CHAPTER 6

Crystal Structures:

 Structures of Some Binary and Ternary Compounds Such as Fluorite, Antifluorite, Rutile, Antirutile, Cristobalite, Layer Lattices - CdI₂, BiI₃; ReO₃, Mn₂O₃, Corundum, Perovskite, Ilmenite and Calcite.

The structure of crystalline compounds can be understood only after knowing the close packing of solid spheres as all the constituent particles (whether they are atoms, ions or molecules) may be treated as somewhat more or less spherical in shape.

The problem of spheres packed closely was first studied in a mathematical framework by Thomas Harriot in 1587. The idea was initiated by a question on piling the cannonballs on ships, and the question was posed to T. Harriot by Sir W. Raleigh when they were on their expedition to the land of America. The usual scheme of piling the cannonballs included the placement in a triangular or rectangular wooden frame, which forms a three or four-sided pyramidal shape. Both arrangements produce a face-centered cubic (fcc) lattice with different orientations to the base. However, the hexagonal-close-packing (hcp) scheme would result in a six-sided pyramidal shape with a hexagonal base. These two simple regular lattices achieve the highest average density and are based upon sheets of spheres placed at the vertices trigonal with a tiling pattern. However, they vary in the stacked style of these sheets.

The packing of identical spheres in two dimensions can be visualized in two arrangements as given below.

![Arrangement I and II](image)

Figure 1. The close packing of identical spheres in two dimensions.

It has been observed that 52.4% of available space is occupied in the arrangement I while 60.4% of available space is occupied in arrangement II. The remaining space is empty and is labeled as void volume. Hence, the arrangement II has greater efficiency than arrangement I. Furthermore, it can be noticed that the coordination
number of each sphere in arrangement II is six but four in case of arrangement I and the lines joining the centers of nearest spheres in the arrangement I form a square but a tringle in arrangement II.

Figure 2. The coordination number and nearest sphere system in close packing of identical spheres in two dimensions.

The two-dimensional packing can successfully be extended to three-dimensional packing just by placing the other layers of packed identical spheres over it. This can be achieved in two ways as depicted below.

Figure 3. The extension of close packing of identical sphere systems in two dimensions to three dimensions.

The first layer is labeled as A, while the second layer B is placed over the first layer in such a way that its spheres are covering the b-voids. Now, if we create a third layer directly over the layer A, then the hcp lattice is formed and if the third layer is placed over a-voids in the first layer, then the fcc lattice is built. In both the arrangements, the fcc as well as hcp, each sphere has twelve neighboring spheres. For every sphere, there is one void surrounded by six neighboring spheres (octahedral site) and two smaller voids surrounded by four
neighboring spheres (tetrahedral site). The distances to the centers of these gaps from the centers of the surrounding spheres are \( \sqrt{3}/2 \) for the tetrahedral, and \( \sqrt{2} \) for the octahedral when the sphere radius is unity.

Figure 4. The illustration of the close-packing of equal spheres in both (a) hcp and (b) fcc lattices.

Figure 5. The ball and stick model of the close-packing of equal spheres in both (a) hcp and (b) fcc lattices.

The number of interstitial sites, tetrahedral as well as octahedral, is the same for fcc and hcp lattice systems. However, the tetrahedral sites are double in number than octahedral ones. A number of crystal structures are obtained by the close-packing of one kind of atom, or by a close-packing of bigger ions having smaller ions.
occupying the void spaces. The hexagonal and cubic patterns of packing are quite close to each other in energy, and therefore, it might be problematic to predict the form preferred using first-principle calculations.

![Diagram of Tetrahedral and Octahedral Voids](image)

Figure 6. The formation of a tetrahedral and octahedral void in close packing of identical spheres in three dimensions.

The location of interstitial sites in hexagonal close packing and cubic close packing is quite important as it is expected to be occupied by smaller ion which is generally cation. Nonetheless, the anions can also occupy these tetrahedral octahedral voids if they are smaller in size.

![Diagram of Octahedral and Tetrahedral Sites in HCP](image)

Figure 7. The location of octahedral and tetrahedral sites in hexagonal close packing or hcp lattices formed by the identical spheres.

In a hcp structure, the arrangement of the third layer is the same as the spheres’ placement of first layer and covers all the tetrahedral voids. The hcp and fcc type packings of equal spheres are of the highest density with the highest symmetry. Though the denser packings are known; they, however, involve spheres of unequal size. Only a packing of non-spherical shapes, like honeycombs, is capable of occupying a hundred percent space.
In addition to the hcp and fcc arrangements, one more common lattice type also exists, called as body-centered cubic or simply the bcc lattice. The placement of the second layer opens the spheres of the first layer and the third layer is exactly eclipsed to the first layer. Each sphere is in contact with spheres of the first layer and four spheres of the third layer giving an overall coordination number of eight.

This arrangement can also be visualized as a derivative of a simple cubic unit cell in which eight spheres are present at the corners of the cube and one extra sphere is placed in the center. The packing efficiency of body-centered cubic packing is lesser than hcp or fcc lattice system and only 68% of the available volume is actually occupied.

Now, as we have studied the packing of equal spheres and the resulting void types, we are ready to discuss the crystal structure of some important binary and ternary compounds.
Fluorite or fluorspar is the mineral form of calcium fluoride, CaF$_2$. The unit cell of CaF$_2$ is shown below.

![Fluorite Crystal Structure](image)

The main features of this crystal structure are as follows:

1. The Ca$^{2+}$ ions are present in cubic close packing or fcc lattice in which they are present at all the corners and at the center of each face.

2. The F$^-$ ions are occupying all the tetrahedral sites.

3. The number of tetrahedral sites for the ccp packing of N spheres is 2N. This means that two tetrahedral sites are formed for each Ca$^{2+}$ ion. Now, because all the tetrahedral sites are occupied by F$^-$ anions, the stoichiometry of the compound becomes 1:2.

4. The coordination number of Ca$^{2+}$ is eight while each F$^-$ ion is surrounded by four calcium ions. The surrounding geometry of Ca$^{2+}$ ion is tetrahedral and of F$^-$ is cubical in nature. Therefore, the coordination number ratio of Ca$^{2+}$ and F$^-$ is 8:4.

The other common examples of this structural prototype are CuF$_2$, BaF$_2$, PbF$_2$, HgF$_2$, SrF$_2$. It is worthy to note that ideally packed samples are colorless but the mineral form of fluorite is usually deep in color, which is obviously due to the presence of F-centres. The high purity fluorite is a source of fluoride for the manufacturing of hydrofluoric acid, an intermediate source of most chemicals that contain fluorine. The transparent fluorites of high optical purity have low dispersion, and therefore, are used to make lenses with less chromatic aberration. This makes them valuable for the telescopes and microscopes devices.
Antifluorite (Na₂O)

Antifluorite is the mineral form of sodium oxide, the unit cell of antifluorite lattice is shown below.

![Structure of Na₂O](image)

The main features of this crystal structure are as follows:

1. The O²⁻ ions are present in cubic close packing or fcc lattice in which they are present at all the corners and at the center of each face.
2. The Na⁺ ions are occupying all the tetrahedral sites.
3. The number of tetrahedral sites for the ccp packing of N spheres is 2N. This means that two tetrahedral sites are formed for each O²⁻ ion. Now, because all the tetrahedral sites are occupied by Na⁺ anions, the stoichiometry of the compound becomes 2:1.
4. The coordination number of O²⁻ is eight while each Na⁺ ion is surrounded by four oxide ions. The surrounding geometry of O²⁻ ion is tetrahedral and of Na⁺ is cubical in nature. Therefore, the coordination number ratio of O²⁻ and Na⁺ is 4:8.

The other examples of this type of structure are Li₂O, K₂O, Rb₂O. It is worth noting that in this motif the positions of the anions and cations are reversed relative to their positions in CaF₂, with sodium ions tetrahedral coordinated to 4 oxide ions and oxide cubically coordinated to 8 sodium ions. The Na₂O is a primary component of windows and glasses though it is added in the form of "soda" (Na₂CO₃). The Na₂O does not exist in glasses explicitly since glasses are cross-linked polymers of complex profile. The Na₂CO₃ also serves as a flux to lower the temperature for melting the silica. The melting temperature of soda glass is much lower than pure silica but has a slightly higher value of elasticity.
Rutile (TiO$_2$)

Rutile is the mineral form of titanium oxide, TiO$_2$. The unit cell of titanium oxide is shown below.

The main features of this crystal structure are as follows:

1. The Ti$^{4+}$ ions are present in distorted body-centered cubic close packing in which they are present at all the corners and at the center of the distorted cube. The unit cell cannot be labeled as cubic because all the three sides are not equal to each other. One of the edges is different from the other two. Hence, the structure is described as tetragonal in nature.

2. The Ti$^{4+}$ ions are surrounded by six O$^{2-}$ ions while each oxide ion is surrounded by three Ti$^{4+}$ ions, occupying all the tetrahedral sites. The coordinating geometry of Ti$^{4+}$ ion is octahedral and of O$^{2-}$ is trigonal in nature. Therefore, the coordination number ratio of Ti$^{4+}$ and O$^{2-}$ is 6:3.

The refractive index of rutile at visible wavelengths is highest than any known crystal, and also shows a particularly high dispersion and large birefringence. These properties make it useful for the manufacturing of some particular optical elements like polarization optics for longer visible and infrared radiations. Now because the rutile is also a large band-gap semiconductor, it has been in the limelight for the research area of finding its applications as a functional oxide for dilute magnetism and photocatalysis.
Antirutile is the mineral form of titanium nitride, Ti$_2$N. The unit cell of Ti$_2$N lattice is shown below.

The main features of this crystal structure are as follows:

1. The nitride ions are present in distorted body-centered cubic close packing in which they are present at all the corners and at the center of the distorted cube. The unit cell cannot be labeled as cubic because all the three sides are not equal to each other. One of the edges is different from the other two. Hence, the structure is described as tetragonal in nature.

2. The nitride ions are surrounded by six titanium ions while each titanium ion is surrounded by three titanium ions. The coordinating geometry of titanium ion is trigonal and of nitride is octahedral in nature. Therefore, the coordination number ratio of Ti and N is 3:6.

It is worth noting that in this motif the positions of the anions and cations are reversed relative to their positions in TiO$_2$ (rutile), with titanium ions trigonally coordinated to three nitride ions and nitrides are cubically coordinated to six titanium ions. Therefore, the name antrutile is assigned due to the reversal of the positions of nitride and titanium ions. Seldom, the antirutile structure is encountered where the metal and non-metals have changed places. The number of formula units present per unit cell is two, same as in case rutile structure.
The mineral cristobalite has the same structural formula to quartz i.e. SiO$_2$, but a different crystal structure. The cristobalite phase is stable above 1470°C (β–Cristobalite), but can also be crystallized metastably at lower temperatures in α–Cristobalite. The crystal structure of the two forms can be discussed as:

1. β–Cristobalite: The unit cell of this high-temperature form is shown below.

![Structure of β–Cristobalite](image)

The main features of this crystal structure are as follows:

1. β–cristobalite crystallizes in the tetragonal lattice in which silicon atoms are present at all the corners and at four faces unit cell.

2. The oxygen atoms are surrounded by two silicon atoms while each silicon atom is coordinated by four oxygen atoms. The coordinating geometry of silicon ion is tetrahedral and of oxygen is V–shaped in nature. Therefore, the coordination number ratio of Si and O is 4:2.

3. The number of formula units present per unit cell is 4.

Cristobalite is found as white spherulites or octahedra in acidic volcanic rocks and in converted diatomaceous deposits in California.
2. $\alpha$–Cristobalite: The unit cell of this high-temperature form is shown below.

The main features of this crystal structure are as follows:

1. $\alpha$–cristobalite crystallizes in the tetragonal lattice in which three silicon atoms are present inside while two silicon atoms are situated at two opposite faces unit cell.

2. The oxygen atoms are surrounded by two silicon atoms while each silicon atom is coordinated by four oxygen atoms. The coordinating geometry of silicon ion is tetrahedral and of oxygen is V–shaped in nature. Therefore, the coordination number ratio of Si and O is 4:2.

3. Like $\beta$–cristobalite, the number of formula units presents per unit cell is also 4.

The high temperatures $\alpha$–cristobalite form transforms into $\beta$–cristobalite if it is cooled below 250°C at ambient pressure. This transition is variously called the low-high or $\alpha$ – $\beta$ transition. In the transitioning $\alpha$–$\beta$ phase, only one of the three degenerate cubic crystallographic axes preserve a 4-fold axis of rotation in the tetragonal phase. Moreover, various twins can form within the same grain due to the arbitrary choice of axis. The coupling of discontinuous nature of the transition with different twin orientations can cause significant mechanical damage to the substance in which the cristobalite phase is present and that pass recurrently through the transition temperature.
Cadmium iodide is a layered lattice of cadmium and iodine with formula \( \text{CdI}_2 \). It is pretty much notable for its lattice profile, which is quite common for the \( \text{MX}_2 \) type compounds with strong polarization effects. The unit cell of \( \text{CdI}_2 \) is shown below.

The main features of this crystal structure are as follows:

1. In cadmium iodide, the \( \text{I}^- \) anions form a hcp arrangement, while the \( \text{Cd}^{2+} \) cations fill all of the octahedral voids in the alternate layers.

2. Each \( \text{Cd}^{2+} \) ion is surrounded by six iodide ions while each \( \text{I}^- \) is coordinated by three cadmium cations. The coordinating geometry of cadmium ion is octahedral and of iodide ion is a trigonal pyramid in nature. Therefore, the coordination number ratio of \( \text{Cd}^{2+} \) and \( \text{I}^- \) is 6:3.

3. The resultant structure comprises of a layered lattice in which the \( \text{Cd}^{2+} \) ions are occupying all octahedral sites but in between the alternate layers of \( \text{I}^- \). It can be visualized as if the cadmium ions layer is sandwiched between the two layers of iodide ions. Moreover, these sandwiched are piled over each other in such a way that the upward iodide ion layer of one sandwich is in contact with the downward iodide ion layer of the other sandwich. The same holds for the downward iodide-ion layer. This same basic structure is found in many other salts and minerals. This can be depicted as:
4. Cadmium iodide is bonded mostly in ionic fashion but does have partial covalent character too.

The other examples of this type of structure are PbI₂, MgI₂, TiI₂, V₁I₂, TiCl₂, V₁Cl₂, CoI₂, FeI₂, Mg(OH)₂, Ni(OH)₂ and Ca(OH)₂. Cadmium iodide is used in photography, electroplating, lithography and the synthesis of phosphors.
Bismuth iodide, BiI₃, is a layer lattice of bismuth and iodine. It is notable for its crystal structure, which is typical for MX₃ type compounds. The unit cell of BiI₃ is shown below.

The main features of this crystal structure are as follows:
1. Bismuth iodide adopts a distinctive crystal structure, with I⁻ occupying a hcp lattice while bismuth centers occupy either none or two-thirds of the octahedral sites in the alternating layers. Hence, we can say that one-third of all octahedral sites are actually occupied.
2. Each Bi³⁺ ion is surrounded by six iodide ions while each I⁻ is coordinated by two bismuth cations. The coordinating geometry of bismuth ion is octahedral and of iodide ion is V-shaped in nature. Therefore, the coordination number ratio of Bi³⁺ and I⁻ is 6:2.
3. The resultant structure consists of a layered lattice. The $\text{Bi}^{3+}$ ions are occupying one-third of all octahedral sites but in between the alternate layers of $\Gamma$. However, only two-thirds of all octahedral voids in every other layer are actually occupied. It can be visualized as if the bismuth ions layer is sandwiched between the two layers of iodide ions. Moreover, these sandwiched are piled over each other in such a way that the upward iodide ion layer of one sandwich is in contact with the downward iodide ion layer of the other sandwich. The same holds for the downward iodide-ion layer. This can be depicted as:

![Layered Structure of $\text{BiI}_3$](image1.png)

Figure 14. The layered lattice of $\text{BiI}_3$ crystal system.

4. The number of formula units present per unit cell of bismuth iodide is six.

5. The third side of the trigonal (hexagonal) lattice is approximately three times to that of the remaining two sides which are equal to each other.

The $\text{BiI}_3$ crystal belongs to a class of layered lattices of heavy metal semiconductors with fascinating anisotropic optical and electronic properties. The single crystals and thin films of bismuth iodide have been studied for X-ray imaging due to the relatively wide bandgap, high mass density and high atomic numbers of the constituent elements. It can also be used as hard radiation detectors. Moreover, because $\text{BiI}_3$ can be processed in the solution phase; cost-efficient, large-scale device fabrication could be facilitated.
The rhenium oxide or ReO$_3$ is a reddish inorganic solid with a metallic luster, which looks like copper. It is the only trioxide of group seven which is stable. The unit cell of ReO$_3$ is shown below.

The main features of this crystal structure are as follows:

1. Rhenium oxide crystallizes with a primitive cubic unit cell. Re atoms are present at all the corners while the oxygen atoms are situated center of at all the edges.

2. Each Re atom is surrounded by six oxygen atoms while each O atom is coordinated by two rhenium atoms. The coordinating geometry of rhenium atom is octahedral and of oxygen atom is linear in nature. Therefore, the coordination number ratio of Re and O is 6:2.

3. The number of formula units present per unit cell is one.

4. The octahedron units, ReO$_6$, share corners to form the 3-dimensional structure.

5. The ReO$_3$ structure is similar to perovskite (ABO$_3$), just large A cation absents at the unit-cell-center.

Rhenium trioxide finds some use in organic synthesis as a catalyst for amide reduction. Rhenium trioxide (ReO$_3$) is a thermally stable but highly insoluble substance that is quite suitable for optic, glass and ceramic based other devices.
Manganese oxide is an inorganic solid of manganese and oxygen. Mn₂O₃ generally exists in two forms, α-Mn₂O₃ and γ-Mn₂O₃. The heating of MnO₂ in the air at below 800 °C produces α-Mn₂O₃ (higher temperatures produce Mn₃O₄) while γ-Mn₂O₃ can be produced by oxidation followed by dehydration of Mn(OH)₂. The crystal structure of the two forms can be discussed as:

1. α-Mn₂O₃: The unit cell of α-Mn₂O₃ crystal form is shown below.

The main features of this crystal structure are as follows:
1. The crystallization of α-Mn₂O₃ takes place in an orthorhombic lattice with five different octahedral coordinative environments around manganese ions.

2. Each Mn³⁺ ion is surrounded by six oxide ions while each O²⁻ ion is coordinated by four metal ions. The coordinating geometry of all five types of manganese ions is distorted octahedra and of all the six types of oxide ions are distorted tetrahedral in nature. Therefore, the coordination number ratio of Mn³⁺ and O²⁻ is 6:4.

3. The number of formula units present per unit cell is 16.

4. α-Mn₂O₃ has the cubic bixbyite structure, which is an example of a C-type rare earth sesquioxide.

The bandgap emission of nanocrystalline α–Mn₂O₃ is important due to their applications as ultra-violet (UV) emitters.
2. \( \gamma\text{-Mn}_2\text{O}_3 \): The unit cell of \( \gamma\text{-Mn}_2\text{O}_3 \) form is shown below.

The main features of this crystal structure are as follows:

1. The crystallization of \( \gamma\text{-Mn}_2\text{O}_3 \) takes place in a cubic lattice with two different octahedral coordinative environments around manganese ions.

2. Each Mn\(^{3+}\) ion is surrounded by six oxide ions while each O\(^{2-}\) ion is coordinated by four metal ions. The first type coordinating geometry around manganese ions is distorted octahedra while the second type coordinating geometry around manganese ion is a perfect octahedron. However, only one kind of coordinative environment around oxide ions is observed with a distorted tetrahedral symmetry in nature. Therefore, the coordination number ratio of Mn\(^{3+}\) and O\(^{2-}\) is 6:4.

3. The number of formula units present per unit cell is 16.

4. \( \gamma\text{-Mn}_2\text{O}_3 \) has a structure related to the spinel structure of Mn\(_3\)O\(_4\) where the oxide ions are cubic close-packed. This is similar to the relationship between \( \gamma\text{-Fe}_2\text{O}_3 \) and Fe\(_3\)O\(_4\).

\( \gamma\text{-Mn}_2\text{O}_3 \) is ferrimagnetic with a Neel temperature of 39 K and nanoparticle form has found a great deal of interest for applications in biology and material science.
Corundum is a crystalline state of $\text{Al}_2\text{O}_3$ typically having traces of titanium, vanadium, iron, and chromium in general. The corundum is a rock-forming mineral. It is a transparent material naturally but can show many colors when the impurities are present. The transparent specimens are used as gems, called padparadscha if pink-orange and ruby if red; while the remaining colors are called sapphire in common, e.g., green sapphire for a greenish specimen.

The main features of this crystal structure are as follows:

1. $\alpha$-$\text{Al}_2\text{O}_3$ crystallizes in the trigonal lattice in which oxide ions form a slightly distorted hcp, in which two-thirds of the voids between the octahedral sites are occupied by aluminum ions.

2. Each $\text{Al}^{3+}$ ion is surrounded by six oxide ions while each $\text{O}^{2-}$ ion is coordinated by four aluminum ions. The coordinating geometry of $\text{Al}^{3+}$ is distorted octahedral and of oxide, the ion is distorted tetrahedral in nature. Therefore, the coordination number ratio of $\text{Al}^{3+}$ and $\text{O}^{2-}$ is 6:4.

3. The number of formula units present per unit cell is six.

Besides its use as a valuable gem, corundum mineral also finds some use as an abrasive due to the extreme hardness of the material (9 on Mohs hardness scale). It is used for grinding optical glass and for polishing metals and has also been made into sandpapers and grinding wheels.
Perovskite

The perovskite is an oxide mineral of calcium titanium with formula CaTiO$_3$. The mineral was found by Gustav Rose in the Ural Mountains of Russia in 1839 and is also named after a Russian mineralogist Lev Perovskite. The unit cell of perovskite is shown below.

![Unit Cell of Perovskite (CaTiO$_3$)](image)

Figure 19. The unit cell of the perovskite crystal system.

The main features of this crystal structure are as follows:

1. CaTiO$_3$ crystallizes with a cubic unit cell in which Ti atoms are present at all the corners while the oxygen atoms are situated center of at all the edges. The large Ca$^{2+}$ cation is present at the center of the unit cell.

2. Each Ti atom is surrounded by six oxygen atoms while each O atom is coordinated by two titanium atoms. The coordinating geometry of rhenium atom is octahedral and of oxygen atom is linear in nature. Therefore, the coordination number ratio of Ti and O is 6:2. Furthermore, the calcium cation is surrounded by twelve oxygens.

3. The octahedron units, TiO$_6$, share corners to form the 3-dimensional structure.
4. The number of formula units present per unit cell is one.

5. The structure of perovskite is adopted by many other oxides which have the ABO$_3$ formula.

6. The relative size different ions, required for stability of the cubic lattice are pretty much inflexible; therefore, very slight distortion and buckling can generate many lower-symmetry distorted versions, with coordination numbers of B cations. A cations or both are decreased. The tilting of BO$_6$ polyhedra reduces the coordination of an undersized cation A from twelve to as low as eight. Conversely, off-centering of an undersized cation B within its polyhedral unit allows it to attain a stable bonding pattern. The resulting electric dipole is accountable for the ferroelectricity possessed and shown by some perovskites like BaTiO$_3$ which are distorted in profile.

7. The tetragonal and orthorhombic crystal phases are the most common non-cubic types.

8. The possibility of disordered and ordered variants results in some complex perovskite kinds which contain two dissimilar B-site cations.

Perovskite structures possess many intriguing and interesting properties from theoretical as well as the application viewpoint. Massive magnetoresistance, superconductivity, ferroelectricity, charge ordering, high thermos-power, spin-dependent transport and the interplay of magnetic, structural and transport properties are the most commonly observed features in this class. These compounds are used as catalyst electrodes and sensors in some types of fuel cells and are good candidates for spintronics applications and memory devices.
Ilmenite is an oxide mineral of titanium and iron with formula FeTiO$_3$. It is a weakly magnetic steel-gray or black solid material. The unit cell of Ilmenite is shown below.

The main features of this crystal structure are as follows:

1. FeTiO$_3$ crystallizes in a trigonal crystal system which can be considered as an ordered imitative of the corundum structure. In corundum, all cations are the same but in FeTiO$_3$, the Fe$^{2+}$ and Ti$^{4+}$ ions occupy alternating layers, perpendicular to the trigonal c-axis. Ilmenite is paramagnetic due to high spin ferrous centers.

2. Each Ti$^{4+}$ and Fe$^{2+}$ ion is surrounded by six oxide ions while each O$^{2-}$ atom is coordinated by two Ti$^{4+}$ and two Fe$^{3+}$ ions. The coordinating geometry of titanium ion and ferrous ion is distorted octahedral and of oxide ion is distorted tetrahedral in nature. Hence, the coordination number ratio of Ti$^{4+}$, Fe$^{3+}$ and O$^{2-}$ ions is 6:6:4.

As far as the commercial importance is concerned, the ilmenite is the best ore for Ti. It is the primary source of TiO$_2$, which is used in fabrics, paints, paper, food, plastics, cosmetics and sunscreen.
Calcite

The carbonate mineral calcite is the most stable polymorph of CaCO₃ (calcium carbonate). The word calcite is a derivative of German word calcit, a term coined in the nineteenth century from the Latin for lime, and the suffix -ite for minerals. The unit cell of Ilmenite is shown below.

Figure 21. The unit cell of calcite crystal.

The main features of this crystal structure are as follows:

1. CaCO₃ crystallizes in a trigonal (hexagonal) crystal system in which layers of Ca²⁺ metal ions are in alternation with stacks of carbonate layers. The carbonate layers are made-up of flat triangular-shaped CO⁻³ ions, with a central carbon surrounded by three oxygens at each corner of a triangle. This triangular structural unit is the key component in the trigonal symmetry of this mineral group.
2. Each Ca\(^{2+}\) ion is surrounded by six oxygen atoms while the carbon atom of carbonate ion is coordinated by the oxygens in a trigonal fashion. However, each oxygen is coordinated by two Ca\(^{2+}\) ions and one C atom. The coordinating geometry of calcium ion is octahedral and of carbon is trigonal in nature. Hence, the coordination number ratio of Ca\(^{2+}\), C and O ions is 6:3:3.

The optical calcite of very high-grade was used in the second world war (WWII) for gun sights, specifically in bomb sights and anti-aircraft artillery. Also, various experimental studies have been carried out to use calcite for a cloak of invisibility. The calcite precipitated microbiologically, has a wide range of applications, like soil-stabilization, soil remediation and concrete repair. Calcite, obtained from an 80-kg sample of Carrara marble, is used as the IAEA-603 isotopic standard in mass spectrometry for the calibration of C\(^{13}\) and O\(^{18}\).
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Other Books by the Author

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