Chapter 18

Properties of explosives

18.1 INTRODUCTION

The sole purpose of drilling blastholes is to fill them with explosives and blast them so that the shock wave formed, the gases generated and the heat evolved by the explosion after blasting the holes causes fragmentation of the rock mass. Thus, for blasting, the most important material is explosive.

This chapter is devoted to giving broad information about different properties of explosives. Explosives used in large surface mines are the center of attention in the treatment of the topics. Tests carried out for evaluating the properties are dealt with separately in chapter 22.

18.2 EXPLOSIVES

Many materials burn. Whenever they burn, there is a layer in which the burning action is in progress. On one side of the layer the material is in burnt form. The burning layer propagates towards the other side where the material is yet to be burned. The speed of propagation of the front surface of this layer differs from material to material. Based on the speed of propagation, five classes of burnable materials viz. combustible, inflammable, highly inflammable, low explosives and high explosives are usually recognized.

Table 18.1 clarifies the differences in these classes.

For a chemical to be considered as an explosive, it must exhibit the following characteristics.

1 Rapid expansion
2 Quick liberation of heat
3 Fast reaction
4 Need to initiate the chain of reactions

Rapid expansion can occur when a material burns to evolve gases. Thus, an explosive must be largely composed of gas-forming elements viz. carbon, hydrogen, oxygen and nitrogen. Further, for the rate of burning to be high, either the particles must have sufficient oxygen content so the chemical action readily gives oxygen, or the size of particles of the material must be very fine so that the atmospheric oxygen is available in close vicinity of a very large surface area.

Table 18.1 Classes of burnable materials.

Class	*Classification norm (m/s)*	*Typical material*
Combustible	Less than 0.01	Wood, Coal
Inflammable	Between 0.01 to 1	Kerosene, Paraffin
Highly Inflammable	Between 1 to 700	Petrol, Sulfur, Magnesium
Low Explosive	Between 700 to 2000	Black Powder
High Explosive	More than 2000	Nitroglycerin, TNT

Coal burns slowly in atmospheric air. If it is finely powdered it can burn in air very rapidly. If it is mixed with liquid oxygen it can burn violently and cause an explosion.

Quick liberation of heat in the chemical reaction can occur depending upon the composition of the material. The gases formed in the chemical reaction expand and have devastating effect only when quickly-released intense heat is available.

A kilogram of coal has five times the calorific value of one kilogram of nitroglycerin. However, detonation of nitroglycerin causes an explosion and gives much higher shattering effect than the slow burning of coal.

Rapid expansion of the material and quick liberation of gases can take place only when the chemical reaction takes place very rapidly.

For a chemical to be considered as an explosive, the explosion must occur only when an instance designed by a human occurs. Without such a characteristic the explosive cannot be very useful.

The process of very rapid burning of the low explosives is called deflagration, whereas the process of lightning-fast burning of high explosives is termed detonation.

Low explosives do cause a heavy push or powerful lift of the material that surrounds them but do not cause a shatter. Often, low explosives are mixtures of a combustible substance and an oxidant that decomposes rapidly to give a high quantity of oxygen for the quick burning.

High explosive materials decompose very rapidly through detonation under certain circumstances to evolve a huge volume of gases, extremely high quantity of heat, rapidly traveling shock waves in atmospheric gases as well as the ground rock mass, light, deafening noise and hazardous flyrock.

The build-up of pressure on the walls of a blasthole upon blasting low and high explosives is shown in Figure 18.1.

In this book we will be concerned with high explosives as they are used for rock blasting.

High explosives are further classified as shown in Figure 18.2.

Primary explosives are very easily influenced by heat, friction or shock to cause detonation. Commonly used primary explosives are mercury fulminate, lead styphnate and lead azide. These are also termed as initiating explosives.

PETN is a benchmark explosive. All explosives more sensitive than PETN are primary explosives. Secondary explosives are relatively insensitive to heat, shock or friction. They are also called base explosives. Since they are not easily influenced by

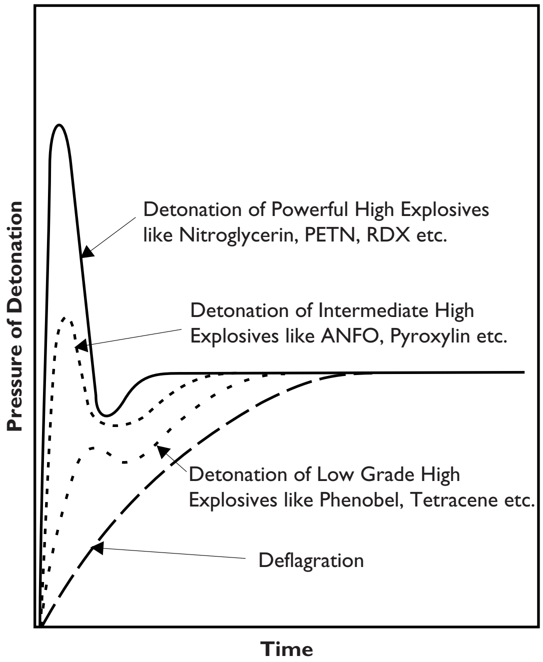

Figure 18.1 Build-up of pressure on the walls of blasthole.

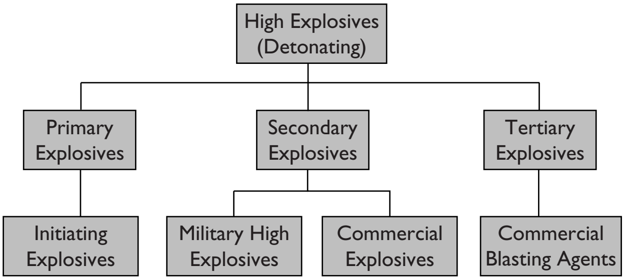

Figure 18.2 Classification of high explosives.

heat, friction or shock, they can be cautiously used in large quantities during warfare as well as rock blasting.

Some secondary explosives may burn when exposed to heat or flame in small, unconfined quantities, but detonation can occur. Secondary explosives usually need a small device containing a very small quantity of primary explosive for their detonation.

Most of the secondary explosives are chemical compounds rather than mixtures. Explosives, such as dynamite, TNT, PETN, RDX, HDX etc., are mainly used for warfare activities. Some of these, particularly dynamite, were used for rock blasting in the early days but now they are being replaced by tertiary explosives.

Tertiary explosives are those which are very insensitive to shocks. They cannot be reliably detonated by a limited quantity of primary explosive. Therefore, the detonation device used for them contains a small quantity of secondary explosives. Explosives in a confined state that cannot be detonated by means of test blasting cap no. 8 are classified as tertiary explosives.

Tertiary explosives are also called blasting agents.

Tertiary explosives contain primarily an inorganic nitrate and a carbonaceous fuel. For certain purposes they also contain non-explosive substances like powdered aluminum.

The most commonly used tertiary explosive is ANFO. Almost 80% of mining blasts are made by using it. ANFO is actually a mixture of ammonium nitrate and fuel oil. Slurry or "wet bag" explosives are also tertiary explosives.

Apart from the above classification, explosives are also classified on other criteria such as their consistency or form.

Permissible explosive is a term used to refer to low explosives which are somewhat freely permitted for use. They are often used for making fire crackers and entertainment fireworks.

Manufacturers add several other ingredients to the explosives for some specific purposes. These include combustibles, oxygen carriers, antacids, absorbent and antifreeze.

Table 18.2 Chemicals used in explosives and fireworks.

Ingredient	*Formula*	*Purpose*
Ammonium Nitrate	$NH_4\ NO_3$	Explosive Base, Oxygen Carrier
Chalk/Calcium Carbonate	$CaCO_3$	Antacid
Charcoal or Lampblack	C	Combustible
Ethylene Glycol Dinitrate	$C_2H_4(NO_3)_2$	Explosive Base and Antifreeze
Kieselguhr	SiO_2	Absorbent
Lead Azide	$Pb(N_3)_2$	Primary Explosive
Lead Styphnate	$PbC_6H(NO_2)_3O_2$	Primary Explosive
Liquid Oxygen	O_2	Oxygen Carrier
Mercury Fulminate	$Hg(ONC)_2$	Primary Explosive
Nitrocellulose (Guncotton)	$(C_6H_7(NO_3)_3O_2)_n$	Explosive Base, Gelatinizing Agent
Nitroglycerin	$C_3H_5(NO_3)_3$	Explosive base
Paraffin	CnH_{2n+2}	Combustible
Pentaerythritol Tetranitrate (PETN)	$C_5H_8\ N_4O_{12}$	Explosive Base for Caps and Detonation Fuse
Potassium Nitrate	KNO_3	Oxygen Carrier
Sodium Nitrate	$NaNO_3$	Oxygen Carrier
Sulfur	S	Combustible
Tetranitro diglycerine	$C_6H_{10}\ N_4O_{13}$	Explosive Base and Antifreeze
Trinitrotoluene (TNT)	$C_7H_5\ N_3O_6$	Explosive Base
Zinc Oxide	ZnO	Antacid

A combustible is meant to burn and consume excess oxygen formed in the explosion so as to reduce the formation of poisonous gases such as nitrous oxide, nitrogen dioxide etc. due to their burning; they also lower the heat of explosion.

Oxygen carriers are meant to ensure complete oxidation of the carbon in the explosive. In this manner they inhibit the formation of carbon monoxide. Sometimes their purpose is to lower the heat of explosion and create a less efficient blast.

Antacids are added to an explosive compound to increase its long term storage life, and to reduce the acidic value of the explosive base, particularly nitroglycerin.

Absorbents, like saw dust, nut shells etc., are mixed with dynamite and some other explosives so as to hold the explosive base from exudation, seepage and settlement to the bottom of the cartridge or container.

Antifreeze is meant to lower the freezing point of the explosive.

Table 18.2 lists some chemicals and compounds used in making explosives and fireworks.

18.3 PROPERTIES OF EXPLOSIVES

Explosives have many distinct properties. They are summarized in Table 18.3.

18.3.1 Velocity of detonation

The velocity of detonation is the most important property of an explosive. It is a measure of the speed at which the detonation front moves.

The velocity of detonation depends upon composition of the explosive, density achieved in charging the blasthole, diameter of the blasthole, degree of confinement, presence of voids in the rock mass, rock mass temperature, and temperature generated at the initiation element of the detonators that are used for firing the explosive.

Different explosives have different velocities of detonation. Some military explosives have velocities of detonation reaching to 10300 m/s but explosives used in rock blasting have velocities of detonation ranging between 2000 to 7000 m/s.

Velocities of detonation of some explosives are given in Table 18.4.

If the explosive is filled in a blasthole by proper tamping or compressive force as recommended, the density of explosive in the blasthole increases. Similarly when cartridges of explosives are filled in the factory with higher compression and achieve higher density, the velocity of detonation increases with density of explosive. For example, the detonation velocity of ANFO at a density of 0.8 g/cc is about 3048 m/s and at a density of 1.2 g/cc it is about 4572 m/s.

For the same explosive, detonated in the same manner, the velocity of detonation increases with increasing hole diameter. Variation of detonation velocity with diameter of holes for some common explosives is shown in Figure 18.3.

It is very natural that detonation velocity depends upon the degree of confinement. If an explosive is detonated in a blasthole drilled in soft rock, it gives lower detonation velocity than that in a blasthole drilled in hard rock. This is due to the fact that the increase in the diameter of the blasthole is larger in the soft rock than in hard rock.

If the rock mass has voids or joints in it, the gases formed in the explosion first fill the voids and joints. Therefore, the pressure remaining for expansion of the blasthole is less. This reduces the velocity of detonation.

Table 18.3 Properties of explosives.

Explosive property	*Meaning*
Velocity of Detonation	Velocity in m/s at which the shock front of the detonation layer travels within the column of explosive.
Detonation Pressure	Pressure developed by detonation of the explosive in the detonation zone. It is usually measured in GPa.
Blasthole Pressure	Pressure exerted on the wall of the blasthole immediately after the detonation.
Strength	Total amount of energy released by the explosion in MJ for each kg of explosive. This includes the energy released in the form of heat as well as the pressure exerted by the gases generated in detonation.
Heat of Explosion	Total amount of heat released by the detonation in kcal for each kg of explosive.
Specific Gas Volume	Amount of gas generated by detonation of one kg of explosive under normal conditions.
Sensitivity	Possibility of causing detonation by such means as friction, pressure, heat etc.
Transport and Handling Safety	How easily the explosive can be handled and transported through different modes of transport.
Brisance Value	Brisance value indicates the shattering effect of the explosive.
Charging Density	Weight of the explosive in kg, contained in each liter volume of the blasthole.
Toxic Fumes	Volume of poisonous gases generated in terms of liters per kg of explosive detonated.
Water Resistance	Whether the properties of explosive remain unchanged by mixing the explosive with water.
Hygroscopicity	Hygroscopicity is a measure of water-absorbing capacity of an explosive.
Minimum Hole Diameter	What is the smallest diameter of blasthole in which the explosive can be charged and detonated to get the desired explosion effect.
Storage Life	How long the explosive can be stored in originally packed and unpacked condition without a change in it's properties.
Volatility	How much is the volatility of the explosive.
Material Coexistence	This is the ability of the explosive to coexist with other materials.

Table 18.4 Velocities of detonation of some explosives.

Explosive	*VOD (m/s)*	*Explosive*	*VOD (m/s)*
Lead Azide	4630	Nitroglycerin	7700
Mercury Fulminate	4250	Dynamite (65% Gelatine)	6500
Picric Acid	7350	Ammonium Picrate	7150
Trinitrotoluene (TNT)	6900	Black Powder	400
PETN	8400	Lead Styphnate	5200
RDX	8750	Nitrocellulose	4492
HMX	9100	Nitroglycol	8250

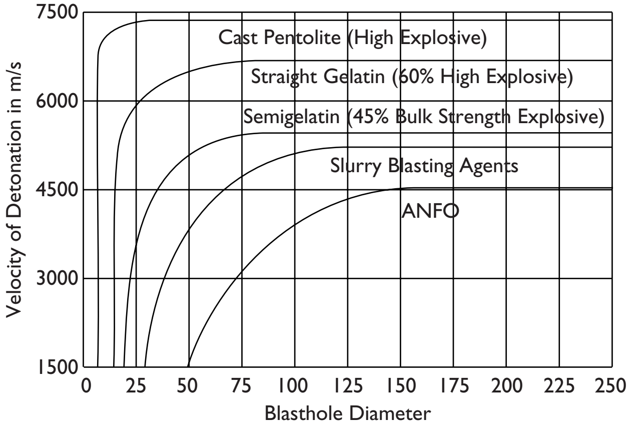

Figure 18.3 Increase in detonation velocity with blasthole diameter.

If the rock mass temperature is very low, the heat energy evolved in the detonation is absorbed by the surrounding rock to a much greater degree. This also reduces the velocity of detonation.

To initiate the detonation of the main explosive filled in a blasthole, some small volume of very high explosive material is used in the blasting cap i.e. detonator. If the temperature generated in such initiation element is lower, then the velocity of detonation is also less.

It must also be borne in mind that if the explosive is being used a long time after its manufacture, it loses some of its strength. Therefore, the velocity of detonation of such explosive is low.

18.3.2 Detonation pressure

Detonation pressure is the pressure developed immediately after the detonation of the explosive just behind the detonation front. It cannot easily be measured by any test but is usually estimated from the known properties of the explosive by using the following equation.

$$P_d = (1/2) * \rho_e * C_d * 10^{-9}$$

where

P_d = Detonation pressure in GPa
ρ_e = Density of explosive in kg/m^3
C_d = Velocity of detonation in m/s

Detonation pressure can also be calculated with reasonably good accuracy by analysis of chemical equations in the detonation process.

18.3.3 Blasthole pressure

Pressure exerted on the wall of the blasthole by the expanding gases formed in the detonation of the explosive is called the blasthole pressure. It is obviously dependent upon the detonation pressure generated by the explosive and the confinement of the explosive in the blasthole.

If the rock mass has cracks, joints, cavities etc., the blasthole pressure tends to be very low, but otherwise it is often of the order of 50% to 60% of the detonation pressure.

18.3.4 Strength

Strength of an explosive means the energy output by unit weight or unit volume of the explosive. Such strength is related to density and detonating velocity as well as heat and gas volume liberated in the detonation of the explosive.

The total energy E_t released by an explosion can be divided into two components, viz. shock energy E_s and bubble energy E_b. The shock energy is actually caused by the shock wave. It travels away from the place of its generation, i.e. the detonation zone, in the form of a strain wave. The bubble energy is caused by the heat evolved by the chemical reactions involved in the detonation process. Table 18.5 gives shock wave and bubble energy of some explosives.

Energy released in the detonation is either usefully consumed in fragmentation or wasted through heat, ground vibrations, light, sound waves and flyrocks.

The efficiency of an explosive depends upon the explosive formulation, blasthole parameters, rock mass conditions, environmental factors and the manner of blasthole charging.

Terms used in context of strength of explosive are:

1 Weight and bulk strength.
2 Absolute and relative strength.

18.3.4.1 Weight and bulk strength

The energy released by one unit weight of explosive, expressed in terms of the concurrent energy units is called weight strength measured as kcal/kg.

Energy released by one unit volume of explosive, expressed in terms of the concurrent energy units is called bulk strength, for example kcal/liter.

Table 18.5 Bubble, shock and total energy of some explosives.

Explosive name	*E_b in Cal/g*	*E_s in Cal/g*	*E_t in Cal/g*
Pentolite (50% TNT+ 50% PETN)	490	234	724
TNT	505	215	720
OCG	495	408	903
Emulsion	460	370	830
ANFO	500	340	840
Heavy ANFO	470	360	830

18.3.4.2 Absolute and relative strength

When the strength of an explosive is given in terms of kcal/kg or kcal/liter, it is called absolute strength because it is expressed in absolute units. It is difficult to measure strength of explosives in terms of absolute units. However, several tests enable the effect of the strength of an explosive to be assessed in an easily measurable way. Such tests give indicators of the strength of an explosive with respect to the strength of a common explosive, which is treated as 100. Strength expressed in terms of such an indicator is called relative strength.

18.3.5 Heat of explosion

The quantity of heat generated by an explosive after its detonation is a very important aspect of an explosion. It is treated in detail in chapter 19 on the thermochemistry of explosives.

18.3.6 Specific gas volume

As stated earlier, specific gas volume means the volume of gas evolved by explosion of one kg of explosive measured in liters. It obviously depends upon the chemical composition of the explosive. For an explosive to be very effective, it must generate an optimum volume of gas and an optimum quantum of heat upon detonation. This is because heat is required to expand the gases. Only after such expansion are the walls of the blasthole subjected to high pressures, which is one of the reasons for rock fragmentation.

More on the specific volume is contained in chapter 19 on the thermochemistry of explosives.

18.3.7 Sensitivity

Sensitivity of an explosive is a measure of the ease with which it can be detonated. An explosive is called very sensitive if it can be detonated very easily by such factors as heat, pressure or relatively low flame temperature.

Till they are consumed, explosives have to be handled very frequently. They have to be loaded in vehicles, godowns and blastholes. They require transportation from factory to godown to worksite etc. Naturally, an ideal explosive for use in rock blasting should be very insensitive so it does not detonate in all these storing or transportation processes.

Explosives used in olden days, e.g. nitroglycerin, were very sensitive and exploded even by gentle scratching. Thousands of miners must have died while handling explosives. Today explosives used for rock blasting are far less sensitive and thus have become far safer.

Sensitivity of an explosive can be reduced by adding certain components, like glass bubbles, to the main explosives material.

Sensitivities of explosives can be in relation with different type of disturbances as under.

1 Sensitivity to shocks
2 Sensitivity to friction

3 Sensitivity to heat
4 Sensitivity to detonator strength
5 Air gap sensitivity

Details are given below.

18.3.7.1 Sensitivity to shocks

When an explosive is subjected to shock, the molecules in the explosive move vigorously. In the process they impinge upon each other and the bonds that hold the atoms in the molecule together are disturbed. If the bonds are loose they break and release energy. This release of energy causes many more molecules to release energy. In a very short time the material detonates if the bonds in it are loose. Materials which contain nitrogen along with carbon, hydrogen and oxygen are usually very prone to detonate.

Sometimes the magnitude of the shock to which an explosive is subjected is too low to cause detonation but deflagration of the explosive occurs.

Shock sensitivity indicates how easily an explosive can detonate when it is subjected to a shock.

18.3.7.2 Sensitivity to friction

Friction always generates heat. If an explosive material rubs against another hard material, heat is generated and is imparted to the molecules of the explosive. The bonds between the atoms in the explosive molecules can withstand only a certain quantum of heat. If the heat imparted to explosive molecules exceeds this quantum, the bonds which have been holding the atoms together break and release energy. The consequent chain reaction leads to detonation or deflagration of the explosive material.

18.3.7.3 Sensitivity to heat

If an explosive is subjected to slowly increasing temperature by applying controlled heat to it, at a particular temperature it suddenly decomposes and starts deflagrating. This temperature is called the Ignition Temperature.

It is to be noticed that some explosives, like black powder, have an ignition temperature between 300 to 350°C but are detonated by even a tiny spark. As against this some industrial explosives have an ignition temperature between 180 to 230°C but need a detonator for causing detonation.

18.3.7.4 Sensitivity to detonator strength

This is more commonly known as cap sensitivity.

It is essential that an explosive should detonate only by use of a blasting cap of a certain strength, and not less than that strength. Further, such detonation of the explosive with the particular blasting cap must occur with 100% certainty. Thus, explosives are classified by the strength of the blasting cap.

18.3.7.5 Gap sensitivity

In many blastholes the explosives are in the form of cartridges. Similarly bulk explosives in polythene bags are also used when the blastholes have water seeping into them. Naturally there is a gap in the two explosive containers. In most situations it is desirable that once one cartridge or bag of explosive is detonated, the neighboring cartridge must also be detonated automatically by the shock wave generated by the first. This type of sensitivity naturally depends upon the gap between the explosives and hence it is termed the gap sensitivity.

From the viewpoint of storage of explosives, the gap sensitivity is measured in unconfined conditions. From the viewpoint of blast in a blasthole, the gap sensitivity is measured in confined conditions.

Gap sensitivity of an initiating explosive is the highest, often of the order of 8D or even more. For blasting agents it can be as low as 2D.

18.3.8 Handling and transport safety

While an explosive is being handled and transported it is subjected to shocks and elevated temperatures.

There are no specific indicators for handling and transportation safety of an explosive, because it can be correlated to different types of sensitivities like shock, friction, heat, gap etc.

Handling and transport safety is usually expressed in relative terms.

18.3.9 Brisance value

The term brisance originates from the French word briser which means to break or shatter. It is a measure of the rapidity with which an explosive builds the maximum pressure in its confined state.

Usually the explosives that have high detonation velocities also have high brisance values because the shock wave generated by them is highly energetic. If two explosives having equal energy output and confined in identical enclosures are exploded, the one with higher brisance value will break the casing into smaller fragments.

The brisance values of different explosives are estimated by the sand crush test. They are always relative to TNT.

One of the most brisant of the explosives is cyclotrimethylene trinitramine, i.e. RDX.

Explosives with high brisance value are very desirable in military explosives but in mine blasting this property is somewhat undesirable because such explosives create a large volume of very fine rock fragments and a lot of dust. This is one of the reasons why explosives like RDX, PETN, HMX etc. are not used for rock fragmentation in mines.

18.3.10 Charging density

Charging density means the density of the explosive as it exists in the blasthole. It is measured as mass per unit length. It is computed by the following equation.

$$\rho_c = 7.854 * 10^{-4} * D^2 * \rho_e$$

where

ρ_c = Charge density in kg/m
ρ_e = Density of explosive in g/cc
D = Diameter of blasthole in mm

In many charging methods the density achieved in charging the blasthole may be quite different than ρ_e. Hence in such cases it is more practical to calculate the charging density as

$$\rho_c = W/L$$

where

ρ_c = Charge density in kg/m
W = Weight of explosive in kg
L = Blasthole length in m over which the explosive is filled

If the charging density of an explosive in a blasthole is very low, it is very sensitive to the detonating cord. In such circumstances the detonation of the explosive starts from the top of the blasthole before the primer cartridge detonates and the blast becomes very ineffective.

When charging density is higher the molecules of the explosive are nearer to each other. Naturally the detonation of the explosive having higher charging density takes place in a shorter time, and the devastation effect of the explosion is greater.

Charging density depends upon many factors such as the density of explosive itself, the manner in which the hole is filled with explosive, the diameter of the blasthole and the inclination of the blasthole.

Several methods of charging a blasthole e.g. tamping, pellet loading, press loading, cast loading etc. are practiced.

When the diameter of the blasthole is larger it is possible to achieve a higher loading density by using the same explosive and the same loading method.

Depending upon the loading method used, a charge density of 80 to 99% of theoretical maximum density can be achieved.

When the molecules of explosive are densely packed they do not have much room to move with respect to each other. With this, sensitivity of the explosive reduces. However, beyond a certain value of density the crystals of the explosive get crushed and the sensitivity increases.

Some explosives can be pressed very heavily. Such pressing is called “dead-pressing”. Dead-pressed explosives do not detonate easily. Some do not detonate at all.

18.3.11 Toxic fumes

If an explosive produces only water vapor, carbon dioxide and nitrogen after its detonation, it can be looked upon as an ideal explosive because all these products are harmless.

However, the end products of most explosives contain the following ingredients in small quantities.

1 Non-toxic but irritating gases like methane (CH_4), ammonia (NH_4), acetylene (C_2H_2).
2 Poisonous gases, such as carbon monoxide (CO), nitrogen dioxide (NO_2), nitrous oxide (N_2O), nitrogen oxide (NO), sulfur dioxide (SO_2), hydrogen sulfide (H_2S).

Since all these products are in gaseous form they are called fumes.

Exposure of a human to these gases is dangerous. How some of these gases are hazardous is explained in Table 18.6.

Three limiting values of tolerable concentrations of these gases in atmospheric air have been recognized. The values are in ppm, meaning parts per million.

1 Threshold Limit Value (TLV) – the amount of exposure to a gas for an 8 hour day for 5 days a week without any harmful effects. This is also called the permissible exposure limit.
2 Ceiling Limit (CLV) – the amount of gas a person cannot be exposed to at any time.
3 Immediately dangerous to life or health (IDLH) – the maximum concentration of a gas at which one could escape without any irreversible health effects.

TLV, CLV and IDLH values for different gases likely to be evolved in a mine explosion are given in Table 18.7.

Table 18.6 Hazardous effects of poisonous gases on humans.

Poisonous gas	*Hazardous effect*
Carbon Monoxide	Since carbon monoxide has about 300 times higher affinity to hemoglobin than oxygen, when carbon monoxide enters the lungs, the hemoglobin molecules start supplying carbon monoxide to cells in the body rather than oxygen. Cells of the human brain need very high quantity of oxygen. They start dying quickly if they are not given oxygen. Therefore, carbon monoxide quickly results in brain death of a human.
Nitrogen Oxide	Nitrogen oxide, in very low concentrations, dilates blood vessels and increases blood supply in the human body. However, when it is inhaled it acts the same way as carbon monoxide. In addition it also generates more toxic free radicals.
Nitrogen Dioxide	When nitrogen dioxide is inhaled it goes into the lungs and immediately forms Nitric acid by combining with water molecules in the blood plasma. This causes pulmonary edema and heavy damage to the cells. Final outcome is death.
Hydrogen sulfide	Hydrogen sulfide causes paralysis of the respiratory system.
Sulfur Dioxide	Hazardous effects of sulfur dioxide are similar to those of nitrogen dioxide but it forms sulfuric acid rather than nitric acid.

Table 18.7 Exposure limits of poisonous gases.

Poisonous gas	*Formula*	*TLV (ppm)*	*CLV (ppm)*	*IDLH (ppm)*
Carbon Monoxide	CO	50	200	1500
Nitrogen Oxide	NO	20	?	100
Nitrogen Dioxide	NO_2	1	3	20
Hydrogen Sulfide	H_2S	10	15	300
Sulfur Dioxide	SO_2	5	10	100

Depending upon the quantity of undesirable toxic gases formed during detonation, the explosives are given fume class ratings. If an explosive produces a small quantity of gases, it has a better rating.

For blasting in the open atmosphere, such as surface blasts, the fume classes are not as important as they are in a confined space. However, they should not be ignored in surface blasting operations.

The US Bureau of Mines recognizes two fume classes viz. A and B as specified in Table 18.8. This classification is applicable for permissible explosives and is based on the measurements of CO, NO, NO_2 and H_2S.

Another classification is stipulated by the Institute of Makers of Explosives. It has three classes viz. 1, 2 and 3 as shown in Table 18.9. This classification is applicable for non-permissible explosives. It is based only on measurements of CO and H_2S.

The factors which influence the volume of toxic fumes formed in an explosion are:

Insufficient charge diameter
Improper delay timings
Deterioration of explosive by water
Insufficient priming
Use of plastic liners or paper wrappers in blasthole

18.3.12 Water resistance

Water reduces the effectiveness of an explosive to a very great extent. This happens because one or more ingredients of the explosive dissolves in water and becomes ineffective.

Another way in which water can affect the process of explosion in a blasthole is the formation of hot spots. If the pressure exerted on the explosive by a water column in the blasthole is high, the size of air bubbles reduces by compression. Such

Table 18.8 Fume classes for permissible explosives (USBM).

	Noxious gases produced	
Fume class	*ft³/lb*	*l/kg*
A	<1.25	<78
B	1.25–2.5	78–156

Table 18.9 Fume classes for non permissible explosives (IMA).

	Noxious gases produced	
Fume class	*ft³/lb*	*l/kg*
1	<0.36	<22.5
2	0.36–0.75	22.5–46.8
3	0.75–1.52	46.8–94.9

compressed air is not easily usable in the process of explosion. Therefore, some portion of the explosive can become desensitized. This portion is called the hot spot.

In very low temperature regions, the water may cool a water-resistant explosive to such a low temperature that a much higher detonation energy is required to ensure its detonation.

Resistance of an explosive to water is measured in terms of the number of hours over which the explosive can remain submerged below water and still retain its ability to reliably detonate.

On the basis of results of tests carried out on samples, the manufacturers express water resistance of the explosive as Excellent, Very Good, Good, Limited or Poor.

18.3.13 Hygroscopicity

Hygroscopicity is the tendency of a substance to absorb moisture. Water is the strongest enemy of an explosive. It affects explosives in many ways as under.

1 Water forms a film around an explosive molecule and inhibits the effective transfer of heat, shock etc. Thus, velocity of detonation is reduced greatly.
2 The heat of explosion is quickly absorbed by water. It vaporizes but in the process the heat is lost and the effectiveness of the explosive in fragmentation reduces. In other words energy output is reduced.
3 Water can cause some undesirable chemical reactions with one or more components of the explosive, and in the process the explosive detonates very weakly or sometimes it does not detonate at all. This way the sensitivity of the explosive is reduced.
4 Some chemical reactions of water with an ingredient of the explosive give rise to some highly corrosive chemicals which severely affects the containers of explosive. This finally results in reduction of shelf life.

For all these reasons explosives must be made with only such ingredients which have very low hygroscopicity.

18.3.14 Storage life

Storage life, also called shelf life, of an explosive is measured in terms of the number of years over which it can be stored and used later without any loss or degradation of its properties.

Storage life depends upon the characteristics of the explosive as well as the storage place.

Explosives which contain radicals such as nitrites ($-NO_2$), nitrates ($-NO_3$) and azides ($-N_3$), are intrinsically under a state of stress. They are easily affected by external factors such as presence of heat, moisture, radiation and electromagnetic fields etc.

It is very difficult to ascertain the shelf life of any explosive by taking into consideration all these factors because they change with every storage place.

For most explosives products, a shelf life of one year can be taken for granted so long as their original packing is not broken. In most cases satisfactory performance can be expected from most products two, three, and even four years later. This is because the explosive manufacturers are over-cautious and usually do not stipulate a longer shelf life.

18.3.15 Volatility

Volatility means the ease with which the substance vaporizes. This obviously depends upon the temperature.

Higher volatility is an undesirable property of an explosive because if one or more components of the explosive reduces in its proportion after vaporization, the explosive may become dead or dangerous.

All mining explosives have insignificant volatility at the atmospheric temperatures at which they are stored or used.

Volatility has very significant importance in the case of military explosives, which have to be stored over a long period of time. The maximum allowed volatility for military explosives is 2 mL volume of gas per kg weight of the explosive in 48 hrs.

18.3.16 Material coexistence

An explosive may chemically affect certain materials or may be affected itself by certain materials if they are brought in contact with each other. Under such circumstances the explosive may become dead or dangerous. Thus, the two materials have very poor coexistence. Since explosives are supposed to be stored in the containers in which they are supplied, the data about their coexistence with the packing materials is not published but the manufacturer always verifies the safe coexistence between the explosive and packing material.

Coexistence gains more importance in the case of bulk explosives because when they are charged, they are in direct contact with the minerals in the rock mass.

There have been instances when ANFO loaded in the blastholes drilled in copper mines exploded prematurely. Later investigations revealed that ammonium nitrate, being a very strong oxidizer, chemically reacted with pyrite and oxidized it. In the process substantial heat was generated. This heat caused the rise in temperature to a level that detonation occurred.

18.3.17 Minimum hole diameter

When an explosive is charged in a blasthole and the detonation is initiated, the detonation layer moves away from the point of initiation. In a mine blast it is very essential that the movement of the detonation layer is neither discontinued nor diminished in any manner. For this objective to be achieved, the diameter of a blasthole cannot be less than a certain value called the critical diameter.

The critical diameter depends upon the chemical composition of the explosive, and to a much lesser extent the temperature as well as the thermal conductivity of the rock mass.

In general it can be said that the critical diameter is inversely proportional to the velocity of detonation. The mathematical relation between the two, however, includes constants that have to be determined by tests.

Table 18.10 Critical blasthole diameters.

Explosive	*Critical diameter in (mm)*
Cast Pentolite (High Explosive)	About 10
Straight Gelatin (60% High Explosive)	About 28
Semigelatin (45% Bulk Strength Explosive)	About 42
Slurry Blasting Agents	About 75
ANFO	About 100

Critical diameters of the blastholes for certain explosives as can be found from measurements of the velocity of detonation and their plots as in Figure 18.3. In the plot it can be seen that for an explosive the velocity of detonation remains unchanged beyond a certain blasthole diameter. In other words this is the maximum velocity of detonation.

Since there is no specific definition of critical diameter, it can be said the critical blasthole diameter of an explosive is the one where the velocity of detonation in the blasthole exceeds 90% of its maximum velocity of detonation.

Critical diameters of certain explosives arrived at on the above basis are given in Table 18.10.