Homogeneous crystals containing variable proportions of isomorphous substances crystallise in general from the solution of end members. These are known as "mixed crystals" or more appropriately called solid solutions. Depending upon the complete or partial miscibility of the solids, a complete or an incomplete series of solid solution can be obtained. Solid solutions may occur in a crystal in any of the following two ways:

(i) If the ideal formula of a crystal is represented by $AB$, then some amount of an element $C$ may be present in the formula in addition to $AB$. The formula of the crystal may then be written as $ABC_p$, where $p$ is some irrational factor usually very small. This is known as additional solid solutions or sometimes interstitial solid solutions. The formation of such solid solution takes place when the additional atom is inserted into some of the interstices of the crystal lattice resulting usually in very small increase in unit cell volume of the crystal.

(ii) In the ideal formula of the crystal, if the place of $B$ is taken by $C$, the formula of the crystal is written as $A_{B_1-p}C_p$. In this case the replacement of an atom of one kind in the crystal lattice by atoms of the second kind with nearly the same size and
symmetry takes place. The formation of such solid solutions is accompanied either by an increase or decrease of the unit cell volume depending on whether the substituent is bigger or smaller than the atom replaced. This is known as substitutional solid solution. This type of solid solution is the most common.

Usually adopted methods of preparation of substitutional solid solutions are:

(i) Co-precipitation in aqueous media
(ii) Crystallisation from the molten mixture and
(iii) equilibration of powered sample of one of the members of convenient particle size with a solution of other member.

The formation of homogeneous solid solutions over the entire compositional range is dependent upon the closeness of the ionic radii and the symmetries of the atoms concerned.

It has been established through X-ray diffraction techniques that the ionic radii ($Ca^{2+} = 0.99 \text{ Å}$, $Cu^{2+} = 0.72 \text{ Å}$ and $Pb^{2+} = 1.21 \text{ Å}$) are close together and $CaHA$, $CuHA$ and $PbHA$ constitute isomorphous substances. All of them belong to the hexagonal class of crystal symmetry with lattice constants $a = 9.37 \text{ Å}$, $c = 6.86 \text{ Å}$ for $CaHA$, $c = 6.83 \text{ Å}$ for $CuHA$, and $c = 6.64 \text{ Å}$ for $PbHA$.
a = 9.86 \text{Å}^0 \text{ and } c = 7.38 \text{Å}^0 \text{ for PbHA, } a = 8.83 \text{Å}^0 \text{ and } c = 6.53 \text{Å}^0 \text{ for CuHA. These factors suggest that solid solutions in the systems Ca-Cu-PbHA are possible.}

Muller\textsuperscript{89} prepared solid solutions of CaHA and MHA by substitution of calcium by divalent metal cations in synthetic crystals by fusing mixtures of the end members at a temperature of the order about 1500°C. Such crystals were known to be found in mineral apatites in vivo which was recognised by MaC Donald\textsuperscript{103}. For the preparation of pure and solid solutions of CaHA, CuHA and PbHA, such solid state reaction is useless. Hence coprecipitation method was developed by Patel and Agrawal\textsuperscript{104-105} and Patel and Mishra\textsuperscript{106-108} for this purpose was found to be convenient.

The following experimental conditions used by the authors in order to achieve goal of the preparation of homogeneous solid solutions of Ca-Cu-PbHA need careful and elaborate discussion. These conditions were selected such that impurities and crystal imperfection were minimised and crystal size enhanced.
PRE-PRECIPITATION CONDITIONS

The most important factor in pre-precipitation conditions is the scrupulous maintainance of pH of about 12 during the precipitation. This was done by the addition of ammonium hydroxide or ethylene diamine to the solution used. The three dissociation constants $K_1$, $K_2$ and $K_3$ of orthophosphoric acid at $25^\circ C$ are shown to be $0.75 \times 10^{-2}$, $7.99 \times 10^{-8}$ and $4.80 \times 10^{-13}$ respectively. It can be shown from these values that in fairly dilute solutions, in the medium of pH of about 9 predominantly the second dissociation is favoured while at pH of about 12, the third dissociation takes place exclusively to the existence of only orthophosphate ions.

Due to high surface activity of precipitated hydroxylapatites consequent upon the particle size which lies within the range of colloidal dimensions, ions of the type $\text{HPO}_4^{2-}$ can lead to the surface reaction of the type given below.

$$3 \text{Ca}_5(\text{PO}_4)_3(\text{OH})_2 + \text{HPO}_4^{2-} \rightarrow 5 \text{Ca}_3(\text{PO}_4)_2 + 2 \text{OH}^- + 2 \text{H}_2\text{O}$$

Such reactions are to be avoided when samples of high purity are to be prepared. Berry and Samachson independently observed the possibilities of missing of a few $\text{Ca}^{2+}$ ions in the composition of CaHA when it was formed in acidic or nearly neutral regions resulting in the formation of calcium deficient apatites of low Ca/P mole ratio ranging from 1.33 to 1.67. This non-stoichiometry was explained...
by Hendricks and Hill\textsuperscript{112} on the basis of surface adsorption of phosphate ions on the precipitated solid. An alternative explanation was suggested by Mc Connell\textsuperscript{113} on the possibility of simultaneous presence of CaHPO\textsubscript{4} and Ca\textsubscript{8}H\textsubscript{2}(PO\textsubscript{4})\textsubscript{6} 5H\textsubscript{2}O solid precipitate in the acidic or nearly neutral regions. Posner\textsuperscript{114} proposed a general formula for the series of the apatites formed with low Ca/P mole ratio as Ca\textsubscript{10-}{x}H\textsubscript{2}{x}(PO\textsubscript{4})\textsubscript{6}(OH)\textsubscript{2} and Winand\textsuperscript{115} by Ca\textsubscript{10-}{x}H\textsubscript{x}(PO\textsubscript{4})\textsubscript{6}(OH)\textsubscript{2-x} in which both Ca\textsuperscript{2+} and OH\textsuperscript{-} defects are involved. Kuhl and Nebergall\textsuperscript{116} also proposed the general formula as Ca\textsubscript{10-}{x-y}(HPO\textsubscript{4})\textsubscript{x}(PO\textsubscript{4})\textsubscript{6-x}(OH)\textsubscript{2-x-2y} where 0 ≤ x ≤ 2 and y = 1 - (x/2).

In any case it is clear that the inclusion of H\textsuperscript{+} ions in the apatite lattice may take one or two forms either as HPO\textsubscript{4}\textsuperscript{2-} ions or through reaction with OH\textsuperscript{-} to form water according to the following reaction:

$$\text{Ca}_{10}(\text{PO}_4)_6(\text{OH})_2 + 2x\text{H}^+ \rightarrow \text{Ca}_{10-x}(\text{HPO}_4)_x(\text{PO}_4)_{6-x}(\text{OH})_{2-x} + x\text{H}_2\text{O} + x\text{Ca}^{2+}$$

Samachson\textsuperscript{106} proposed the following equation for the formation of hydroxylapatites:

$$10 \text{Ca}^{2+} + 6\text{HPO}_4^{2-} + 2\text{H}_2\text{O} \rightarrow \text{Ca}_{10}(\text{PO}_4)_6(\text{OH})_2 + 8\text{H}^+$$
The mechanism can be considered to occur in acidic region or nearly neutral regions. In order to produce pure CaHA, the $H^+$ ions released during the reaction must get rid off as its presence increases the possible replacement of $Ca^{2+}$ by it. If CaHA is precipitated in acidic or neutral regions, there will be more of $H^+$ ions in the reaction medium resulting in the formation of impure CaHA containing trapped $H^+$ ions either in the form $HPO_4^{2-}$ or $OH^-$ as $H_2O$ in the crystal lattice. In order to get pure CaHA, all the interacting solutions used for the precipitation of the samples were scrupulously maintained a high pH of about 12 avoiding the possibility of occurrence of any possible complications introduced during preparation.

Since the number of workers\textsuperscript{117-119} have reported regarding the environmental pollution in the atmosphere in the recent times, the samples of CaHA, CuHA, PbHA and their solid solutions were prepared at $37 \pm 0.5^\circ C$ to explain certain biological procedures related to calcification and resorption. In spite of the fact that high dilution of interacting solutions can facilitate the bigger crystals due to slow nucleation dilutions higher than those used for precipitation of the samples were considered inconvenient. The rate of mixing of the solutions were slow accompanied by uniform stirring to help the establishment of slow and uniform nucleation. The molar ratio $\frac{Ca^{2+}}{Cu^{2+} + Pb^{2+}}$ in the solution was maintained the same as was expected for the solid solutions. The precipitation was brought about in an atmosphere completely free from carbon dioxide.
to avoid the formation of carbonate apatite and the likely alteration of the pH of the precipitation medium.

POST-PRECIPITATION CONDITIONS

The homogeneity of the samples and the size of the crystals are further increased by aging the precipitate with the mother liquor and hence the samples precipitated were aged by boiling under reflux for about 30 minutes and the precipitate was retained in contact with the mother liquor over night. The precipitate was filtered and washed repeatedly with carbon dioxide free water until the filtrate did not show indication of absorbed Ca$^{2+}$, Cu$^{2+}$ and Pb$^{2+}$ ions. Though heating of the samples to 900°C for 6 h was supposed to help ionic diffusion contributing to homogeneity of the samples, it was thought that introduction of bigger ion like Pb$^{2+}$ and smaller ion like Cu$^{2+}$ in place of Ca$^{2+}$ might bring about instability in the lattice thereby resulting in its decomposition and hence the samples were acetone washed to remove the water that is absorbed on the surface of the crystals and further dried by heating to 110°C for 6 h.

Among the analytical methods employed, method I need not be much of clarification, since it is established one and usually employed for similar determinations. Since phosphate interferes in the complexometric determination of calcium, it was first separated
as ammonium phosphomolybdate which was filtered through IG crucible and calcium in the filtrate was determined complexometrically. Ammonium phosphomolybdate was dissolved in the minimum volume of 0.1 M sodium hydroxide and in the presence of thymol blue indicator. The phosphorus was precipitated as magnesium ammonium phosphate and was determined by the method of titration with 0.1 M magnesium sulphate using Eriochrome Black-T as indicator at a pH of about 10. The initial separation of phosphate was found to be necessary and if not done, it precipitates calcium phosphate in the alkaline medium (pH of about 10) required for EDTA titrations. Quantitatively phosphate was precipitated as ammonium phosphomolybdate in the medium of nitric acid at a temperature of 50°C, higher temperature or excess of ammonium molybdate gives white needles of ammonium tetra molybdate, while at lower temperature, the complete precipitation and the filtrability of ammonium phosphomolybdate was difficult. The gravimetric determination of phosphate in the precipitate was found to be unsuitable since the composition of ammonium phosphomolybdate was indefinite. Ammonium tetra molybdate, molybdic acid and occluded ammonium nitrate contaminate the precipitate of ammonium phosphomolybdate hence it was subsequently dissolved in a solution of sodium hydroxide, precipitated as magnesium ammonium phosphate which was complexometrically determined.

In method II, phosphate was determined as usual and
copper content in the filtrate was determined by direct titration with Murexide indicator.

In method III, phosphate was separated first as earlier method and lead content in the filtrate was determined by direct titration with Eriochrome Black-T as indicator.

In the complexometric determination of more than one ion present in a solution the usual methods adopted\(^{97}\) are

(i) precipitation of one of the components by using a suitable precipitant and determining the free ion left in the solution

(ii) complex formation of one of the ions which facilitates the complexometric determination of the free ion left in the solution.

In the complexometric determination of calcium, copper, lead and phosphate in the solid solutions, phosphate was precipitated, separated and determined as usual. The lead content in the filtrate was masked with 2,3-dimercaptopropanol in ethyl alcohol, then free calcium and copper in the same filtrate were determined by titrating agent EDTA using Murexide as indicator.

In a separate aliquot of calcium, copper and lead,
lead was masked as earlier and copper with potassium cyanide then free calcium was titrated as above.

In an another aliquot of calcium, copper and lead, calcium was masked with ammonium fluoride and copper with potassium cyanide, then lead was determined as earlier method-III.

The g-atom ratio $\frac{Ca}{P}$, $\frac{Cu}{P}$, $\frac{Pb}{P}$ and $\frac{Ca+Cu+Pb}{P}$ were calculated for the samples based on the results of chemical analyses. In all cases, this ratio was close to the theoretical value of 1.67 which could be explained on the basis of high degree and accuracy available with the methods of chemical analyses I - VI employed as suggested by the results of applicability of methods to synthetic mixtures of known compositions (See tables 4-7). This further indicated that the samples prepared were pure and homogeneous.

It is seen from X-ray diffraction analysis that with increase of Pb$^{2+}$ in the solid solutions, the lattice parameters "a" and "c" increased (Fig.14) resulting in the dilation of unit cell volume and with the increase of Cu$^{2+}$ in the solid solutions, the lattice parameters "a" and "c" decreased resulting in the contraction of unit cell volume (see Fig.11). This is understandable since Ca$^{2+}$ in the apatite was isomorphously substituted by bigger ion Pb$^{2+}$ and smaller ion like Cu$^{2+}$ resulting in the formation of homogeneous solid solutions.
A systematic increase in density of the samples was observed with increase in the proportion of (Cu+Pb) content as indicated in tables 11, 17 and 23 and the values were found in figs. 13, 16 and 19 which according to Rotgers indicated the homogeneity of the solid solution prepared.\textsuperscript{120}

The electronmicrographic scannings contain needle shaped crystals. These are the characteristic of apatites which were found to increase in the dimension with increase in lead content and decrease in the dimension with increase in copper content. The absence of extraneous phases indicated the presence of a single phase of apatite in the sample. The average dimensions of the crystals of the solid solutions were found to range between those of end members. The overall increase in crystal size with increase in the proportion lead content in the samples were in agreement with the dilation of the crystal lattice and the overall decrease in crystal size with increase in proportion of copper content in the samples were in agreement with contraction of the crystal lattice in the samples prepared.

The apatites concerned have hexagonal crystal structure.\textsuperscript{55} They are interesting examples of solid state of fairly simple molecules of tetrahedral symmetry where bands become allowed due to relaxation of the molecular symmetry Selection Rules due to the influence of site symmetry of $PO_4^3-$ groups in these compounds is "m". This
symmetry is imposed by the static field of the ions surrounding it. Besides the static field, there is dynamic interaction between the ions which also has strong influence on the internal vibration of $\text{PO}_4^{3-}$. This is shown by the Infrared and Raman spectral studies of $\text{PO}_4^{3-}$ ions in fluorapatites by Klee and Engel.\(^{56}\) Taking into consideration of this dynamic effect, the correct symmetry group according to the Selecting Rules called Unit Cell Group, which is isomorphous with crystallographic point, groups is $6/m$. Theoretically nine infrared active internal vibrations of the phosphate group are possible. Six out of which are due to the moment of the atoms which are symmetric with respect to the mirror plane. The remaining three are due to the atoms which are antisymmetric with respect to the mirror plane under these conditions only a few fundamental frequencies of $\text{PO}_4^{3-}$ and $\text{OH}^-$ are observable.\(^{116}\) The absorption corresponding to the $\gamma_3$ at about $1075 \text{ cm}^{-1}$ and $\gamma_4$ at about $570 \text{ cm}^{-1}$ of $\text{PO}_4^{2-}$ and $\gamma_3$ at about $3450 \text{ cm}^{-1}$ of $\text{OH}^-$ were clearly observed. An interesting effect of isomorphous substitution of $\text{Ca}^{2+}$ by $\text{Cu}^{2+}$ and $\text{Pb}^{2+}$ in the formation of solid solutions causes a shift of the $\gamma_3$ ($1075 \text{ cm}^{-1}$) and $\gamma_4$ ($570 \text{ cm}^{-1}$) vibrations of $\text{PO}_4^{3-}$ to lower frequencies. However, similar effect in $\gamma_3$ ($3450 \text{ cm}^{-1}$) frequency of hydroxyl groups were also observed. This may be due to the effect of binding energies and atomic mass. In the substitution of $\text{Ca}^{2+}$ by $\text{Cu}^{2+}$ and $\text{Pb}^{2+}$ resulting in the formation of solid solutions, the effect of decrease of the force constant is reinforced by increase of atomic mass and as such there is usual lowering of $\gamma_3$ and $\gamma_4$ frequencies of
\( \text{PO}_4^{3-} \) and \( \nu_3 \) frequencies of \( \text{OH}^- \) are observed. Similar observations were made by Bhatnagar when \( \text{PO}_4^{3-} \) and substituted by \( \text{AsO}_4^{3-} \) and \( \text{VO}_4^{3-} \) in apatite.

For solubility of a solute more energy must be available to break down the architecture of the crystal than what is liberated in building up the ionic lattice. The required energy for its dissociation is provided by

(i) the dipolar attraction between the solvent molecules and ions in the crystal

(ii) the interaction between these ions and the solvent molecules leading to the formation of the solvated ions.

These two types of energies are collectively called as the Energy of Solvation. The solubility of a given solid is consequently a function of the difference between its lattice and Solvation Energies. Thus for a given lattice energy the solubility is proportional to Solvation Energy. In addition to these factors, the solubilities of certain substances are based on proton donating, proton accepting tendencies in acid-base equilibria\(^{122-123}\).

The following observations are made from the results on the studies of solubility equilibria of CaHA, CuHA and PbHA.
(i) In acidic region CaHA was found to be more soluble than CuHA and PbHA.

(ii) At a given pH, a decrease of solubility was observed with increase in molecular weight of hydroxylapatites.

The investigations on kinetics of dissolution of CaHA, CuHA and PbHA suggested that the processes obey first order kinetics and become pseudo unimolecular in presence of large excess of solvent. This suggests that CaHA, CuHA and PbHA have basically the same mode of dissolution\textsuperscript{124} the process can be represented by the following equations:

\[ \text{Ca}_{10}(\text{PO}_4)_6(\text{OH})_2 \rightarrow 4 \text{Ca}_2(\text{HPO}_4)(\text{OH})_2 + 2 \text{Ca}^{2+} + 2 \text{HPO}_4^{2-} \]
\[ 2 \text{Ca}_2(\text{HPO}_4)(\text{OH})_2 \rightarrow 8 \text{Ca}^{2+} + 4 \text{HPO}_4^{2-} + 8 \text{OH}^- \]

The dissolution of CaHA is initiated by the hydrolysis of \( \text{PO}_4^{3-} \) of the hydroxylapatite lattice according to the following scheme:

\[ \text{Ca}_{10}(\text{PO}_4)_6(\text{OH})_2 + \text{H}_2\text{O} \rightarrow 10 \text{Ca}^{2+} + 6\text{HPO}_4^{2-} + 8 \text{OH}^- \]

or

\[ \text{Ca}_{10}(\text{PO}_4)_6(\text{OH})_2 \rightarrow 3 \text{Ca}_3(\text{PO}_4)_2 + \text{Ca}({\text{OH}})_2 \]
In this hydrolysis, the stage determining steps for the rate is

\[ \text{PO}_4^{3-} + \text{H}_2\text{O} \rightarrow \text{HPO}_4^{2-} + \text{OH}^- \]

It is observed that the solubility of basic salt is governed by the solubility products of hydroxides allowing for the common ion effects when required\(^{125}\). The dissolution of CaHA, CuHA and PbHA would be analogous with the solubility product of Ca(OH)\(_2\), Cu(OH)\(_2\) and Pb(OH)\(_2\). Since Ca(OH)\(_2\) is more soluble than Cu(OH)\(_2\) and Pb(OH)\(_2\) and increase of OH\(^-\) in the medium shifts the equilibrium Ca(OH)\(_2\) \(\rightarrow\) Ca\(^{2+}\) + 2OH\(^-\) to the left more than that in case of Cu(OH)\(_2\) and Pb(OH)\(_2\). Hence CaHA shows greater solubility than CuHA and PbHA.