr., although carbonate of lime begins to decompose at a lower temperature. **Too high a temperature is undesirable**, as this may produce a chemical combination between the lime and the impurities which all lime-stones contain to a greater or less degree. **If these impurities are siliceous, silicates of lime are formed which fuse and prevent the lime from slaking properly**. The formation of such silicates **may also take place with the ash of coal. This is known as clinker and is carefully thrown out in drawing the lime from the kiln.** Smaller particles, however, cannot be separated and injure the quality of the lime.

It is necessary that a current of air should pass through the kiln, when lime is burned, to carry off the carbonic acid, as carbonate of lime, when heated in a vessel from which the gas cannot escape, is not decomposed and no lime is formed. A current of steam is even more desirable than air, but this is never used in practice, as it is hardly economical. **The limestone is, however, often sprinkled with water which has, to a small degree, the same effect.**

SOURCES OF LIME.

Limestone and marble are the usual sources of lime, but it can also be made from chalk, some marls, and oyster shells. Chalk is not found in this country, marl is used only for Portland cement, and oyster-shell lime principally for fertilizers and purifying gas. **Stone lime is preferable for building purposes to any of the other forms.**

CHANGES IN LIMESTONE IN BURNING.

The changes which a limestone undergoes in burning are loss of weight by the removal of carbonic acid, water, and organic matter if present; change of volume, of density, of color, and of hardness.
Massive limestones, or marbles such as are used in making lime, have a specific gravity and density of from 2.65 to 2.75. Lime in the form of the stone from which it is made, that is, in lumps, is porous owing to the loss of carbonic acid and water. It has, therefore, a density of only 1.5 to 1.85, although the specific gravity of the lime is usually about 2.8 to 3.1, and that of the pure oxide 3.16. The color of many limestones is due to organic matter which burns away and leaves the caustic lime white. If it does not burn away it is due to mineral impurities which are undesirable.

The hardness of lime is of course inferior to that of the stone from which it is made owing to the porous condition in which it is left, and there is a slight increase in volume due to the expansion of the gas in the stone.
From pure carbonate of lime exactly 56 per cent, of oxide or caustic lime should be obtained, but owing to the loss of water and organic matter, as well

as carbonic acid and to waste, this figure is never reached except when there are admixtures of clay or silica. Then the loss of carbonic acid is not as great as from pure carbonate of lime. When the limestone contains much carbonate of magnesia the product of burnt lime may be considerably reduced, as this carbonate contains more carbonic acid than carbonate of lime. **Such a limestone is known as dolomite and is of inferior value for making lime.**

Effect of Impurities.

We find limestones which are nearly pure, having 97.2 per cent, of carbonate of lime, in the form of white marble, and 96.0 per cent, in a blue limestone. In contrast are stones which contain silica or clay as well as silica, as shown by the presence of iron and aluminum, and those which are mixed with carbonate of magnesia. All the forms have their peculiar properties. **The purest should be, of course, selected for lime burning**. **The impurities in a limestone have an important influence on the character of the caustic lime made from it.**
A quicklime prepared from a limestone comparatively free from impurities and consequently nearly pure calcium oxide is called a rich or fat lime. With the increase of admixture of other substances the lime becomes poor, that is to say, it does not slake easily, and **when this exceeds 10 per cent, the burnt stone begins to slake with more difficulty or fails to do so at all, and can be no longer regarded as a mere lime, but is hydraulic or magnesian lime depending upon whether the admixture is clay or carbonate of magnesia.** Already with from 5 to 8 per cent, of clay in the limestone, the lime has **hydraulic properties**, and these increase until it is very highly hydraulic with 25 per cent.

When the admixture is magnesian and the rock is composed of carbonate of lime and magnesia, without clay, the **resulting lime does not attain hydraulic properties, but merely becomes poor and fails to slake readily.** With even 10 per cent, of magnesia, lime becomes poor, and with a larger amount still more unsatisfactory. Lime from dolomite, or magnesian limestone, which is very common in the United States, contains about 21 per cent, of magnesia, **and is of inferior value for building purposes. Too much of this lime is used in the country, and it should be avoided as far as possible under all circumstances.**
Lime containing a large amount of magnesia, if free from impurities may be used, however, for furnace linings as it resists heat well and is very basic, not fusing as readily as pure lime in presence of silica.

COMPOSITION OF CAUSTIC LIME.
The composition of commercial quicklime is varied, depending on the kind of rock from which it is made. The following are analyses of some typical limes, found in our markets: —

1)New York, from limestone: Lime 95.6%; Magnesia 0.6%; iron and alumina 0.8%; silica and silicates 1.2%
2) Baltimore County, from marble: Lime 95.3%; Magnesia 0.8%; iron and alumina 0.9%; silica and silicates 2.2%

3) Washington DC, from dolomite: Lime 73.3% Magnesia 21.4%; iron and alumina 4%; silica and silicates 0.9%
4) Connecticut, from limestone: Lime 85.1%; Magnesia, iron and alumina 5.8% silica and silicates 2.8%
5) Connecticut, from dolomite: Lime 55.3%; Magnesia 36.4% iron and alumina 3.2%; silica and silicates 1.4%
6) West Virginia, from limestone: Lime 89.9%; Magnesia 2.2%; iron, alumina, silicates 5.8%
7) West Virginia, from limestone: Lime 74.2%; Magnesia 2.4%; iron and alumina 1.5%; silicates 3.9%

It appears that limes which are 95 to 96 per cent, pure are the best that are attainable commercially and that they are frequently less pure. When fresh from the kiln lime would, of course, show no loss on ignition, but on storage it absorbs water with great avidity from the air until, as in that numbered seven, it has reached 17 per cent., when it is nearly half air slaked. **Fresh lime, or that which has been carefully protected from the air, is of much greater value for building purposes, although too often this is unattainable.**

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CHARACTERISTICS OF GOOD LIME.

PURE calcium oxide consists of 71.4per cent of calcium and 28.6 per cent of oxygen. Its ordinary form is that of a more or less porous earthy white solid which, in a pure condition, is very resistant to heat. It has, as has been shown, a great affinity for moisture and must be preserved out of contact with air from which it absorbs water and carbonic acid.
Caustic lime, for building purposes, should have the following properties — :
Except when made from coarsely crystalline marble, or from marl or shells, it should be in hard lumps.
It should be white, or nearly so, in color. Lime of a yellow or brownish color, with veins of silicious matter, is inferior.
It should be free from semi-fused or fused stone, showing over-burning, and from unburnt ash of fuel or clinker.
It should contain less than 10 per cent, of impurities, but often has more.
It should slake rapidly, showing that it is rich and fresh.
Good lime in lumps should weigh, as packed, with about 40 per cent of voids, 60 lbs. to the cubic foot, 75 lbs. to the bushel, and from 220 to 230 lbs. to the barrel of 3 bushels. If ground or in powder it will weigh less when packed loosely, but when well shaken down it will weigh as much as 270 lbs. to the barrel. A lump of hard lime, I ft. cube, would weigh about 95 lbs., having a density of 1.52.

THE SLAKING OF LIME.

Caustic lime combines with water with the evolution of heat to form calcium hydrate. **Every 100 parts of caustic lime require 32 parts of water for its conversion into hydrate. If one third of its weight of water is sprinkled on quicklime it becomes very much heated, cracks open, if of the massive variety, swells up and falls to powder.**
The heat developed is sufficient, at times, to ignite wood. The quicklime becomes slaked lime. **This consists of 75.7 per cent, of calcium oxide and 24 3 per cent of water.** It has a specific gravity, when pure, of 2.07. **The increase of volume in the process of slaking is due to the formation of steam, which tears the particles of lime apart and expands the mass.** If a current of dry steam is passed over heated caustic lime confined in a tube it becomes slaked without any increase of volume.
The smaller the amount of impurities the more energetic is the act of slaking and the greater the increase of volume. In rich and pure limes the increase of volume under ordinary conditions will be **over twice** that of the unslaked material, including the voids, while with very poor limes it may be much less. **The statement frequently made that lime increases three volumes in slaking** *(Vicat, amongst others)* **is based upon the increase in volume due to the excess of water often used in slaking.** In this case it may be as great as 3.4. **The amount of increase of volume for the same lime may be very variable, depending on the conditions under which it is slaked.** We have seen that it is a reaction between water and caustic lime where much heat is generated, and that to the steam evolved is largely due the expansion of the lime. **It is evident, therefore, that the provisions for augmenting and retaining this heat are of importance**. If water is added slowly but comparatively little heat is developed, while slaking in an open space will not give as much as when it occurs in a closed box. Cold water also will not accelerate the action as well as warm. **The amount of water used has a marked effect on the volume of slaked lime produced. With an equal volume of water the increase for a good, rich lime is from 2 to 2.4.** An increase or reduction in the amount of water or in the volume weight of the lime may increase or diminish this.
The following experiment shows the effect of different amounts of water on an ordinary lime

Volume of water	Increase in volume
½	1.6
1	2.0
2.5	2.5

With poor dolomitic lime the volume increase was only 2 to 1.7

It appears, therefore, **that the increase of volume to be expected of any lime is dependent on conditions which may be very variable.** For example, a peck of lump lime with 44 per cent, of voids between the lumps gave, on slaking with its own volume of water, 2 pecks of fine powder of slaked lime, which is a fair

increase in volume for lump lime. From I peck of closely packed lime, however, 2.5 volumes of slaked lime were obtained. The difference in volume is of course due to the difference in weight of the lime as packed in the two ways.
The proper comparison, therefore, is one of volume from weight 10 lbs. of caustic lime, for instance, should give 6.8 bushels of slaked lime, an increase of volume of 2.25. Gilmore found in some of his experiments increases as great as 2.46, 2.83, 3.21, 2.40, and 2.14, but the weight of lime in his unit volumes was much greater than occurs in practice, and large amounts of water were used in slaking **so that he was dealing with paste instead of dry slaked lime.** …

General Totten found in experiments on slaking limes no increase in volume greater than 2.27 when no more than an equal volume of water was used. The increase of volume is commonly used as a test of the quality of lime.
Air Slaking.
Slaked lime is also produced by exposure of caustic lime to the air, from which it absorbs sufficient water to become hydrated, as well as some carbonic acid. This is known as air-slaked lime. **It is of little value for mortar making, because there has not been enough heat produced in its formation to tear apart and expand the particles which will alone enable it to form a rich paste.** The larger particles have also to a certain extent become hardened on their surfaces by a kind of setting, and by the absorption of carbonic acid from the air.

Practice in Lime Slaking.

In practice, the slaking of lime for mortar is conducted in several ways. **Either sufficient water is sprinkled over the lime to combine with it and resolve it to a powder, providing also an excess for that lost in the form of steam, or an excess is added at once, sufficient to make the finished mortar.**

The first method is in some ways the best, because a finer, looser powder is produced, in the manner already described, and **because the poorer limes are much more easily and thoroughly slaked in this way with the aid of the greater heat evolved. When too large an amount of water is used the development of heat is prevented, and the operation is much less complete.** The particles of lime which are left unslaked go into the mortar in that condition and, being subsequently slowly hydrated by the moisture of the air, expand with injurious effect after it has been used. The popping of mortar, frequently noticed in the walls and ceilings of dwellings, is due to this cause. **For the same reason, given above, all the water which is to be used should be added at once or nearly so. If it is added in small portions the effect is to cool down the whole mass and prevent thorough slaking.**

We have seen that a third of its weight of water is theoretically necessary for slaking lime. **In practice, however, to allow for vaporization as steam, and for the slight excess necessary to bring all the particles in contact with moisture, this amount must be increased to at least an equal weight**. It is difficult to say what volume of water should be used, as this depends on the volume weight of the lime, which is variable. It is ordinarily about that of the lime itself plus its voids. **Practically it is convenient with fat lime to use two and a half volumes of water, which will suffice for slaking and for the production of a paste. Poor magnesian limes require less.**

As heat assists in the expansion of the lime, the operation is best carried on in a covered box. One half of the water is added at first, and as soon as the lime begins to fall to pieces the rest is poured in and thoroughly mixed with the slaking material. The entire mass will thus be raised to a high temperature. The operation thus carried on takes place rapidly, but it can hardly be considered completed until the mass has become cool, or until even after a longer time. In cold weather it is advantageous to use warm water, especially with poor limes.

Water for Slaking and Mixing.
Water used for slaking lime and making mortar should be pure. When it contains salts, such as chlorides and sulphates, the mortar effloresces and gives rise to stains. **For this reason sea water is unsuitable, although it has been used successfully with hydraulic cement.**

LIME PASTE OR CREAM.
The lime paste made in the manner previously described may be too stiff for mortar if a very rich lime has been used, or if a very large volume of sand is to be employed in making the mortar. There is no difficulty in thinning it, however, to the proper consistency, depending on the character of the mortar to be made. **If, however, more than two and a half volumes of water are added to the lime at first the resulting paste will have a tendency to be granular and to contain lumps which, in the thin cream, it is impossible to break up.** In careless practice as much as three or four volumes of water are sometimes used in slaking lime, when it is intended to make a mortar with a large volume of sand. **Stretching the cream in this manner to make a small amount of lime fill a large volume of sand voids makes the resulting mortar very porous when dry.**

Good paste of lime should not contain at the extreme more than three volumes of water as compared to the measured volume of the quicklime.
As there are generally some hard and unslaked particles even in the best limes, **the cream should be run through a sieve if possible, after standing over night, before mixing it with the sand.** It should be remembered that the longer the paste stands before use the smoother it becomes. As will be seen later, this improvement goes on after the mortar has been mixed.

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LIME MORTAR.

Mortar is a mixture of some cementing material with sand.
Lime mortar is composed of lime paste and sand, with the addition, for certain parts of plastering, of hair and similar bonding material.

Necessity of Sand in Mortar. —

Good cream of lime might be used alone as cement, as it hardens on exposure to the air by drying, were it not that, under these conditions, it shrinks and cracks very badly. It is, therefore, customary, both on this account and for economy, to temper it with sand. This should be clean, sharp, and rather coarse for masonry, finer for plastering. When discussing hydraulic mortars and concretes there will be occasion for a further consideration of sand and its qualities and proper use.

Proportion of Sand to Lime.

A mortar made of lime paste should, theoretically, contain so much sand that the cream of lime **will more than fill the voids**, that is to say, the volume of the mortar should be greater than that of the sand. **In fact it is necessary that it should considerably more than fill them in order to thoroughly coat each particle and provide for shrinkage. If too much sand is present there is not sufficient cementing material to make a firm bond, while on the other hand, if there is too little the mortar will tend to shrink and crack on drying. If too little lime is used the deficiency must be made up with water, that is to say, the paste is made very thin.**

In ordinary sands the voids are from 30 to 40 per cent, of the volume of the sand. With sand, having 40 per cent, such as that which is used for the best lime mortar, 1 volume of paste would fill the voids in 2.5 volumes of sand with no excess. **As a matter of fact, practice leads to the addition of only from 1.25 to 2 volumes of sand to 1 of paste which, when the caustic lime yields 2.5 volumes of paste, means 3 to 5 volumes of sand to 1 measured volume of caustic *(quick)* lime.** In this way a plastic mortar and one that will not crack in drying is made. **With fat lime and sharp sand 3 volumes of sand to 1 of lime forms a rich mortar and these proportions are often required in the best specifications. The greater part of the mortar used in ordinary brickwork is, however, made with 5 volumes of sand, or more, and is probably satisfactory.**

The experiments *tables omitted here)*, it will be noticed, were carried out with a pure and fat lime. The sand in use was not very coarse, and had 40 per cent, of voids. From the results the following conclusions may be drawn: —

Slaking. — Slaking with a volume of water equal to the measured volume of the lime, with 44 per cent, of voids, or with a weight of water equal to the weight of the lime, gives a volume of paste, after the addition of another volume of water, equal to that of the water used, only. **This paste is very thick.**
Slaking with two volumes of water, with the addition of half a volume, after slaking is finished, making 2.5 volumes of water in the paste, gives 2.56 volumes of paste which is thick and rich.

Slaking with 2.5 volumes of water added all at once gives 2.71 volumes of thick paste suitable for good mortar.
Slaking with 3 volumes of water added at once gives 3.12 volumes of thin paste.
Slaking with 4 volumes in the same way yields 4.12 volumes which is too thin to be of value.
It appears, then, that slaking with 2.5 volumes of water added at once is the most advantageous method of procedure, and that but a small departure from these proportions on either side will result in forming a less satisfactory paste.

Density.
The density of the paste naturally decreases with the increase of water it contains.

Volume of Sand for Mortar. —

If but twice the volume of the lime is added to the paste in the form of sand, the resulting mortar is too rich. It contracts and cracks on drying. Three volumes of sand make a very rich and satisfactory mortar such as should be used for laying up fronts and pointing.

Five volumes form a mortar good enough for ordinary brick masonry where not exposed to moisture, while greater amounts of sand furnish mortars which are very porous, but serve for cheap work in absolutely dry situations.

Density of the Mortars. —-The density of these mortars is, of course, proportionate to the amount of sand they contain. Their porosity is larger the more water the paste contains.

Volume of Mortars. — With a small amount of sand the volume of the mortar is, where twice the volume of the lime is sand, 66 per cent more than the volume of the sand; **where the volume of the sand is three times the lime, 46 per cent, more;** where 5 volumes, 1 7 per cent.; with 7 volumes the mortar is less in volume than that of the damp sand owing to its closer compaction.
The amount of water in the paste plays a prominent part in the relation of the volume of mortar to the volume of sand and to the amount of sand which can be added to any paste.

Composition of Wet Mortars. —

Calculation shows that these varied mortars contain from 30 to 15 per cent, by weight of water or from 1.7 to 3.9 per cent, of lime, but the relation of water to lime increases with diminution of the amount of lime, that is to say, with the increase of sand, from 1.7 in the richest mortar to 3.9 times as much water as lime in the poorest mortar with the thinnest cream. These figures show why the richest mortar contracts the most on drying from loss of the largest amount of water, and that the poorest mortars, although not having as large a per cent by weight of water still have not enough lime to form proper cement.

Composition of Dry Mortar.—
The dry mortars contain from 22.6 to 45% of lime, but as the two extremes of combination would never be used in practice, it appears that mortars as ordinarily mixed may contain from **15 to 8 per cent, of lime**. This corresponds to the results obtained by analysis of many mortars actually employed in masonry.

Strength of Dry Mortar. —
The set of mortars acquired **by simply drying out** gives them a tensile strength of from thirty to forty pounds per section of 1 sq. in. *(.20 to .28 mpa)* and a crushing strength of about 85 to 95 in 2 in. sq. section *(.59 to .66 Mpa)*. There is not such a difference between the different kinds of mortars at this stage, but with age there would be but little increase in strength with the poorer ones. The physical properties of the latter are also against them as they cannot resist moisture.

Professor Smith's tests, given in the January number of The Brickuuilder, show also that **with a diminution in the cross section of the mortar there is an increase in the strength per square inch of section**. This is due to the liability of shrinkage cracks in tests pieces made with larger cross sections.

General Conclusions. —
It appears that fat limes should be slaked with 2.5 volumes of water, added at once in a closed box, to obtain the best and largest amount of good paste; **that with this, three times the volume of the lime in the shape of moist sand may be mixed for fine work, such as pointing, plastering, and in places exposed to dampness, and that 5 volumes of sand is not too much for ordinary brickwork.**

The amount of mortar which a barrel of lime, of average weight, under the same conditions as in the experiments, would yield is,

Parts sand	parts water	cubic feet
3	2.5	16.5
4	2.5	20.6
5	2.5	24.8

or, 4 cu. ft. of lime with 2.5 parts water, and 4 volumes of sand would yield 22 cu. ft. of mortar, which, according to authorities, is sufificient to lay one thousand brick in ordinary brickwork with coarsely drawn joints. With more compact work one barrel of lime will lay one thousand bricks. A barrel of poor or magnesian lime will not yield more than three quarters of these quantities.

Amendments to lime mortar.

Lime mortar, made of ordinary rich lime, is not suited for masonry where it is exposed to water, dampness, or to the absorption of water by capillarity from

the soil. The hardest lime mortar will absorb 15 to 21 percent of its volume of water. **If hydraulic cement cannot be substituted for it, on the score of economy, a certain degree of improvement may be made in the mortar by mixing it with finely ground brick-dust or burnt clay, which yield the necessary silica to make it somewhat hydraulic and less porous; or a certain portion of the lime, one third, for instance, may be replaced by hydraulic cement. This is seldom done, as it is cheaper in the end to use cement alone.**

Effect of Frost on Lime Mortar. —
The most thorough experiments of Tetmaier show that **lime mortar cannot be used at temperatures below freezing, especially with porous materials, and attain any bond.** No additions, such as salt, soda, glycerine, or sugar will prevent lime mortar, when frozen for any length of time, from becoming a friable material.

Mortar can be mixed by hand or machinery. **The latter is of course preferable.** When done by hand, **as is the common custom**, the operation should be carried on in a closed box, or on a surface through which water cannot escape, and with suitable walls of sand. Machine mixing is much more thorough than that done by hand, and is coming into vogue rapidly in our larger cities where there is such a use of mortar as to make it an economy to prepare it on a large scale. Such mortar is more regular in composition than hand made. All the material can be accurately gauged and weighed, which is most desirable.

SETTING OF LIME MORTAR.

The setting of lime mortar is the result of three distinct processes which, however, may all go on more or less simultaneously. **First, it dries out and becomes firm. Second, during this operation, the calcic hydrate, which is in solution in the water of which the mortar is made, crystallizes and binds the mass together.** Hydrate of lime is soluble in 831 parts of water at 78 degs. F ; in 759 parts at 32 degs., and in 1136 parts at 140 degs. **Third, as the per cent, of water in the mortar is reduced and reaches 5 per cent., carbonic acid begins to be absorbed from the atmosphere. If the mortar contains more than 5 per cent, this absorption does not go on. While the mortar contains as much as 0.7 per cent, the absorption continues. The resulting carbonate probably unites with the hydrate of lime to form a subcarbonate, which causes the mortar to attain a harder set, and this may finally be converted to carbonate. The mere drying out of mortar, our tests have shown, is sufficient to enable it to resist the pressure of masonry, while the further setting furnishes the necessary bond.**

There is also supposed to be a formation of lime silicate in the course of setting. The evidence in favor of this has been obtained by German investigators from the analyses of very old mortars.

It **appears more plausible** that the soluble silica found in these mortars was derived from silica contained in the limestone from which the lime was derived, and which was rendered soluble in the process of burning by combining with lime, than that it was due to any combination of the lime of the mortar with the silica of the hard quartz grains of sand, which seems highly improbable. In these old mortars the amount of carbonic acid is high, and in several cases it is sufficient in amount to have converted the lime and magnesia completely to carbonate, although the percentage of these bases is in most cases much greater than good practice demands.