

Chapter 2

Theoretical Part

2.1 Properties of Bone.

2.1.1 Bone structure:

In biological terms bone is described as a connective tissue. A tissue is an aggregation of similar specialized cell united in the performance of a particular function. Connective tissue is the tissue which binds together and is the support of the various structures of the body. In mechanical terms, bone is a composite material with several distinct solid and fluid phases. Bone is unique among the connective tissue, it is hard because of the extracellular collagenous matrix. The major organic component of all connective tissue is impregnated with a mineral phase principally hydroxyapatite ($\text{Ca}_{10}(\text{PO}_4)_6(\text{OH})_2$) or very similar crystals.

At the macroscopic level, there are two major forms of bone tissue: compact or cortical bone and cancellous or trabecular bone. The location of these bone types in a

femur is illustrated in Fig.1. Cortical or compact bone is a dense material with a specific gravity of about 2. The external surface bone is generally smooth and is called the periosteal surface. The interior surface is called the endosteal surface. It has a roughened texture which resembles cancellous bone. Cancellous bone also exists in the epiphysial and metaphyseal region of long bones and within the confines of the cortical bone coverings in the smaller flat and short bones. Cancellous bone is also called trabecular bone because it is composed of short struts of bone material called trabeculae. The connected trabecular give cancellous bone a spongy appearance, and it is often called spongy bone. There are no blood vessels within the trabeculae but there are vessels immediately adjacent to the tissue, and they weave in and out of the large spaces between the individual trabeculae. Cancellous bone has a vast surface area as would be suggested by its spongy appearance.

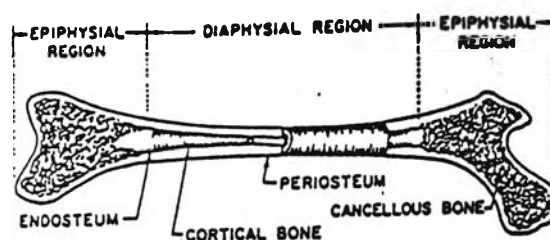


Fig.1 Longitudinal section of the femur, illustration
cancellous and cortical bone

2.1.2 Bone composition

The composition of tissue is, very roughly, equal thirds by volume of minerals, water and the extracellular collagenous matrix. In order to be more precise about bone composition, one must specify species, age, sex, the specific bone in question, the type of bone tissue (cancellous or cortical) and whether or not a bone disease occurred. Table 1 presents data on the specific gravity, water fraction, and organic fraction of cortical bone for 16 different vertebrates including human.

Results of hydrated bone assay for both cortical and trabecular bone for four species are reported , in Table 2. Comparision of the data given in Table 2 for trabecular bone with that given for cortical bone shows that the water fraction is greater and the ash fraction is less for trabecular bone . The organic fraction for the two bone types is fairly close.

Table 1 Results of hydrated bone assays for 16 species using cortical bone from the tibia and femur. (Skalak, 1987)

Species	Specific gravity	Water content. vol.%	Mineral ash. vol.%	Organic+CO ₂ vol.%
Fish	1.80	39.6	29.5	36.9
Turtle	1.81	37.0	29.2	40.1
Frog	1.93	35.2	34.5	38.5
Polar bear	1.92	33.0	36.2	40.1
Human	1.94	15.5	39.9	41.8
Elephant	2.00	20.0	41.4	41.5
Monkey	2.09	23.0	42.6	41.1
Cat	2.05	23.6	42.2	40.5
Horse	2.02	25.0	41.0	40.5
Chicken	2.04	24.5	41.7	38.7
Dog	1.94	28.0	38.7	35.5
Goose	2.04	23.0	42.7	37.6
Cow	2.05	26.2	42.6	36.2
Guinea pig	2.10	25.0	43.5	37.0
Rabbit	2.12	24.5	45.0	37.2
Rat	2.14	20.2	49.9	38.3

Table 2 Results of hydrated bone assays of cortical and trabecular bone for four species using cortical bone from the tibia or trabecular from the vertebrae (Skalak and Chien, 1987)

Species	Specific gravity	Water fraction.vol%	Ash fraction.vol%	Organic fraction.vol%	Volatile inorganic fraction
Trabecular bone:					
Human	1.92	27	33.9	34.9	4.2
Monkey	1.89	27.1	32.9	36.1	4.0
Cow	1.93	28.1	33.5	34.2	4.2
Dog	1.91	28.8	32.6	34.5	4.2
Cortical bone:					
Human	1.99	23.9	37.7	33.8	4.6
Monkey	2.04	23.7	38.2	33.7	4.7
Cow	2.00	25.2	36.6	33.6	4.6
Dog	2.00	22.3	36.8	36.3	4.6

2.2 Chemistry of Phosphorous Compounds

There is a variety of calcium phosphates. Phosphorous pentoxide (P_2O_5) is the only oxide of phosphorous found in fertilisers. There are three phosphoric acids, from a combination of phosphorus pentoxide with one, two, or three molecules of water. These are known respectively, as:

- a) Metaphosphoric acid. $P_2O_5 \cdot H_2O$ or HPO_3
- b) Pyrophosphoric acid. $P_2O_5 \cdot 2H_2O$, or $H_4P_2O_7$
- c) Orthophosphoric acid. $P_2O_5 \cdot 3H_2O$, or H_3PO_4

Orthophosphoric acid is the most common species. Pyrophosphoric acid only occurs in substances which have been subjected to heat. In term of a qualitative detection, metaphosphoric acid gives a white precipitate, both with barium chloride and silver nitrate and it coagulates a solution of albumen. Pyrophosphoric acid gives no precipitate with barium chloride, but a white precipitate with silver nitrate, and it does not possess the power of coagulating albumen; orthophosphoric acid gives no precipitate with barium chloride, but a yellow precipitate with silver nitrate, and does not coagulate albumen. Researchers have investigated the composition of the aqueous solutions containing calcium hydroxide and phosphoric acid. A significant part of their

results will be found in Tables 3, 4 and 5 illustrated as the solubilities of the solid phases at temperature 25°C, 40°C and 50.7°C. A study of these results will prove peculiarly instructive .

Table 3 - 5 Condition of equilibrium of the calcium orthophosphates in aqueous solutions of phosphoric acid. (Parrish et al, 1939)

Table 3

25°C		
CaO (g. per 100 g. of saturated solution)	P_2O_5 (g. per 100 g. of saturated solution)	Solid Phase
3.088	36.11	$Ca(H_2PO_4)_2 \cdot H_2O$
4.908	28.34	"
5.808	24.20	$Ca(H_2PO_4)_2 \cdot H_2O; CaHPO_4$
5.523	22.29	$CaHPO_4$
4.990	17.55	"
2.638	9.100	"
1.878	6.049	"
0.826	2.387	"
0.165	0.417	$CaHPO_4; CaHPO_4 \cdot 2H_2O$
0.070	0.166	$CaHPO_4 \cdot 2H_2O$
0.060	0.140	"
0.050	0.118	"
0.040	0.093	"
0.030	0.070	More basic than $CaHPO_4 \cdot 2H_2O$
0.020	0.047	"
0.010	0.023	"

Table 4

40°C

CaO (g. per 100 g. of saturated solution)	P ₂ O ₅ (g. per 100 g. of saturated solution)	Solid Phase
1.768	42.42	Ca(H ₂ PO ₄) ₂ ·H ₂ O
3.584	36.79	"
5.755	27.25	Ca(H ₂ PO ₄) ₂ ·H ₂ O:CaHPO ₄
4.813	21.67	CaHPO ₄
3.810	16.35	"
2.536	9.905	"
1.847	6.979	"
1.267	4.397	"
0.576	1.819	"
0.156	0.426	"
0.0592	0.158	"
0.0508	0.128	Ca ₃ (PO ₄) ₂ ·H ₂ O
0.0098	0.0262	"

Table 5

50.7°C		
CaO (g. per 100 g. of saturated solution)	P_2O_5 (g. per 100 g. of saturated solution)	Solid Phase
0.336	62.01	$Ca(H_2PO_4)_2 : Ca(H_2PO_4)_2 \cdot H_2O$
0.635	58.08	$Ca(H_2PO_4)_2 \cdot H_2O$
1.428	50.25	"
2.974	41.92	"
4.880	33.18	"
5.725	29.61	$Ca(H_2PO_4)_2 \cdot H_2O : CaHPO_4$
3.507	15.48	$CaHPO_4$
2.328	9.468	"
1.563	6.157	"
0.692	2.281	"
0.0596	0.1527	$CaHPO_4 \cdot 2H_2O$
0.0514	0.1331	$Ca_3(PO_4)_2 \cdot H_2O$
0.0351	0.0942	"
0.0106	0.0309	"
0.0007	0.0007	"

2.3 Solubility Chemistry of Calcium Phosphates

Orthophosphate salts, which have PO_4^{3-} group, are distinguished from metaphosphates and pyrophosphates which have PO_3^- and $\text{P}_2\text{O}_7^{4-}$ groups, respectively. Since we will be concerned here with orthophosphate compounds only, the prefix ortho will be omitted. The principal calcium phosphate salts given in Table 6 are listed in the order of increasing Ca/P mole ratio. This is also the order of increasing basicity. Except for FAp, all compounds are members of the ternary system, $\text{Ca}(\text{OH})_2\text{-H}_3\text{PO}_4\text{-H}_2\text{O}$.

Table 6 Calcium (Ortho) Phosphate Compounds and their Solubility Product Constants. (Laurence, 1991)

Compound	Formula	Ca/P	$\log(K_{sp})$ at 25°C	$\log(K_{sp})$ at 37°C
Monocalcium phosphate monohydrate (MCPM)	$\text{Ca}(\text{H}_2\text{PO}_4)_2 \cdot \text{H}_2\text{O}$	0.5	highly soluble	
Monocalcium phosphate anhydrous (MCPA)	$\text{Ca}(\text{H}_2\text{PO}_4)_2$	0.5	highly soluble	

Dicalcium phosphate dihydrate (DCPD)	$\text{CaHPO}_4 \cdot 2\text{H}_2\text{O}$	1.0	6.59	6.63
Dicalcium phosphate anhydrous (DCPA)	CaHPO_4	1.0	6.90	7.02
Octacalcium phosphate (OCP)	$\text{Ca}_8\text{H}_2(\text{PO}_4)_6 \cdot 5\text{H}_2\text{O}$	1.33	96.6	95.9
Alpha-Tricalcium phosphate (α -TCP)	$\alpha\text{-Ca}_3(\text{PO}_4)_2$	1.5	25.5	25.5
Beta-Tricalcium phosphate (β -TCP)	$\beta\text{-Ca}_3(\text{PO}_4)_2$	1.5	28.9	29.5
Hydroxyapatite (OHAp)	$\text{Ca}_5(\text{PO}_4)_3\text{OH}$	1.67	58.4	58.6
Fluorapatite (FAP)	$\text{Ca}_5(\text{PO}_4)_3\text{F}$	1.67	60.5	
Tetracalcium phosphate (TTCP)	$\text{Ca}_4(\text{PO}_4)_2\text{O}$	2.0	38-44	42.4

2.3.1 Solubility Product Constants

Solubility is one of the most important properties of calcium phosphate compounds. It is the solubility that determines the direction of nearly all ambient temperature chemical reactions (like dissolution, precipitation or phase transformation in nature) in which calcium phosphates are involved. Gravimetric solubility, i.e., the mass of a solid

solid that can dissolve into a unit volume of the solution, is a simple way of describing solubility. The quantity, however, can change significantly with other solution parameters such as the pH, the concentrations of other components, etc., and is not considered suitable for describing the solubility properties of a calcium phosphate salt under a broad range of condition. A more fundamental parameter for describing solubility is the thermodynamic solubility product constant, K_{sp} , a quantity related to the Gibbs free energy of the solid, K_{sp} is expressed in a form related to the formula of the compound, e.g., for OHAp,

$$K_{sp}(\text{OHAp}) = (\text{Ca})^5 (\text{PO}_4)^3 (\text{OH}) \quad (1)$$

where quantities in () in the right hand side of the equation denote activities. Table 6 lists the K_{sp} values for the salts at 25°C and 37°C. For most calcium phosphate salts, the K_{sp} values determined by different investigators are generally in good agreement.

2.3.2 Solubility Phase Diagrams

Based on Gibb's phase rule, a ternary system with two phases, a solution and a solid, in equilibrium at a fixed temperature and pressure has a single degree of freedom. Thus a line, known as a solubility isotherm, in the

phase diagram (Fig.2) defines the compositions of all the solution that are saturated with respect to that salt. The solubility isotherm of a salt calculated based on the knowledge of the solubility product constant for that salt, the dissociation constants of phosphoric acid, the stability constant of ion pairs, and an appropriate model for calculating the activity coefficients for the various species.

Fig.2(a). shows the isotherm of the important salts: dicalcium phosphate dihydrate (DCPD), dicalcium phosphate anhydrous (DCPA), octacalcium phosphate (OCP), β -tricalcium phosphate (β -TCP), and hydroxyapatite(OHAp), in the form of the logarithm of total calcium concentration, $\log(\text{Ca})$ and a function of the logarithm of the total phosphate concentration, $\log(\text{P})$, of the saturated solution. These isotherms have positive slopes in the more concentrated (also more acidic) regions in the phase diagram. This means that if phosphoric

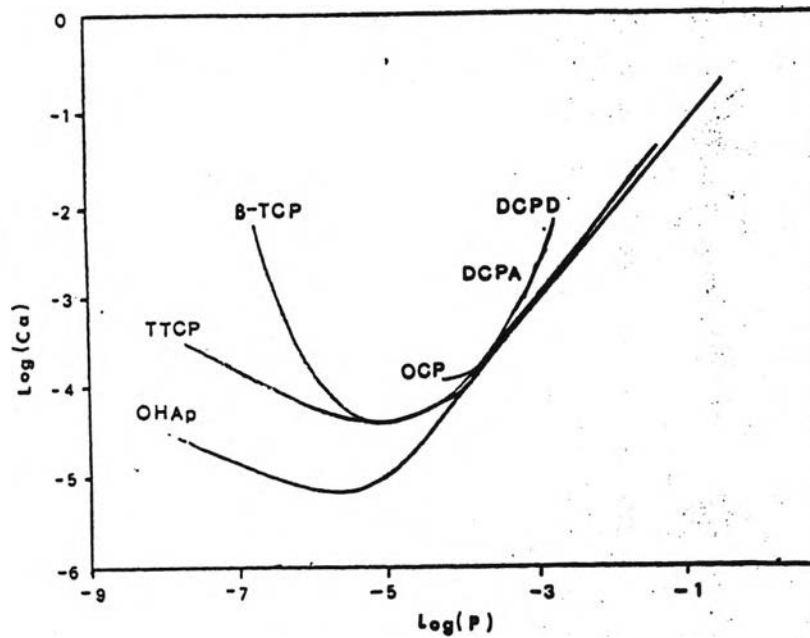
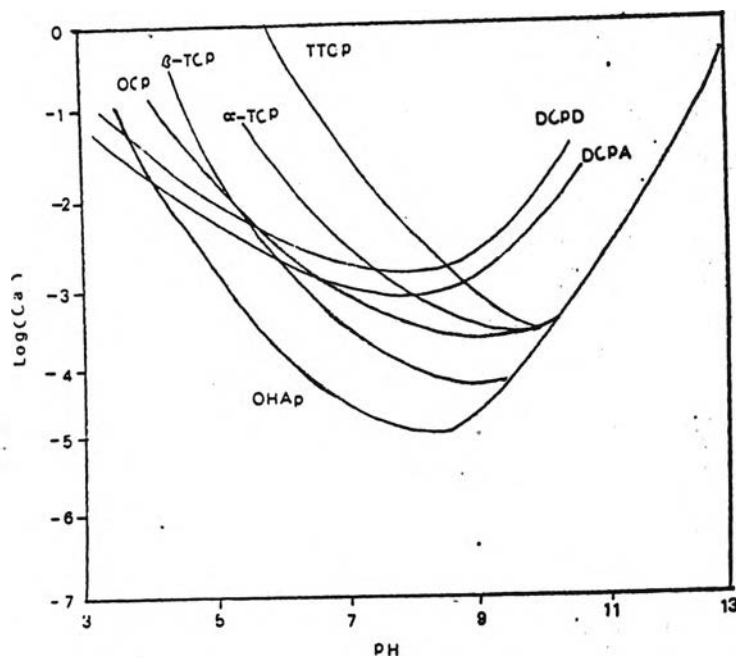


Fig.2(a) Solubility phase diagram for the ternary system $\text{Ca}(\text{OH})_2\text{-H}_3\text{PO}_4\text{-H}_2\text{O}$ at 25°C: solubility isotherms showing $\log(\text{Ca})$ and (P) of solution in equilibrium with various salts. (Laurence and Scozo, 1991).

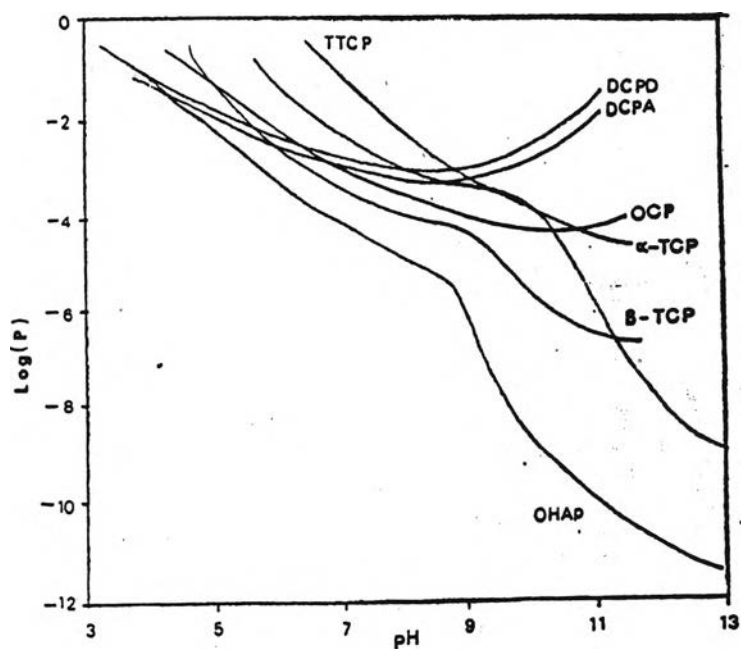
acid is added to a solution saturated with respect to a salt, the composition will shift to the right, making the solution undersaturated. This is because phosphoric acid is a weak acid. When it is added to a neutral or acidic solution, the decrease in pH would cause protonation of the phosphate species. This in turn would result in a net decrease in the activities of HPO_4^{2-} and PO_4^{3-} , despite an increase in the total (P). Consequently, a higher (Ca) would be needed to satisfy the

K_{sp} . In the more dilute (and more basic) regions of the phase diagram, the isotherms for the basic salts β -TCP, OHAp, and TTCP have negative slopes. This is because when phosphoric acid is added to a high pH solution, the alkalinity of the solution is sufficiently strong to resist a significant decrease in pH, and this allows the added acid to dissociate, thus increasing the activities of PO_4^{3-} and making the solution supersaturated.

Fig.2(b). shows the same isotherms but expressed in terms of $\log(Ca)$ as a function of pH of the solution. Fig.2(c) shows the isotherms for the same compounds in the form of the logarithm of the total phosphate concentration, $\log(P)$, of the saturated solution as a function of pH.

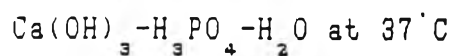


(b)



(c)

Fig.2. Solubility phase diagram for the ternary system



(b): solubility isotherms showing $\log(\text{Ca})$ and pH of solutions in equilibrium with various salts.

(c): solubility isotherm showing $\log(\text{P})$ and pH of the solutions

(Laurence, 1991)

The isotherms in both figures have negative slopes in the neutral and acidic regions, i.e., pH below 7, of the phase diagram. This reflects the fact that all these compounds are more soluble as the pH decreases. The slope of the isotherm is an indication of how rapidly the (gravimetric) solubility of the salt increases with decreasing pH. Since for a given drop in pH, the solubility of a basic salt would increase more than would an acid salt. For example, the acidic salts, DCPD and DCPA, have smaller negative slopes than do the basic salts, TTCP, OHAp and TCP.

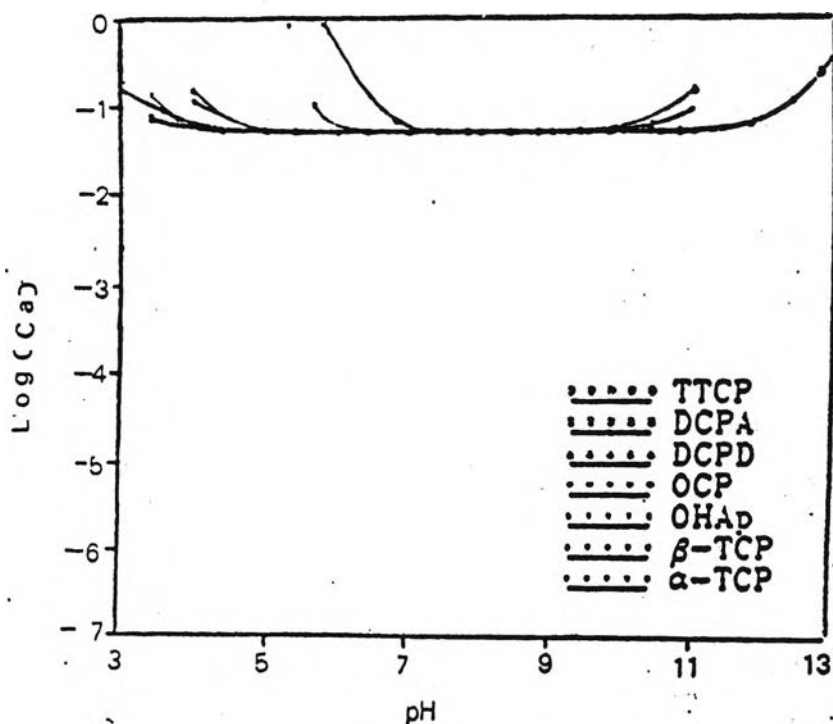
In the alkaline regions of the phase diagram, the Ca concentration increases with increasing pH (Fig.2(b)), but with the exception of DCPA and DCPD, the P concentration decreases with increasing pH (Fig.2(c)). The reasons for the different shapes of the $\log(p)$ vs pH isotherms are also related to the basicity of the compound as has been described previously. It may be concluded that the solubility behavior of a calcium phosphate salt is principally determined by two factors: the thermodynamic solubility product constant and the basicity of the compound.

The solubility phase diagrams shown in Fig.2(b) and 2(c) are quite useful because they reveal the relative stabilities of the salts at various pHs. At a given pH a

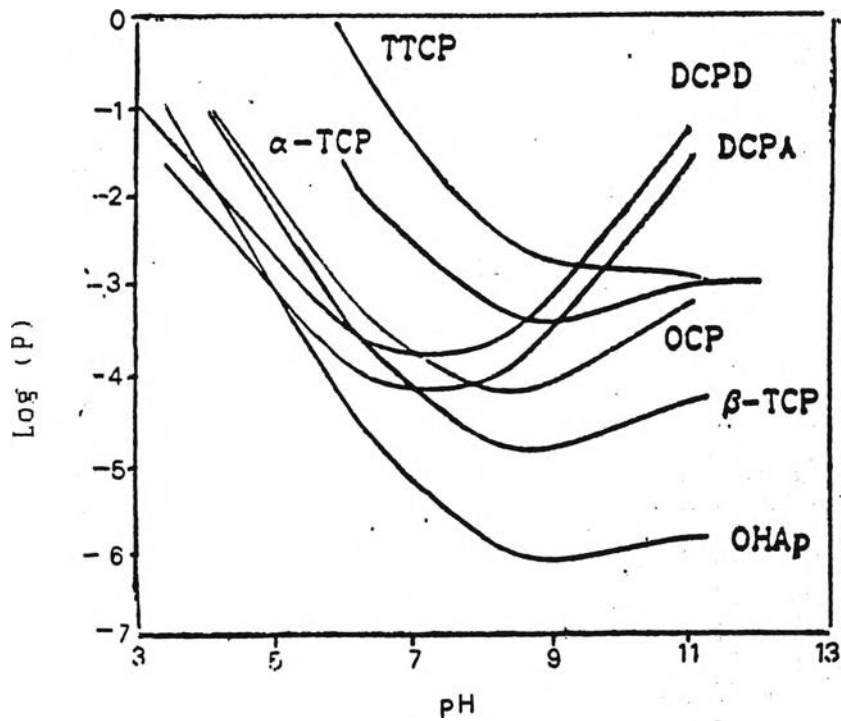
salt whose isotherm lies below that of another salt is less soluble (more stable) than the other. Thus, it is readily seen from the phase diagrams that OHAp is the least soluble among all salts until the pH falls below approximately 4.2 where DCPA becomes the least soluble. Similarly, TTCP is the most soluble salt for pH below 8.5; above that DCPD is the most soluble. The relative stabilities of the various salts are the major driving forces for the reactions that occur in calcium phosphate cement.

The phase diagrams shown in Fig. 2(a), 2(b) and 2(c) apply only to the ternary system, $\text{Ca(OH)}_2\text{-H}_3\text{PO}_4\text{-H}_2\text{O}$. This means that the compositions described in these phase diagrams can be obtained by equilibrating a salt in aqueous solutions of H_3PO_4 or Ca(OH)_2 only and not in solutions that contain components other than those in the ternary system, e.g., HCl or NaOH. However, diagrams similar to Fig. 2(b) and 2(c) can be drawn for a quaternary system when a parameter is held constant. Fig. 3(a) and 3(b) show phase diagram for the system $\text{Ca(OH)}_2\text{-H}_3\text{PO}_4\text{-HCl-H}_2\text{O}$ in which the isotherms are for a fixed concentration of HCl at 0.1 mol/l. It can be seen that the primary effects of HCl, which does not form stable ion-pairs or insoluble salts with calcium or phosphate ions, are to shift the loci of the isotherms. The Ca

concentration of all points on all the isotherms are increased from the corresponding values in the ternary system, simply to balance the negative charges carried by the Cl^- ions. This results in a collapse of the separations between the isotherms plotted in the form of $\log(\text{Ca})$ vs pH (Fig.3(a)). Additionally, the increase in Ca concentration causes a reduction in the P concentration needed to satisfy the K_{sp} such that the isotherms plotted in the form of $\log(\text{P})$ vs pH are significantly shifted toward lower P concentrations Fig.3(b). Diagrams similar to Figs.3(a) and 3(b) may be produced for different concentrations of HCl or other acids. In the cases where acid is partially dissociated or forms stable complexes with calcium or phosphate ions, knowledge of the acid or complex dissolution constants is required to produce the phase diagram.



(a)



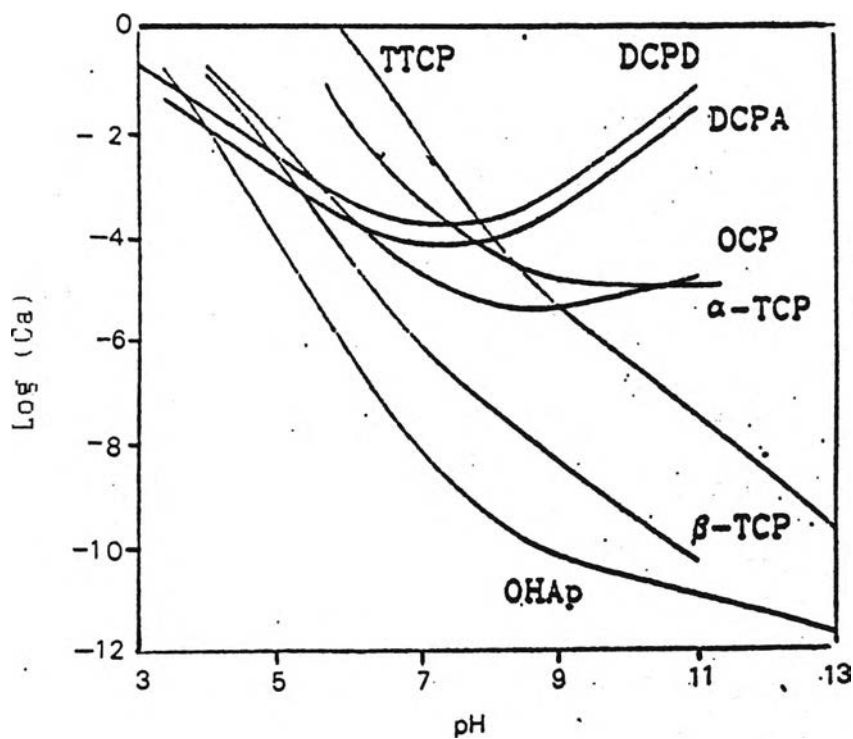
(b)

Fig.3 Solubility phase diagram for the quaternary system $\text{Ca}(\text{OH})_2\text{-H}_3\text{PO}_4\text{-HCl-H}_2\text{O}$, at 37°C and fixed HCl concentration of 0.1 mol/l.

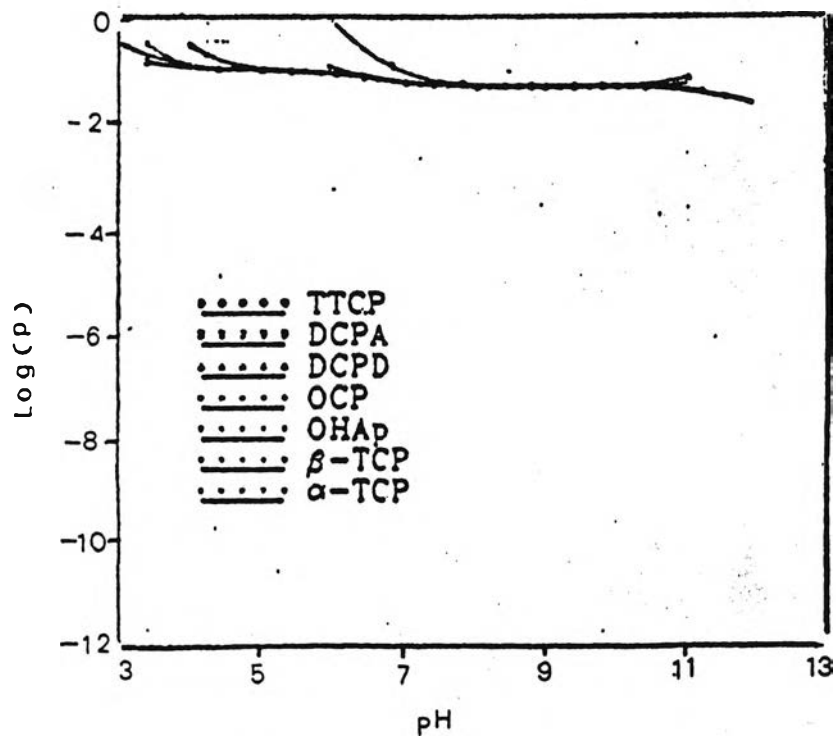
- (a) solubility isotherms showing $\log(\text{Ca})$ and pH of solution in equilibrium with various salts.
- (b) solubility isotherms showing $\log(\text{P})$ and pH of the solutions.

(Laurence, 1991)

Shown in Fig. 4(a) and 4(b) are isotherms for the $\text{Ca}(\text{OH})_2\text{-H}_3\text{PO}_4\text{-NaOH-H}_2\text{O}$ system in which the concentration and the increase of P concentration compared to the corresponding solution in the ternary system. The isotherms in the $\log(P)$ vs pH phase diagram becomes superimposed because all solutions below pH12 would have a minimum P concentration to balance the charges of Na^+ ions.



(a)



(b)

Fig.4 Solubility phase diagram for the quaternary system.

$\text{Ca}(\text{OH})_2 - \text{H}_3\text{PO}_4 - \text{NaOH} - \text{H}_2\text{O}$, at 37°C and fixed NaOH concentration of 0.1 mol/l

(a) solubility isotherms showing $\log(\text{Ca})$ and pH of solutions in equilibrium with various salts

(b) solubility isotherms showing $\log(P)$ and pH of the solutions

(Laurence , 1991)

Fig.5 shows a phase diagram in which a series of isotherms for OHAp are drawn at fixed concentration of the fourth component, HCl or NaOH. It can be seen that the primary effect of HCl or NaOH, as a fourth component does not influence dissolution or precipitation reaction of OHAp, is simply to shift the isotherm such that for a given (P), the required (Ca) increases or decreases, respectively.

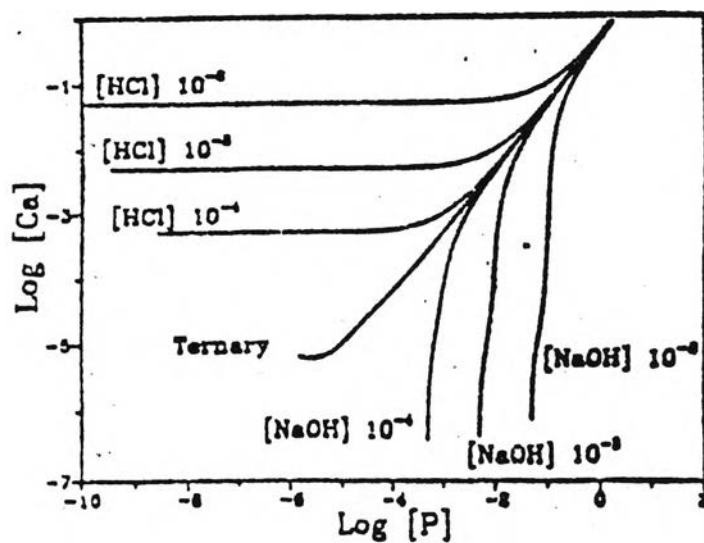


Fig.5 Solubility isotherm of the 4- component system at concentration of the fourth component, HCl or NaOH.

(Laurence and Scozo, 1991)

From equation;

$$K_{sp}(\text{OHAp}) = (\text{Ca})^5 (\text{PO}_4)^3 (\text{OH}) \quad (1)$$

the expression for the solubility product constant of OHAp may be rearranged to have the form,

$$((\text{Ca})(\text{OH})^2)^5 ((\text{H})^3(\text{PO}_4))^3 = K_{sp} ((\text{H})(\text{OH}))^9 \quad (2)$$

By taking the logarithm, equation 2 becomes

$$5\log((\text{Ca})(\text{OH})^2) + 3\log((\text{H})^3(\text{PO}_4)) = \log K_{sp} + 9\log K_w \quad (3)$$

where $K_w = (\text{H})(\text{OH})$ is the dissociation constant of water. Thus, a plot of the $\log((\text{Ca})(\text{OH})^2)$ value versus the $\log((\text{H})^3(\text{PO}_4))$ values for the series of solutions, all of which are saturated with respect to OHAp, would yield a straight line with a slope of $-3/5$ (Fig. 6). The same situation also applies to solutions saturated with respect to other salts, with the slope being equal to the negative P/Ca ratio of the salt in equilibrium with the solution (Fig. 6). These types of diagrams are shown as the potential phase diagram, because the quantities being plotted are related to the chemical potentials of the components $\text{Ca}(\text{OH})_2$ and H_3PO_4 . In contrast to composition phase diagram (e.g., Fig. 5), in a potential phase diagram the location of the isotherm for a given solid remains fixed, regardless of the presence of additional components. The potential diagrams are useful, because the $\log((\text{Ca})(\text{OH})^2)$ and $\log((\text{H})^3(\text{PO}_4))$ values, which can be readily calculated from

the compositions of the solutions, may be used to determine which solid is in equilibrium with a series of solution without requiring a prior knowledge or assumption.

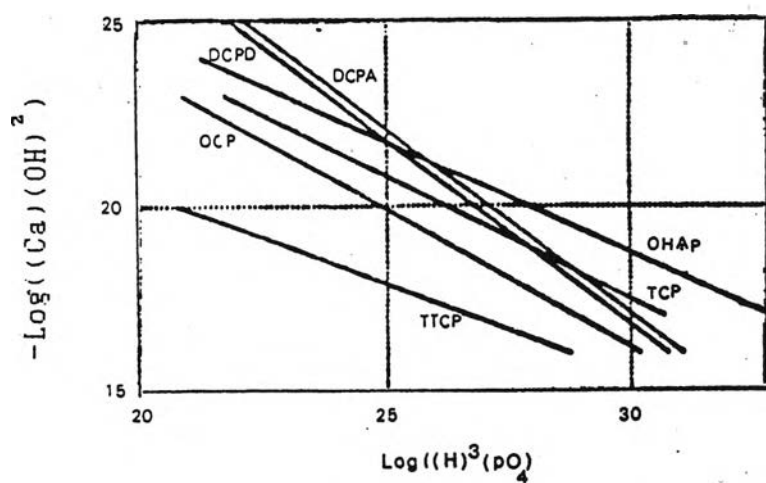


Fig.6 Potential phase diagram for calcium phosphates.

(Laurence and Scozo, 1991)

2.4 Tricalcium Phosphates Ceramics

Recently sintered tricalcium phosphate ceramics have become a subject of interest in field of biomaterials as well as hydroxyapatite ceramics. Tricalcium phosphate ceramics, which is classified as a bioactive and biodegradable material, is already in clinical use, e.g., as bone filler, root canal filler, pulp capping agent, cavity liner, artificial tooth root and skull (Kanazawa, 1989).

The name tricalcium phosphate is given to any calcium phosphate, the Ca/P mole ratio of which is equal to 1.50. Table 7 gives information about various tricalcium phosphate. They generally have well defined structure such as β -, α -, α' -, Hp(high-pressure form) -TCP. On the contrary amorphous (Am) and apatite (Ap), TCP are only roughly defined structurally. Am-TCP is described as composed of spherical clusters of 9-Å in diameter; Ap-TCP looks like an OHAp from XRD point of view, but is not so well defined ;

Table 7 Various pure tricalcium phosphate (Ca/P = 1.50)
(Heughebaert and Bonel, 1986)

Symbol	Chemical Formular	Name
Am-TCP	$\text{Ca}_3(\text{PO}_4)_2$ +adsorbed water	amorphous TCP
Ap-TCP	$\text{Ca}_5(\text{HPO}_4)(\text{PO}_4)_4(\text{OH})$	apatite TCP ($t < 100^\circ\text{C}$)
TCP or β -TCP	$\beta\text{-Ca}_3(\text{PO}_4)_2$	β -TCP ($t < 1120^\circ\text{C}$)
α -TCP	$\alpha\text{-Ca}_3(\text{PO}_4)_2$	α -TCP ($1120^\circ\text{C} < t < 1470^\circ\text{C}$)
α^- -TCP	$\alpha^-\text{Ca}_3(\text{PO}_4)_2$	α^- -TCP ($t > 1470^\circ\text{C}$)
Hp-TCP	$\text{Ca}_3(\text{PO}_4)_2$ high pressure	high pressureTCP ($p = 45\text{Kbar}$)

it is a particular compound of the HAp-like series ; comparison with Am-TCP shows that it contains HPO_4 and OH^- in the structure. TCP-like structure appears in other material of biological interest produced either by precipitation in solution (whitlockite), or by solid state reaction (Table 7). Whitlockite differs from TCP both by the presence of Mg^{2+} and H^+ in its structure and by a lower solubility.

Table 8 Solid of β -TCP structure and chemically close compounds related to this structure. (Heughebaert, and Bonel, 1986)

Symbol	Chemical formula	Name	Ca/P ratio
TCP	$\text{Ca}_3(\text{PO}_4)_2$ or $\text{Ca}_{21}(\text{PO}_4)_{14}$	anhydrous β -TCP	1.50
W	$\text{Ca}_{18}\text{M}^{2+}_2\text{H}_2(\text{PO}_4)_{14}$ ($\text{M}^{2+} = \text{Mg}^{2+}, \text{Fe}^{2+}, \dots$)	whitlockite	1.43
M:TCP	$\text{Ca}_{3-x}\text{M}^{2+}_x(\text{PO}_4)_2$ ($\text{M}^{2+} = \text{Mg}^{2+}, \text{Ni}^{2+}, \text{Cd}^{2+}, \text{Zn}^{2+}, \dots$)	M containing β -TCP	1.50
SO_4 :TCP	$\text{CaSO}_4 - 10\text{Ca}_3(\text{PO}_4)_2$	CaSO_4 containing β -TCP	>1.50
Al:TCP	$\text{Al}_{2x/3}\text{Ca}_{9-x}(\text{PO}_4)_2$	Aluminium containing β -TCP	>1.50

Crystal data on β -TCP are given as

rhombohedral system, R 3c, $a=b=10.439$, $c=37.375$ Å

(hexagonal axes)

cell constants (Z) =21, density = 3.067 g/cm^3

and the structure is shown in Fig.7 which is related to those of $\text{Ba}_3(\text{VO}_4)_2$, $\text{Ba}_3(\text{PO}_4)_2$ and $\text{Sr}(\text{PO}_4)_2$. However, because of

a great difference in size between Ca and Ba ions. $7\text{Ca}_3(\text{VO}_4)_2$ units occupy a volume corresponding to $8\text{Ba}_3(\text{PO}_4)_2$ units and the Ca sites are partly half-occupancy.

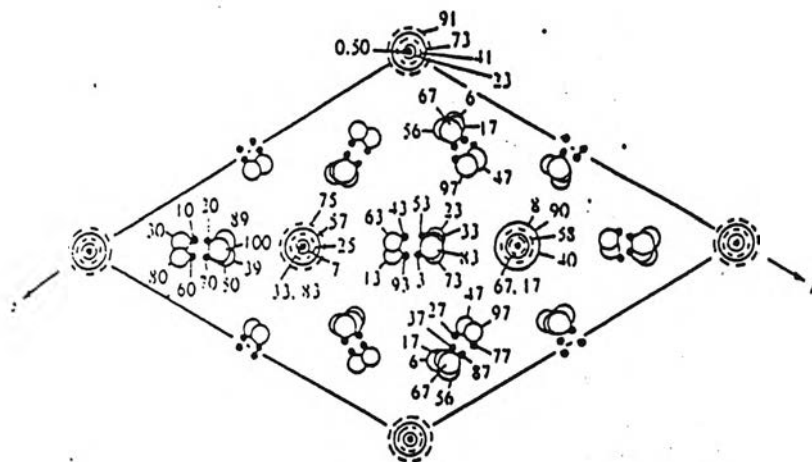


Fig.7 Structure of β -TCP;

\bigcirc :Ca , \bigcirc :Ca (half-occupancy), \bigcirc :P of PO_4

(Dicken et al., 1974)

Crystal data on α -TCP are given as

monoclinic system, $\text{P2}_1/a$, $a = 12.887$, $b = 27.280$,

$c = 15.219 \text{ \AA}$, $\beta = 126.20$, $z = 24$

density = 2.803 g/cm^3

and the structure is shown in Fig.8 . Approximate subcells with $b' = b/3$ exist. There are columns of distorted (Ca-Ca-Ca-Ca) and $(*\text{-PO}_4\text{-Ca-PO}_4)$ along the c axis, where * indicates cation vacancy. The structure is related to that of glaserite

$K_3Na(SO_4)_2$. The ratio of $(Ca+*)/P = 2$ corresponds to that of $(K+Na)/S = 2$. Cation vacancies arise from such a composition situation, not from a size imbalance between cation and anion as in the case of β -TCP. The broken line in the figure 8 outline a cell corresponding to that of the c plane of an OHAp cell, and the corners to the OH sites of OHAp. One of the features of α -TCP is this structural similarity to OHAp. The α -form has a "looser structure" a higher internal energy than the β -form, and thus a higher chemical reactivity than the β -form.

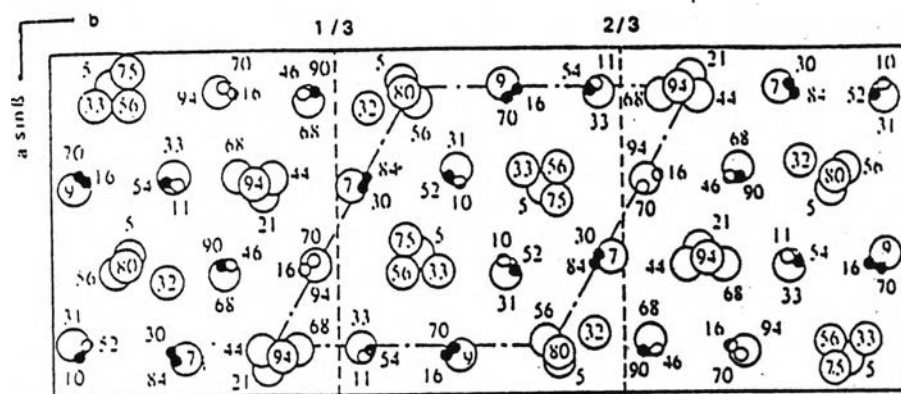


Fig.8 Structure of α -TCP;

O:Ca, :P above O, o:P below O

(Mathew, 1976)

The structure of the α^- form reported is not yet determined, probably due to its difficulty in preparation.

Crystal data on the Hp-form are:

rhombohedral, $R\bar{3}'m$ $a = 5.2487$, $c = 18.674 \text{ \AA}$
 (hexagonal setting) density = 3.469 g/cm^3

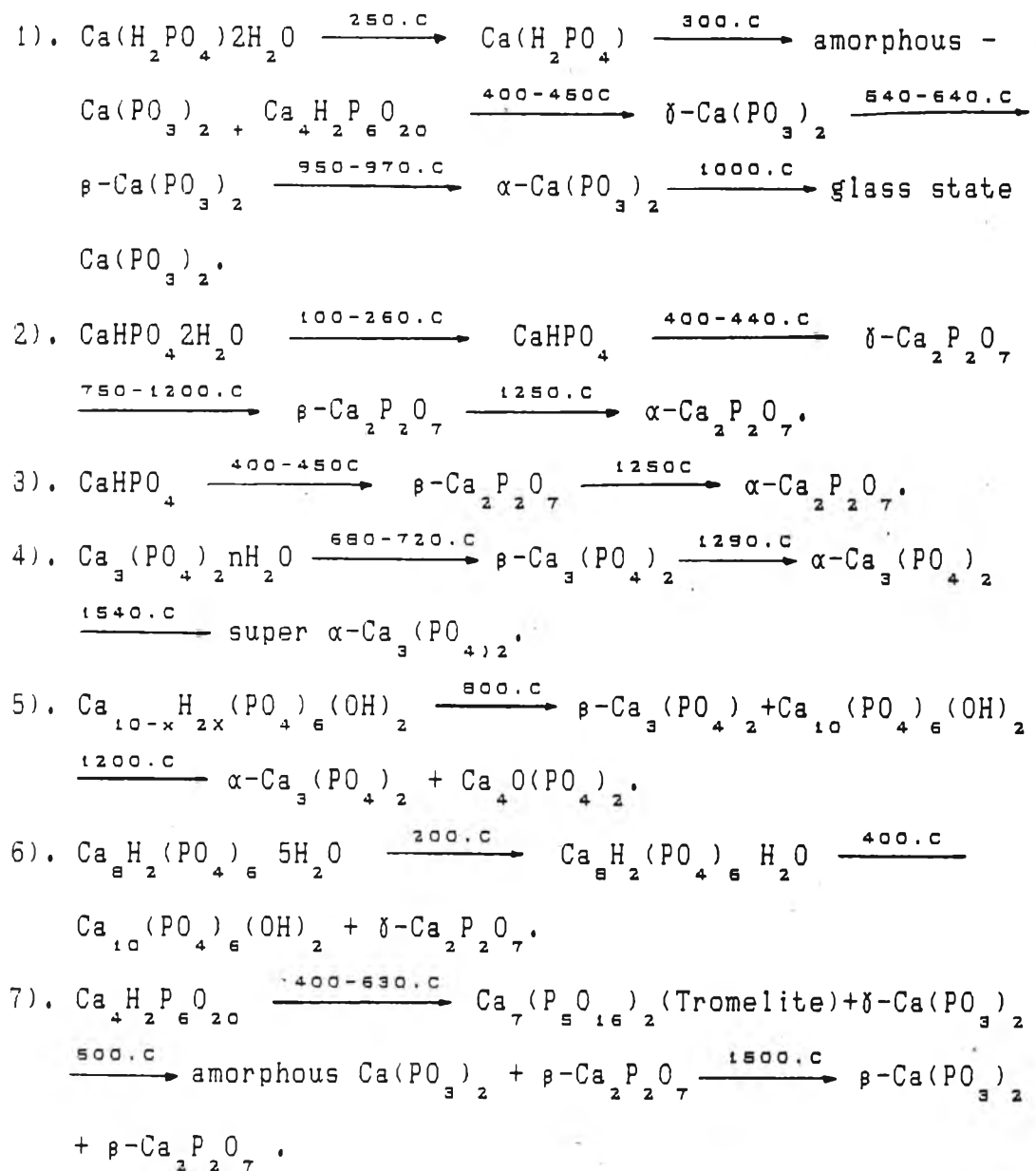
2.5 Thermal transformation of Calcium Phosphates

These calcium phosphates, including monocalcium phosphate monohydrate, $\text{Ca}(\text{H}_2\text{PO}_4)_2 \cdot \text{H}_2\text{O}$; dicalcium phosphate dihydrate, $\text{CaHPO}_4 \cdot 2\text{H}_2\text{O}$; dicalcium phosphate anhydrous, CaHPO_4 ; tricalcium phosphate, $\text{Ca}_3(\text{PO}_4)_2$; tetracalcium dihydrate phosphate, $\text{Ca}_4\text{H}_2\text{P}_6\text{O}_{20}$, Ca-deficient hydroxyapatite or so-called amorphous calcium phosphate (ACP), $\text{Ca}_{10-x}\text{H}_{2x}(\text{PO}_4)_6(\text{OH})_2$ and octacalcium phosphate pentahydrate, $\text{Ca}_8\text{H}_2(\text{PO}_4)_6 \cdot 5\text{H}_2\text{O}$, are synthesized by solution reaction methods. The products obtained from these calcium phosphates heated up to 1500°C in air at a heating rate of $3\text{--}5^\circ\text{C}/\text{min}$ and the products obtained at various temperature are summarized in Table 9. It has been determined that when calcium phosphates are heated at over 1300°C , the final products become a mixture of hilgenstockite, $\text{Ca}_4\text{O}(\text{PO}_4)_2$; α -tricalcium phosphate, $\alpha\text{-Ca}_3(\text{PO}_4)_2$; α -calcium pyrophosphate, $\alpha\text{-Ca}_2\text{P}_2\text{O}_7$; and α -calcium metaphosphate,

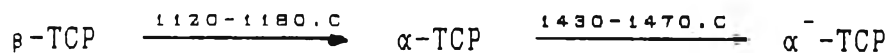
α - $\text{Ca}(\text{PO}_3)_2$. The mixture ratio depends on the Ca/P ratio of the original calcium phosphates.

Table 9 Thermal transformation of seven calcium phosphate.

(Aoki, 1991)



Four polytypes of TCP are as follows:



and high pressure form Hp-TCP

The β - and α - form are prepared by solid state reaction or thermal decomposition. In the solid state reaction, the stoichiometric mixture of $\text{CaHPO}_4 \cdot 2\text{H}_2\text{O}$ or CaHPO_4 or $\text{Ca}_2\text{P}_2\text{O}_7$ and CaCO_3 or CaO is heated at about 1000°C for 0.5-1.0 hour to prepare the β - form, and at above 1200°C for 0.5-1.0 hour to prepare the α -form. In the thermal decomposition method, ACP is heated at 700°C or above 1200°C for the α -form, and at $900-1150^\circ\text{C}$ for the β -form. Complicated features of crystallization are observed depending on preparation conditions as shown in Fig.9. ACP samples prepared from solution with low initial $(\text{Ca})\times(\text{P})$ products tends to first crystallize β -TCP only or an α - and β -TCP mixture. In contrast, ACP from solution with $(\text{Ca})\times(\text{P})$ products of 10^3-10^5 mM^2 first crystallizes α -TCP only. $\text{CaHPO}_4 \cdot 2\text{H}_2\text{O}$ formed in further high $(\text{Ca})\times(\text{P})$ solution products.

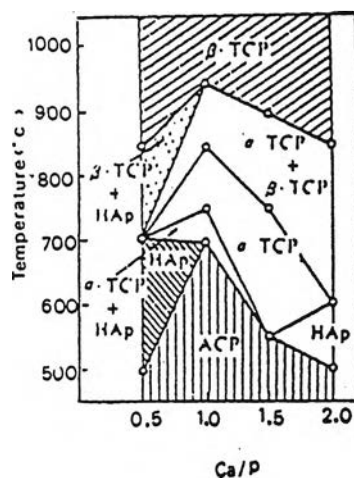
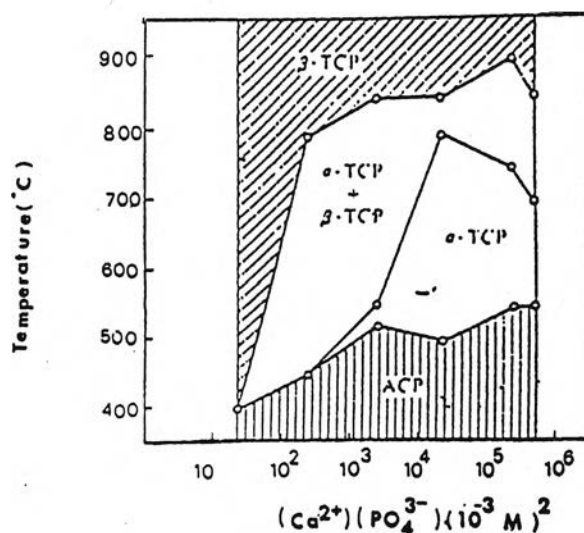


Fig.9 Thermal changes of ACP prepared at different $(Ca) \times (P)$ products (a) and Ca/P mixing ratios (b) (Kanazawa, 1989).

A calcium deficient OHAp (Ca/P=1.50) can be used for the preparation. The Hp-TCP form is prepared by heating β -TCP at $950^{\circ}C$ under 4.0 GPa, or heating OHAp at $1200^{\circ}C$ under 15 GPa.