

Glossary of Minerals

Introduction

This glossary of minerals is intended to bring together optical data on some of the minerals mentioned in the text but excludes data on most aggregates as these are already adequately covered in the literature. The mineral data given has been largely restricted to the type of information that can be gained from thin-section examination. However, in the cases of efflorescences and precipitates the appearance of the mineral in oil immersion has been included. Much of the data on cement and concrete minerals are widely scattered and can be difficult to access and where this is the case references are given. A synoptic listing is given in Highway Research Board (1972). In other cases the general references used are Winchell and Winchell (1951, 1964), Kostov (1968), Troger (1971) and Rigby (1948). For illustrations of textures in colour the reader is referred to McCrone and Delly (1973), Mackenzie *et al.* (1991), Mackenzie and Guilford (1980) and Campbell (1986).

A brief, simplified description of the optical constants and other terminology used in this glossary is given as an aid to the user. The symbols N , ε , ω , α , β , and γ used for the refractive indices have been chosen as they appear to be the ones most commonly used (Bloss 1966). For the reader who is unfamiliar with the practices of optical crystallography, Bloss (1966) is recommended as a simple and clear introduction to the subject.

Isotropic minerals: A limited group of minerals which only have one refractive index (n) and belong to the cubic crystal system. Glasses and amorphous substances are also isotropic and included in this group for convenience.

Biaxial minerals: The bulk of naturally occurring minerals belong to this group which is distinguished by having two optical axes and three refractive indices (α , β , γ). It consists of the triclinic, monoclinic and orthorhombic crystal systems.

α	The smallest refractive index
β	The intermediate refractive index
γ	The largest refractive index
$\gamma-\alpha$	Birefringence
$2V$	The optic axial angle
Sign	$2V$ is +ve when $\beta-\alpha$ is less than $\gamma-\beta$ and -ve when $\beta-\alpha$ is greater.

Uniaxial minerals: A more restricted group of minerals in which the crystals only have one optical axis and two refractive indices. The tetragonal and hexagonal (which includes trigonal) crystal systems belong to this group.

ω	Ordinary refractive index
ε	Extraordinary refractive index which may be greater or less than ω and determines sign
Sign	$\varepsilon > \omega$ optically positive, $\varepsilon < \omega$ optically negative
Bir	The positive difference between the two refractive indices

Sign of elongation: Applies to elongate crystals where one of the vibration directions is parallel to the length which is always the case for the hexagonal, tetragonal and orthorhombic systems. In some cases this may apply to the monoclinic system. However even in the monoclinic and triclinic systems the extinction angle of the index in relation to the length of the crystal may often be small and allow a sign of elongation to be assigned.

Length slow: The vibration direction of the higher refractive index is parallel or sub-parallel to the length and the sign is positive.

Length fast: The vibration direction of the lower refractive index is parallel or sub-parallel to the length and the sign is negative.

Colour: The colour of the crystal as seen in thin-section and the colour in hand specimen may be different and they should not be confused.

Interference colour: The colour seen under crossed polars in thin-section. The maximum interference colour occurs when the crystal is observed perpendicular to the optic plane. If the birefringence is known the interference colour can be estimated from the Michel-Levy scale or vice versa provided the thickness of the crystal is known. Due to differential absorption in some minerals anomalous interference colours occur which are diagnostic.

Interference figure: Conoscopic examination of a crystal under crossed polars allows determination of optical sign and estimation of 2V without the need to measure the refractive indices. Dispersion of the optical axes may also be observed under favourable circumstances.

Pleochroism: In plane polarised light some crystals vary in colour as they are rotated due to differential absorption of light. This can be an important diagnostic feature.

Relief: When a crystal is immersed in a fluid of identical refractive index its outline and details of relief disappear apart from colour fringes due to refraction at crystal edges. As the difference between the index of the immersion fluid and that of the crystal is increased the outline becomes darker and details of relief are highlighted. The amount of relief can be roughly estimated, that is low, medium or high, and whether the immersion fluid has a higher or lower index than the crystal can be determined. If the fluid is less than the crystal, relief is positive, and if its index is higher, the relief of the crystal is negative. In the mineralogical literature relief is quoted using an immersion index of 1.54 which has been adhered to in the data quoted in this glossary. Thin-sections of concrete are often mounted in epoxy resin of which the index can vary between 1.54 and 1.58 so allowance may need to be made for this change of index when estimating relief in thin-sections of concrete.

Examination of crystals in thin-section: It is possible to determine the optical properties of a crystal provided that it can be manipulated to measure its refractive indices. These properties are sufficient to identify the crystal unless it belongs to the cubic crystal system. However, in thin-section sufficiently precise measurement of refractive indices is rarely possible. In addition, many of the recrystallised products formed in hardened cement paste are too small to give interference figures so that the optic sign and 2V cannot be determined. In many cases observations are restricted to estimates of refractive indices and to relief, sign of elongation, birefringence, pleochroism and anomalous interference colours, crystal

Interference figure: +2V varies from 64–69°.

Relief: Relics stand out because of high positive relief.

Birefringence: Usually second-order colours as relic grains in concrete are often larger than 40 μm in size.

Form: Rounded grains, often in clusters set in the clinker matrix (Plates 1, 2, 3).

Cleavage: Poor prismatic cleavage.

Twinning: Lamellar structure is distinctive and nearly always present. For the discussion of lamellar structures observed see Campbell (1984).

Colour: Colourless, pale yellow, yellow, amber or shades of green dependent on substitution.

Occurrence: Larnite occurs naturally in high-temperature contact zones but is rare. Belite is the second most common mineral in Portland cement clinker and ranges from 10–60 per cent dependent on cement type.

Comment: In concrete, relic grains often consist of belite crystals with some adherent clinker matrix. The shape, birefringence and lamella twinning of belite are distinctive. Globules of belite are commonly found inside alite crystals.

XRD: 33-302: 2.790-97, 2.783-100, 2.745-83, 2.610-42. Also see Taylor (1990).

Aluminate phases (tricalcium aluminate, C_3A , alkali aluminate)

$3\text{CaO} \cdot \text{Al}_2\text{O}_3$	Isometric $n = 1.710$	Cubic
$\text{Na}_2\text{O} \cdot 0.8\text{CaO} \cdot 0.3\text{Al}_2\text{O}_3$ (alkali aluminate)	Biaxial -ve $\alpha = 1.702 \quad \gamma = 1.710$	Orthorhombic

Tricalcium aluminate typically contains a mixture of around 13 per cent of ferric, silicon, magnesium, sodium, potassium and titanium ions and in alkali aluminate up to 20 per cent. The alkali content of the cubic form is around 1 per cent and for the orthorhombic form 2–4 per cent which is less than required for NC_8A_3 (Taylor 1990).

Interference figure: –2V varies from 0 to 35°.

Relief: Stands out because of its high positive relief.

Birefringence: Nil to low.

Form: Cubic form typically fills interstices between crystals of belite and ferrite. Alkali aluminate occurs as tablets, laths and stavelike prismatic forms (Plate 1).

Twinning: May be present in alkali aluminate.

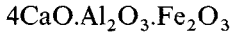
Extinction: Alkali aluminate has oblique extinction and is length slow.

Colour: Colourless in white cement. Tan to brown in Portland cements.

Occurrence: In ordinary Portland cement C_3A averages about 12 per cent but in special cements can range from 0–18 per cent. Production clinkers may contain both the cubic lath-shaped forms especially in high-alkali cements.

Comment: Individual particles of the aluminate phases are not observed in concrete. The brown matrix in relic grains commonly seen in concrete probably contains some aluminate phase. In many clinkers the aluminate and ferrite phases are often poorly differentiated and form the matrix in which the silicate phases are embedded. However, X-ray evidence clearly indicates that the matrix in commercial clinker is usually crystalline even when it appears undifferentiated by microscopic examination.

XRD: 38-1429: 2.699-100, 4.080-12, 1.5578-24. Also see Taylor (1990).

Ferrite phases (brownmillerite, C₄AF, ferrite solid solution)Biaxial -ve
 $\alpha = 1.98 \quad \beta = 2.05 \quad \gamma = 2.08$

Orthorhombic

The composition of ferrite can vary from C₆A₂F to C₆AF₂. However the typical composition of the ferrite phase in ordinary Portland cement is close to C₄AF containing 10 per cent magnesium, silicon and titanium ions replacing the ferric ion (Taylor 1990).

Interference figure: –2V is moderate.

Relief: Very high positive relief.

Birefringence: White to yellow of the first order.

Form: Either bladed, prismatic, dendritic, fibrous, massive or infilling. Form varies from bladed to dendritic and infilling as the cooling rate of the clinker is increased. In modern cement production with fast efficient clinker coolers the dendritic form is common (Plate 1).

Extinction: Crystals are length slow.

Colour: Brown to yellow. Pleochroic, varying from green to almost opaque.

Occurrence: Brownmillerite is a rare natural mineral. It ranges from 5–15 per cent in cements and is typically about 8 per cent in ordinary Portland cement. A ferrite phase of more variable composition constitutes 20–40 per cent of high-alumina cement.

Comment: Ferrite and belite phases are commonly observed in concrete where fragments of clinker have failed to hydrate either because they are too large or the hardened paste has not fully hydrated.

XRD: 32-226: 7.25-45, 2.673-35, 2.644-100, 1.8149-45.

Periclase (magnesium oxide)Isotropic
 $n = 1.736 (1.732 - 1.738)$

Cubic

Relief: High positive relief.

Form: Periclase occurs as small crystals or anhedral crystal aggregates. Synthetic crystals are usually rounded and vary in size and may give a ‘sugary’ appearance but may also be closely packed hexagons or octagons. In cement (Fig. 4.1) clinker is often dendritic.

Cleavage: Perfect, parallel to cube faces. Not always present but develop at high temperature.

Colour: Colourless when pure. In solid solution with FeO, colour changes from yellow to deep brown with increasing iron content. Also coloured red-brown due to minute crystals of magnesioferrite.

Occurrence: A fairly rare, relatively high-temperature mineral in dolomite contact zones which may be hydrated to brucite. Chief constituent of magnesite brick and present in dolomite and basic refractories. Periclase does not crystallise out in cement clinker until MgO exceeds 2 per cent.

Comment: Magnesia slowly hydrates in concrete and magnesium lime plasters and increases in volume. Thus magnesia is limited to 6 per cent or less in Portland cement to prevent unsoundness due to this volume increase. Where problems of unsoundness occur in Portland cement and hydrated magnesium lime they are monitored for unsoundness by the autoclave expansion test.

XRD: 4-289: 2.106-100, 1.489-52, 0.942-17, 0.860-15.

Monocalcium aluminate, calcium aluminate 12:7, gehlenite and wüstite

CaO.Al ₂ O ₃	Biaxial –ve	Monoclinic
	$\alpha = 1.643 \quad \beta = 1.655 \quad \gamma = 1.663$	
12CaO.7Al ₂ O ₃ .0–1H ₂ O (mayenite)	Isometric	Cubic
	$n = 1.61 - 1.62$	
2CaO.Al ₂ O ₃ .SiO ₂ (gehlenite)	Uniaxial –ve Tetragonal	
	$\omega = 1.669 \quad \varepsilon = 1.658$	
Fe(Ca)O (substituted wüstite)	Isometric	Cubic
	$n = 2.32$ less with substitution	

The typical composition of high-alumina cement is 40–50 per cent monocalcium aluminate, 20–40 per cent ferrite phase, together with smaller proportions of calcium aluminate 12:7, β -dicalcium silicate, gehlenite, pleochroite and wüstite (Taylor 1990). In transmitted light, most of the constituents are either glassy or dark coloured and almost opaque (Lea 1970). Apart from pleochroite, which stands out clearly because of its pleochroism, the relics of high-alumina cement in concrete tend to be undifferentiated as shown in Plates 8, 9 and 28. Monocalcium aluminate is strongly hydraulic.

XRD: CA: 34-440:	2.97-100, 2.52-35, 2.41-18.
Mayenite: 9-413:	4.89-95, 2.998-45, 2.680-100, 2.189-40.
Gehlenite: 35-755:	3.063-21, 2.856-100, 1.523-60, 1.299-25.
Wüstite: 6-615:	2.49-80, 2.153-100, 1.523-60, 1.299-25.

Pleochroite

6CaO.4Al ₂ O ₃ .MgO.SiO ₂	Biaxial +ve	Orthorhombic
	$\alpha = 1.669 \quad \gamma = 1.673-1.680$	

The simplified composition given above is variable and is modified by some substitution of calcium by ferrous ion and aluminium by the ferric ion (Taylor 1990).

Interference figure: +2V = 45° approximately.

Relief: High positive relief.

Birefringence: First-order colours modified by pleochroism.

Form: Fibrous to acicular.

Colour: Strongly pleochroic. Distinctively violet.

Occurrence: Occurs in high-alumina cements made under reducing conditions.

Comment: The strong violet pleochroism identifies this mineral which can be observed in some concretes made with high-alumina cement.

XRD: 11-212: 3.70-vs, 2.87-vvs, 2.76-vvs, 1.76-vs.

Melilite (åkermanite–gehlenite solid solution)

2CaO.Al ₂ O ₃ .SiO ₂ (gehlenite)	Uniaxial –ve	Tetragonal
	$\omega = 1.669 \quad \varepsilon = 1.658 \quad (n = 1.638 \text{ glass})$	
2CaO.MgO.2SiO ₂ (åkermanite)	Uniaxial +ve	Tetragonal
	$\omega = 1.632 \quad \varepsilon = 1.641 \quad (n = 1.641 \text{ glass})$	

Birefringence: Åkermanite is first-order grey which for åkermanite/gehlenite 60/40 is almost isotropic and then rises to first-order pale yellow for gehlenite. Melilite in slags often has a distinctive anomalous blue interference colour as shown in Plate 30.

Form: Short prisms or tablets often almost square in outline. In slags distinct zonation is often present.

Extinction: Parallel to edges of crystals.

Colour: Colourless.

Occurrence: Found in some contact zones, ores, and basic volcanic rocks. Formed by the action of lime on fire bricks and is constituent of many blastfurnace slags.

Comment: The refractive indices given above are for the synthetic minerals and the natural minerals will vary because they contain other ions. The indices given above for the synthetic glasses should not be used for the glasses found in blastfurnace slags.

XRD: Akermanite: 35-592: 3.087-25, 2.872-100, 2.478-15, 1.761-20

Gehlenite: 35-755: 3.0629-21, 2.845-100, 2.431-17, 1.754-25

The calcium silicate hydrates

The calcium silicate hydrates may be conveniently divided into three groups, namely (1) the hydrates that are found in hardened cement paste which has been cured at a temperature of less than about 60°C, (2) a range of hydrates that are either formed hydrothermally in autoclaved products and oil-well cements, geothermal grouts and other high-temperature applications and (3) in non-Portland cement systems such as sand lime bricks and refractories. In addition there is a wide range of calcium silicate hydrates that may be synthesised or are found naturally but these are outside the scope of this book.

Calcium silicate hydrate formed at less than 60°C

Calcium silicate hydrate gel, C-S-H(II). In older texts is often referred to as 'tobermorite' gel. The term CSH is often used without discrimination.

$9\text{CaO}\cdot 4\text{-}6\text{SiO}_2\cdot n\text{H}_2\text{O}$ of variable composition. The CaO/SiO₂ ratio may vary between 1.5 and 2.0 and typically is about 1.8 in mature pastes in concrete. However, the ratio measured depends on the method of sample preparation and may also vary from point to point within the paste on the microscale. The water content in a fully saturated mature paste is 42–44 per cent and in a paste dried at –79°C is in the range 20.4–22.0 per cent (Taylor 1990).

Optical properties: Properties observable are those of the cement paste. Transparent, coloured, isotropic although vague indefinite birefringence may be observed. Mottled and/or wavy appearance to the texture. Where pozzolanic admixtures are present and have removed most of the CH the texture appears to become darker and more featureless. Refractive index of a mature paste is around 1.5.

Appearance: In mortars and concretes the gel appears as an indefinite mass infilling the space and surrounding components such as CH, remnant cement grains, pores and aggregates. It may appear as 'hydration rims' around clinker particles which stand out from the indefinite mass of hydrate material. C-S-H(II) is colourless but because of its intimate mixture with the other hydrates appears coloured. The colour of the paste containing C-S-H(II) is brownish to yellow often with some green tints and may have a mottled appearance.

Physical properties: Density is 1.85–2.45 dependent on state of drying. A fully hydrated cement paste has a density of about 2.13.

Structure: A nearly amorphous gel consisting of chains of polymerised silicate anions. Polymerisation increases with curing temperature. The structural appearance of the gel observed by electron microscopy varies according to the age of the sample and method of sample preparation. Soon after mixing a cement with water the gel formed is fibrous or needle-like (type I) in appearance which soon changes to a honeycomb structure (type II). As curing proceeds the gel takes on a more massive appearance with equant grains (type III) and in the mature paste, that is at 28 days, becomes increasingly featureless (type IV) (Diamond 1986). The gel contains pores with equivalent radii between 0.6 and 1.6 nm and pores between gel particles which range from 1.6 to 100 nm. Although pore volumes are comparatively large, C-S-H(II) remains as a stable xerogel in concrete unless attacked by carbon dioxide.

Occurrence: Calcium silicate hydrate gel is formed from the hydration of the alite and belite phases, present in Portland cement. Both alite and belite react to form similar hydrates only differing in the amount of CH formed during hydrolysis. The gel is the main cementing phase present in all concretes cured below 60°C and is intimately mixed with the aluminate and ferrite hydrates and interspersed with crystallites of CH. The reaction between CH and pozzolanas in concrete produces a similar gel although the CaO/SiO₂ ratio may be reduced towards the lower end of the range.

Comment: The most important distinguishing feature is the association of the C-S-H gel with remnant cement grains as even in a fully hydrated cement paste some grains remain. The appearance of C-S-H gel in mortars and concretes is best examined by electron microscopy but this is not a routine petrographic procedure. Optical examination rarely produces any useful data.

XRD: 29-374: Diffuse peaks at 0.27-0.31 Å and a sharper peak at 0.182 Å. Peaks small and not well defined. Other peaks present usually due to CH. Often in hardened concrete only a broad shallow peak around the 0.3 Å area is observed and many of the peaks listed on Card no. 29-374 are absent. Peaks may become sharper as curing temperatures are increased, especially over 60°C.

Thermal analysis: TGA shows a continuous weight loss from 100°C to 500°C with smaller losses to 800°C. Usually superimposed on these weight losses is the weight loss due to the dehydroxylation of CH between 400 and 500°C. DTA does not give a useful diagnostic curve.

Infrared: Does not give useful diagnostic spectra.

The calcium silicate hydrates formed at elevated temperatures and from non-Portland cement systems

Unlike the calcium silicate hydrates formed from the hydration of Portland cement cured in the normal range of temperatures these hydrates are semi-crystalline to crystalline. However, with only one exception, they remain microcrystalline and require electron microscopy and X-ray analysis for their observation and identification. They may be conveniently grouped into the high-silica and high-calcium types formed under hydrothermal conditions and another group formed by heating concrete in the absence of moisture. Many of these calcium silicate hydrates also occur naturally. In addition there are other ranges of hydrates which can be synthesised or are found naturally (Taylor and Roy 1980, Coleman 1984). These are unlikely to occur in the types of building products encountered by the petrographer and are beyond the scope of this book.

The hydrothermal silicates in Portland cement concretes

	High-silica types	CaO/SiO ₂
C-S-H(I)	C ₅ S ₆ H ₉ approx.	0.83
11 Å tobermorite	C ₅ S ₅ H ₅	1.0
Anomalous tobermorite (incl. 0.5Al and 0.1Na)		0.76
Xonotlite	C ₆ S ₆ H	1.0
Gyrolite	C ₂ S ₃ H ₂	0.66
Truscotite	C ₇ S ₁₂ H ₃	0.58
	High-calcium types	
α-dicalcium silicate hydrate	α-C ₂ SH	2.0
Tricalcium silicate hydrate, (jaffeite)	C ₆ S ₂ H ₃	3.0
		Types formed on heating
9 Å tobermorite, (riversideite)	C ₅ S ₆ H ₂	0.83

Occurrence: The high-silica types. These calcium silicate hydrates are formed in hydrothermally cured Portland cement pastes containing ground quartz which is added to concretes used in autoclaved products. In practical terms the minimum temperature of formation for the 11 Å tobermorite starts between 130–150°C and this phase is stable up to 180°C. From 180–250°C anomalous tobermorite may persist by substituting Al and Na into the lattice. Otherwise the stable phase above 180°C is xonotlite which converts to the calcium silicate, wollastonite, above 600°C. In oil-well cements, where the composition is rich in βC₂S and ground quartz is used, truscotite forms in the temperature range 180–350°C. Gyrolite has also been reported in some hydrothermal cementing systems between 140–170°C and forms instead of tobermorite where a more reactive form of silica such as diatomite is used. Below 130°C, even when ground quartz is present, the α-dicalcium silicate hydrate may form together with C-S-H(I) and will only convert to 11 Å tobermorite after extended autoclaving or by increasing the temperature.

High calcium types. These hydrates form above 110°C where the cement does not contain the addition of ground quartz. Up to 180°C α-dicalcium silicate hydrate forms. It has low strength and is the only hydrate that grows large enough to become optically visible. Between 180–400°C tricalcium silicate hydrate is the stable phase. Like αC₂SH it is also a low-strength material.

The degree of crystallinity achieved and the phases formed are dependent both on temperature and the time of heat treatment. For commercial autoclaving, typically carried out at 160–180°C for up to 18 hours, the cement paste may only contain poorly crystalline C-S-H similar to 11 Å tobermorite. Similar phases will be formed for autoclaved products made from sand lime formulations. Where the concrete is steam cured at 60–100°C the phase formed will be C-S-H(II) but increased crystallinity may be detected by better definition of the X-ray diffraction peaks.

The effect of heating concrete, for instance by exposure to fire, is firstly to increase the crystallinity of the phases and then with increasing temperature to contract the layer spacing until above 300°C the 9 Å tobermorite is the major phase which persists to 700°C (Taylor 1957). There appears to be limited information on the composition of the phases in concretes

exposed to fire. Xonotlite is also found in boiler scales and lightweight heat-insulating materials.

Mineral descriptions: Mainly from Heller and Taylor (1956).

C-S-H(I) Probably similar to poorly crystallised natural material from Ballycraigie, Northern Ireland. Seemingly amorphous material with a flaky habit under SEM.

Orthorhombic, $n = 1.49\text{--}1.530$

$n = 1.494$ when $d = 2.00$, $n = 1.525$ when $d = 2.20$

11 Å tobermorite

Natural occurrence: Tobermory in Scotland, Northern Ireland and California. Minute radiating aggregates of fibres with distinctive silky lustre.

Orthorhombic, biaxial +ve, low 2V, both length slow and length fast
 $\alpha = 1.570$ $\beta = 1.571$ $\gamma = 1.575$ (Ballycraigie)

$n = 1.558$ and $1.545\text{--}1.565$ (for other samples)

$n = 1.55\text{--}1.565$ (synthetic material)

Density = 2.44.

Xonotlite

Natural occurrence: Tetela de Xonotla, Mexico. Usually fibrous, colourless to pink.

Monoclinic, biaxial +ve, low 2V, parallel extinction, length slow
 $\alpha = 1.578\text{--}1.586$ $\beta = 1.583$ $\gamma = 1.590\text{--}1.595$

Density = 2.7.

Truscotite

Natural occurrence: Benkulen, Sumatra. White, spheroidal aggregates with fibrous, platy structure and pearly lustre on cleavage.

Hexagonal, uniaxial -ve, parallel extinction, length fast.

Mean $n = 1.560$ $\omega < 1.55$, weak birefringence.

Density = 2.48.

Gyrolite

Natural occurrence: Skye, Scotland. Colourless, lamellar crystals, often in radial aggregates.

Hexagonal, uniaxial -ve, may appear biaxial with small 2V.

$\omega = 1.549$ $\varepsilon = 1.536$, or $\omega = 1.540\text{--}1.549$

Density = 2.39.

α -dicalcium silicate hydrate

Natural occurrence: Colourless, transparent laths or prisms, with parallel growths and twinning.

Orthorhombic, biaxial +ve, $2V = 68^\circ$, parallel extinction, length fast.

$\alpha = 1.614$ $\beta = 1.620$ $\gamma = 1.633$

Density = 2.8.

Tricalcium silicate hydrate

Natural occurrence: Very small, colourless, anisotropic prisms or broad fibres.

Hexagonal, parallel extinction, length slow.

$\alpha = 1.589$ $\gamma = 1.633$

Density = 2.56.

9 Å tobermorite (Riversideite)

Natural occurrence: Crestmore, California. Appearance similar to 11 Å hydrate. Orthorhombic, biaxial +ve, small 2V, both length slow and length fast.
 $\alpha = 1.600$ $\beta = 1.601$ $\gamma = 1.605$
 Density = 2.6.

Comment: Optically all the hydrates except for α C₂SH do not form large enough crystals to be identifiable under the microscope (Plate 21). However, Hadley grains (Barnes *et al.* 1978) are more common in the C-S-H matrix compared to concretes cured at normal temperatures. In geothermal samples exposed to downhole temperatures for up to nine months the hardened paste may contain a background of minute, diffuse, birefringent crystals which it is believed are the crystallised hydrates. After three months' exposure down a geothermal well at 160°C, grouts without ground quartz contained laths of α C₂SH measuring up to 30 μ m in length and 10 μ m in width which tended to form radial groups with optical properties as listed above (St John and Abbott 1987).

Under the SEM xonotlite is often fibrous, etc.

XRD: C-S-H(I):	12.5-vs, 3.04-vs, 2.80-s, 1.82-s (Taylor 1990).
11 Å tobermorite 45-1480:	11.3-100, 3.08-92, 2.972-70, 2.806-68.
Anomalous tobermorite.	No card. Spectrum similar to 11 Å tobermorite.
Xonotlite 29-379:	3.085-100, 2.828-50, 2.697-40, 1.9468-40.
Truscotite 29-382:	4.21-70, 3.141-100, 2.840-80, 1.839-70.
Gyrolite 12-217:	22.0-90, 11.1-70, 4.20-70, 3.160-100, 3.097-90, 2.834-70.
9 Å tobermorite 29-329:	3.59-17, 3.15-19, 3.014-100, 2.784-18.
Tricalcium silicate hydrate 29-375:	8.6-95, 2.998-85, 2.898-95, 2.834-100.
α -dicalcium silicate hydrate 29-373:	4.22-50, 3.302-45, 3.272-100, 2.816-45, 2.418-60, 2.606-45.

Thermal analysis: Refer to Ramachandran (1969).

The hydrogarnets (grossular, hydrogrossular, katoite, hibschite)

Grossular	3CaO.Al ₂ O ₃ .3SiO ₂	Cubic 1.734.
Hydrogrossular	3CaO.Al ₂ O ₃ .6H ₂ O - 3CaO.Al ₂ O ₃ .3SiO ₂	Cubic 1.604-1.734.
Katoite	3CaO.Al ₂ O ₃ .6H ₂ O - 3CaO.Al ₂ O ₃ .1.5SiO ₂ .3H ₂ O	Cubic.
Hibschite	3CaO.Al ₂ O ₃ .1.5SiO ₂ .3H ₂ O - 3CaO.Al ₂ O ₃ .3SiO ₂	Cubic 1.67-1.68.

Hydrogrossular is a solid solution series which mineralogically is identified as katoite and hibschite as given above. It is not an accepted mineral name. The refractive indices given will vary according to the composition.

Relief: Moderately high.

Birefringence: Hibschite may be weakly birefringent.

Twinning: Present in grossular.

Colour: Grossular ranges from colourless to coloured, similar to other garnets.

Hibschite is colourless and it is probable that in cementing systems the other hydrogrossulars are also colourless to white.

Occurrence: Grossular and hibschite occur naturally in contact altered limestones.

Comment: Minor quantities are formed from some composite cements. In Portland cement it is a minor and poorly crystalline hydrated phase. Larger quantities were produced by some older Portland cements and it is a normal hydration product of autoclaved cement-based materials (Taylor 1990). In cementing systems, if sufficient is present, it is detected by X-ray diffraction analysis and scanning electron microscopy.

XRD: Grossular 39-368: 2.962-35, 2.650-100, 2.418-18, 1.583-30.

Katoite 24-127: 5.13-90, 2.810-80, 2.295-100, 2.039-95.

Hibschite 45-1447: 3.072-50, 2.748-100, 2.244-60, 1.994-65.

Thermal analysis: Hydrogrossular decomposes at 200–250°C (Taylor 1990).

Merwinite



Biaxial +ve

Monoclinic

$$\alpha = 1.708 \quad \beta = 1.711 \quad \gamma = 1.724$$

Interference figure: Biaxial positive with $2V = \text{approx. } 70^\circ$.

Relief: Rather high.

Birefringence: Polarises in greys, whites and yellows. The maximum colour being first-order red.

Form: Crystals are granular or prismatic, tending to lozenge-shaped outline.

Cleavage: Poor.

Twinning: Polysynthetic twinning is common.

Extinction: Generally inclined, the maximum extinction angle is 36° .

Colour: Colourless.

Occurrence: Found in limestone contact zones. Occurs in blastfurnace slags.

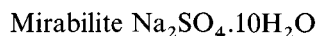
Comment: Can be distinguished by its weak birefringence, polysynthetic twinning and biaxial character. Merwinite is etched by nitric acid and stained by hydrofluoric acid.

XRD: 35-591: 2.756-26, 2.687-100, 2.671-65, 2.653-47.

The sulfate minerals

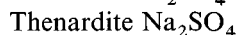
Mirabilite (glauber's salts, sodium sulfate deca-hydrate)

Thenardite (anhydrous sodium sulfate)



Biaxial -ve

Monoclinic



Biaxial +ve

Orthorhombic

Mirabilite $\alpha = 1.394 \quad \beta = 1.396 \quad \gamma = 1.398$

Thenardite $\alpha = 1.464\text{--}1.468 \quad \beta = 1.473\text{--}1.474 \quad \gamma = 1.481\text{--}1.485$

Interference figure: Mirabilite, $-2V = 76^\circ$. Thenardite, $+2V = 83^\circ$.

Relief: Mirabilite has high negative relief compared to thenardite.

Birefringence: Mirabilite gives first-order grey colours. Thenardite gives colours up to red of the second order.

Form: Mirabilite is commonly prismatic to acicular. As massive efflorescent crusts of interlocking fibres. Thenardite is pyramidal, short prismatic or basal plates.

Cleavage: Mirabilite has a perfect 100 cleavage. Thenardite has distinct basal cleavage.

Colour: Both minerals are colourless.

Occurrence: Mirabilite and thenardite are found associated with hot springs and salt lake deposits.

Comment: Mirabilite effloresces and converts to thenardite above 32°C. Occurs as fine silvery needles deposited on surfaces as an evaporation product of groundwater sulfate (St John 1982). Sometimes found as efflorescence on protected surfaces of brick and mortar.

XRD: Mirabilite 11-647: 5.49-100, 3.26-60, 3.21-75, 3.11-60.

Thenardite 37-1465: 4.657-71, 3.077-55, 2.784-100, 3.181-52, 2.648-52.

Thermal analysis: See Mackenzie (1970).

Ettringite (calcium aluminium sulfate hydroxide, high sulfoaluminate)

$\text{Ca}_6\text{Al}_2(\text{SO}_4)_3(\text{OH})_{12}\cdot 26\text{H}_2\text{O}$ Uniaxial – ve Pseudo hexagonal, trigonal

$\omega = 1.466$ $\varepsilon = 1.462$

Interference figure: Crystals usually too small to obtain an interference figure.

Relief: Moderate negative relief.

Birefringence: Maximum interference colour rarely above first order grey-white due to small dimension of needles.

Form: Always appears as needles which under SEM may prove to be rods. Often present as randomly crossed needles in pores and fissures. In very old weathered concretes may form massive curtain-like material in large fissures in which needles are difficult to observe. Needles rarely more than a few microns in cross-sectional dimension. In hardened cement paste, as opposed to cracks, pores and fissures ettringite is usually submicroscopic (Plates 25, 26).

Extinction: Parallel extinction.

Orientation: Needles are length fast.

Colour: Colourless.

Occurrence: Found in metamorphic limestones. Forms as initial hydration product in Portland cement concretes and as a recrystallisation product in concrete associated with movement of water and alkali-aggregate reaction. Can be formed by delayed reaction in steam-cured products. One of the products formed by sulfate attack on concrete. Important phase in some types of shrinkage compensating cements. Is present as one of the hydration products of super sulfated cement. Optical data from Lerch *et al.* (1929).

Comment: Ettringite may convert to thaumasite due to prolonged sulfate attack on concrete. Loses crystallinity at 100°C (Buck 1986) and may become amorphous if heated above 60°C (Taylor 1990). Excessive grinding in preparation for XRD analysis can cause anomalous results. Ettringite is prone to atmospheric carbonation (Grounds *et al.* 1988). The morphology of ettringite is affected by organic additions (Baussant *et al.* 1989). Ettringite can enter into solid solutions with hydroxyl and carbonate ions (Poellmann and Kuzel 1990).

XRD: 41-1451: 9.72-100, 5.61-76, 3.873-31, 2.569-29.

Thermal analysis: Strong endotherm at 125–130°C (Taylor 1990).

Infrared: see Bensted and Varma (1971).

Tricalcium aluminate monosulfate 12-hydrate (low sulfoaluminate, monosulfate)

$3\text{CaO}\cdot\text{Al}_2\text{O}_3\cdot\text{CaSO}_4\cdot 12\text{H}_2\text{O}$ Uniaxial – ve Hexagonal

$\omega = 1.504$ $\varepsilon = 1.488$

Interference figure: Crystals are too small to obtain a figure.

Relief: Moderate negative relief.

Birefringence: Maximum second-order red. In practice, crystals are too small for this colour to be obtained.

Form: Basal plates.

Extinction: Length slow.

Colour: Colourless.

Occurrence: Does not occur naturally. The final product of the reaction between the aluminate and sulfate phases in the hydration of Portland cement.

Comment: Low sulfoaluminate is not visible optically and must be observed by scanning electron microscopy. It is metastable with respect to ettringite which will reform if additional sulfate enters the system. Its composition is variable and complex. See Taylor (1990) for further details.

XRD: 12 hydrate 45-158: 8.9-100, 4.45-70, 2.190-40, 2.070-40.

14 hydrate 42-62: 9.55-100, 4.78-65, 2.753-30, 2.485-45.

Thermal analysis: See Taylor (1990).

Thaumasite (calcium carbonate silicate sulfate hydroxide hydrate)

$[\text{Ca}_3\text{Si}(\text{OH})_6 \cdot 12\text{H}_2\text{O}](\text{SO}_4)(\text{CO}_3)$ Uniaxial – ve Hexagonal
 $\omega = 1.504 \quad \varepsilon = 1.468$

Interference figure: Crystals usually too small to obtain an interference figure.

Relief: Relief varies with rotation of stage.

Birefringence: Maximum interference colour is first-order yellow but rarely above first-order white due to small dimension of needles (Plate 52).

Form: Needles; can be threadlike. May be present as overgrowths on ettringite.

Extinction: Needles length fast with parallel extinction.

Colour: Colourless.

Occurrence: Rare mineral found in altered limestones and basic rocks. Formed from solutions depositing calcite and zeolites in contact with anhydrite. Occurs in concrete and mortars due to sulfate attack (Crammond 1985) where it is favoured by temperatures of 0–5°C and humidities greater than 90 per cent. Close relationship between alkali-silica gel, ettringite and thaumasite claimed. Good literature reviews by Brouxel and Valiere (1992), Berra and Baronio (1987). Solid solution with ettringite and other data (Taylor 1990). Optical data from Erlin and Stark (1966). Occurs as replacement of ettringite in cement mortars in contact with gypsum or lime gypsum mortars (Ludwig and Mehr 1986).

Comment: Appears similar to ettringite and is often misdiagnosed as such. May be present as overgrowths on ettringite. May require a higher optical magnification to distinguish from ettringite or the use of SEM. More thermally stable than ettringite. Usually requires XRD analysis for detection and easily missed in optical examination.

XRD: 25-128: 9.56-100, 5.51-40, 3.41-20, 3.18-16.

Thermal analysis: Strong endotherm at 150°C (Bensted and Varma 1974).

Infrared: Spectral data Bensted and Varma (1974).

Gypsum (selenite, alabaster, satin spar)

$\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$ Biaxial + ve Monoclinic
 $\alpha = 1.520 \quad \beta = 1.523 \quad \gamma = 1.530$

Syngenite

$K_2Ca(SO_4)_2 \cdot H_2O$ Biaxial –ve Monoclinic
 $\alpha = 1.500\text{--}1.501$ $\beta = 1.515\text{--}1.517$ $\gamma = 1.518\text{--}1.520$

Interference figure: $-2V = 28^\circ$.

Form: Tablets or prisms.

Twinning: Common.

Colour: Colourless.

Occurrence: Found in gypsum and anhydrite beds.

Comment: Forms in Portland cement and is one of the causes of premature stiffening (Smillie *et al.* 1993). Does not survive in concrete. Best detected by thermal analysis and XRD.

XRD: 28-739: 9.49-40, 5.71-55, 4.624-40, 3.165-75, 2.835-100.

Thermal analysis: Endotherm at 260°C (Smillie *et al.* 1993).

Ammonium sulfate (mascagnite)

$(NH_4)_2SO_4$ Biaxial +ve Orthorhombic
 $\alpha = 1.521$ $\beta = 1.523$ $\gamma = 1.533$

Interference figure: $+2V = 52^\circ$.

Birefringence: 0.01. First-order greys and whites.

Form: Tablets or nearly equant.

Cleavage: Distinct.

Twinning: Twinning gives pseudo hexagonal habit.

Colour: Colourless or stained grey to yellow.

Occurrence: Found in guano and associated with volcanoes. Present in some fertilisers.

Comment: One of the agents which causes sulfate attack on concrete.

XRD: 40-660: 4.392-49, 4.335-100, 3.052-49, 2.096-22.

Thermal analysis: Decomposes at 350°C .

Magnesium sulfate (epsomite, hexahydrate, kieserite)

Epsomite $MgSO_4 \cdot 7H_2O$	Biaxial –ve	Orthorhombic
Hexahydrate $MgSO_4 \cdot 6H_2O$	Biaxial –ve	Monoclinic
Kieserite $MgSO_4 \cdot H_2O$	Biaxial +ve	Monoclinic
Epsomite	$\alpha = 1.433$ $\beta = 1.455$ $\gamma = 1.461$	
Hexahydrate	$\alpha = 1.426$ $\beta = 1.453$ $\gamma = 1.456$	
Kieserite	$\alpha = 1.523$ $\beta = 1.535$ $\gamma = 1.586$	

Interference figure: Epsomite $-2V = 51^\circ$, hexahydrate $-2V = 38^\circ$, kieserite $+2v = 57^\circ$.

Birefringence: Birefringence of kieserite is strong compared to others.

Form: Epsomite and hexahydrate commonly acicular to fibrous. Kieserite is usually prismatic.

Cleavage: Cleavages present.

Colour: Colourless to white or stained.

Occurrence: Epsomite associated with gypsum and salt deposits and as an efflorescence in some ore deposits. Epsomite dehydrates to hexahydrate in air. Kieserite associated with salt deposits.

Comment: These magnesium sulfate minerals may be associated with sulfate attack on concrete.

XRD: Epsomite 36-149: 5.98-30, 5.34-30, 4.216-100, 4.200-75.
Hexahydrate 33-882: 4.815-75, 3.405-100, 3.351-70, 3.313-70.
Kieserite 24-719: 5.45-50, 5.10-45, 4.39-100, 4.04-45.

Thermal analysis: Refer to Mackenzie (1970).

Arcanite K_2SO_4 , *Calcium langbeinite* $K_2SO_4 \cdot 2CaSO_4$, *Aphthitalite* $(K_2Na)_2SO_4$. These sulfate minerals form in cement clinker but are not observable in concrete. Brief mineralogical details are given by Campbell (1986).

Asbestos and other fibrous materials

A group of hydrous silicates primarily composed of fibrils ranging from 20–200 nm in thickness which form durable, strong fibres that can be either woven or used as reinforcement in materials such as hardened cement and polymeric resins. The optical mineralogy of the asbestiform minerals is well covered in the literature so only a summary of optical data has been given. Crocidolite is a variety of riebeckite and amosite is a commercial name and not a mineral name. The composition of tremolite is $Ca_2Mg_5Si_8O_{22}(OH)_2$ which forms a continuous solid solution with actinolite which is the iron rich member.

	Chrysotile (Antigorite)	Riebeckite (Crocidolite)	Grunerite (Amosite)	Anthophyllite	Tremolite/ Actinolite
Composition	$Mg_3(Si_2O_5)(OH)_4$	$(NaCa)_2(FeMn)_3$ $Fe_2(SiAl)_8O_{22}$ (OH,F) ₂	$(Fe_{0.9}Mg_{0.1})_7Si_8O_{22}$ (OH) ₂	$Mg_5Fe_2Si_8O_{22}$ (OH) ₂	$Ca_2(Mg,Fe)_5$ $Si_8O_{22}(OH)_2$
	Monoclinic	Monoclinic	Monoclinic	Orthorhombic	Monoclinic
α	1.493–1.546	1.693	1.657–1.667	1.598–1.652	1.600–1.628
β	1.504–1.550	1.695	1.684–1.697	1.615–1.662	1.613–1.644
γ	1.517–1.551	1.697	1.699–1.717	1.623–1.676	1.625–1.655
$\gamma - \alpha$	0.011–0.014	0.004	0.042–0.054	0.016–0.025	0.22–0.27
2V	0–50° (+)	5° (+)	10–14° (–)	70–90° (+)	79–85° (–)
Extinction	Parallel	5°	10–15°	Parallel	10–20°
Orientation	Length slow	Length fast	Length slow	Length slow	Length slow
Colour	Colourless	Blue	Colourless	Colourless or pale colour	colourless to pale green
Pleochroism	None	Dark blue to grey blue, strong	Pale brown to yellow, slight	Slightly pleochroic	Trem., none Act., green
Mineral group	Serpentine	Clinoamphibole	Clinoamphibole	Orthoamphibole	Clinoamphibole

Provided that the fibres or fibre bundles are of the order of 1 μm or greater in thickness small numbers of fibres can be detected by the optical method (Plate 72). However, the optical properties of chrysotile are difficult to determine because of the fineness of its fibres. When optical studies are made on fibre bundles, which is often the case for fibre reinforced products, the optical properties are the integrated effects of the individual fibrils. This has the effect that the asbestiform minerals mostly show straight extinction in these cases (Zussman 1979).

X-ray: Antigorite-1M 21-963:	7.29-100, 3.61-80, 2.525-100, 2.458-60.
Riebeckite 19-061:	8.40-100, 3.12-55, 2.801-18, 2.726-40.
Grunerite 31-631:	8.33-100, 3.07-80, 2.766-90, 2.639-70.
Anthophyllite 42-544:	9.37-85, 4.59-80, 4.50-100, 3.23-70.
Tremolite 13-437:	8.38-100, 3.268-75, 3.121-100, 2.705-90.
Actinolite 41-1366:	8.42-75, 3.276-45, 3.117-100, 2.709-55.

X-ray data also given by Zussman (1979) who notes that in powder diffraction of asbestos fibres only the stronger reflections may be detected.

Thermal analysis: See Mackenzie (1970).

Infrared: The infrared spectra of the asbestiform minerals provide an unambiguous means of identification on the basis of characteristic absorption bands in the 200 to 1600 cm^{-1} frequency range.

Synthetic and organic fibres

Many fibres are illustrated and discussed in volume 2 of McCrone and Delly (1973) and the Textile Institute (1985). All the fibres have parallel extinction. The data for cellulose are indicative for flax, jute, kraft and sisal fibres.

	n_{\parallel}	n_{\perp}	Bir.	Length
Acrylic	1.511	1.515	0.004	fast
Aramid (kevlar)	> 2.00			
Carbon	opaque black			
Nylon	1.58	1.52	0.06	slow
Polypropylene	1.530	1.496	0.034	slow
Cellulose	1.60	1.53	0.07	slow

Glass

Synthetic glasses

Of the synthetic glasses only a few are of interest to the petrographer. The compositions given below are indicative of the compositional ranges used (Boyd *et al.* 1994, Shand 1958) of the glasses of interest. The relationship of optical properties to composition and density are summarised by Winchell and Winchell (1964).

	SiO ₂	Al ₂ O ₃	B ₂ O ₃	Li ₂ O	Na ₂ O	MgO	CaO	ZrO ₂
Low-expansion borosilicate	81	2	13	–	4	–	–	–
Soda lime	72	1	–	–	15	3	9	–
E-glass	54	14	–	–	–	4.5	17.5	–
Alkali resistant	71	–	–	1	12	–	–	16

	R.I.	Density
Low-expansion borosilicate	1.47	2.23
Soda lime	1.51–1.52	2.46–2.49
E-glass	1.55	2.60
Alkali resistant	1.54	2.62

Remarks: Crushed low-expansion borosilicate glass commonly referred to as ‘Pyrex’ glass is an aggregate which will give a large expansion in the ASTM C227 mortar bar test and thus can be used as an upper limit. However, its reactivity in the mortar bar test is variable and dependent on its thermal history. Like all glasses, crushed Pyrex exhibits conchoidal fracture. Coloured soda lime glass is occasionally used as an exposed aggregate in concrete or as glass tiles and can result in AAR (Fig 1981).

The common type of fibre-glass used in building products is based on E-glass. Because of the poor alkali resistance of E-glass in concrete an alkali-resistant glass containing zirconia was developed by Pilkingtons under the trade name of ‘Cemfil’. To distinguish between this and E-glass, analysis is required as they cannot be differentiated in thin-section. The fibreglass strand used for building products has filaments of about 7 μm in diameter which are combined to form the strand. The strands are treated with sizes or coupling agents which are tailored to the end use of the fibreglass. The specific compositions of these agents are usually confidential to the manufacturer. Where a thick coating of sizing has been used this may be visible in thin-section especially where degradation of the fibre occurs.

Natural glasses

The common textural names used to describe volcanic glasses or rocks containing large amounts of glass are obsidian, perlite, pitchstone, pumice and scoria. Volcanic glasses can vary from acid to basic in composition and these textural terms need to be qualified. For example rhyolitic obsidian, basaltic scoria, etc.

Obsidian, pumice and scoria: Obsidian is usually a dark coloured glassy rock, often banded, with conchoidal fracture. The term is now restricted to glasses of low water content and excludes those of higher water content such as perlite and pitchstone. Obsidians can range from acid to intermediate in composition with rhyolitic obsidian being the most common. In thin-section the glass ranges from clear to brown in colour and usually contains crystallites. However, it is not uncommon to find obsidian fragments in concrete aggregates which do not contain any crystallites and are wholly glassy. Pumice is a light-coloured vesicular rock derived from frothed volcanic glass usually of rhyolitic composition. Pumices of other composition are not common. In thin-section its texture consists of a mass of vesicles separated by thin walls of clear or light coloured glass. Scoria is a dark vesicular rock derived from basalt or andesite and is noticeably heavier than pumice. In thin-section the glass is always dark in colour and may contain considerable quantities of mineral dust and crystallites.

Compositions: The compositions of volcanic glasses will be similar to the bulk composition of the crystalline rock. However George (1924) points out that natural glasses differ in composition from the related crystalline rocks in that they are more acid and contain more alkali with potash dominating over soda.

Refractive index and glass composition: A good correlation between the silica content of natural glass and refractive index has been claimed (George 1924). However, Tilley (1922)

points out that this relationship is affected by the water content of the glass as it increase the refractive index. Some comparative curves for silica content versus refractive index are given by Williams *et al.* (1954). An average extrapolation from the curves for glass made by whole rock fusion gives the following refractive indices.

Silica content (%)	Refractive index
75	1.49
70	1.505
65	1.52
60	1.54
55	1.565
50	1.595
47	1.62

The following information is taken from Grout (1932) as it gives some idea of the range of indices to be expected from rocks. However, it is not clear how much of this data is applicable to glass groundmass as opposed to essentially whole rock glass.

Name of rock	Average refractive index	Range recorded
Obsidian or rhyolitic glass	1.492	1.48–1.51
Pitchstone	1.500	1.492–1.506
Perlite	1.497	1.488–1.506
Pumice (Plate 70)	1.497	1.488–1.506
Dacite	1.511	1.504–1.529
Trachyte	1.512	1.488–1.527
Andesite	1.512	1.489–1.529
Leucite tephrite	1.550	1.525–1.580
Tachylite, scoria, basalt glass including palagonite	1.575	1.506–1.562

The glassy groundmass in volcanic rocks

The composition of the glassy groundmass of a volcanic rock is differentiated from the parent rock. It is the portion that remains after other components of the rock have crystallised. Thus an important distinction must be made between natural glasses such as obsidian and the glass which occurs in the groundmass of fresh volcanic rock. Glasses such as obsidian will approximate to the bulk composition of the rock type. However, the glass in the groundmass of a typical andesite may contain between 60 and 70 per cent silica. This increase in silica content occurs because of differentiation as the glass is the residual material remaining after the minerals have crystallised.

The glass in granulated blastfurnace slag

$n = 1.57$ to 1.66 dependent on composition.

The refractive indices of a range of slag glasses have been investigated by Battigan (1986) who found the above results. There appears to be a good relationship between refractive index and the calcium/silica ratio. Addition of alumina and magnesia into the ratio does not significantly affect the correlation indicating that the combined effect of these ions appears to be neutral.

The range in composition of blastfurnace slags is given by Lea (1970) and Taylor (1990). Glass contents vary dependent on method of manufacture. Granulated slags may contain in excess of 95 per cent glass while in pelletised slags it may be as low as 50 per cent. Methods for estimating glass content of slag by transmitted light microscopy have been described by Drissen (1995) and Hooton and Emery (1983). Alternatively, glass content may be estimated by quantitative X-ray diffraction techniques using internal standards and Rietveld analysis (Howard *et al.* 1988) but both microscopy and X-ray diffraction methods will fail if microcrystallinity is present (Taylor 1990).

The silica minerals and mineraloids*Quartz*

SiO ₂	Uniaxial +ve $\omega = 1.544 \quad \varepsilon = 1.553$	Trigonal
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Interference figure: Easily obtained if the crystal is large enough. May be pseudo-biaxial with a small 2V angle if the crystal is strained.

Birefringence: In standard 30 μm thickness section maximum birefringence gives an interference colour of white with a slight tint of yellow. For concrete sections which are 27 μm or less in thickness the colour is white to greyish white. Quartz is the main mineral used for estimating the thickness of a thin-section under the microscope.

Form: Quartz occurs in a wide variety of forms which are well-described in literature on optical mineralogy. This literature should be consulted for further details.

Twinning: Although twinning is common in quartz it is rarely observed in thin-section.

Orientation: Euhedral crystals are length slow.

Colour: Colourless

Occurrence: Quartz is a ubiquitous mineral found in many rocks as an essential, accessory, or secondary mineral. It is especially abundant in sandstones, arkoses, quartzites, granites, rhyolites and gneisses. It is one of the most common detrital minerals.

Comment: In loose detrital material quartz can be confused with some of the feldspars. The forms of quartz of particular interest to the concrete petrographer are those exhibiting undulatory extinction and varieties of microcrystalline and disordered quartz of which the latter are difficult to define either in thin-section or by electron microscopy. The method for estimating the undulatory extinction quartz has been described by Smith *et al.* (1992). Measurement of undulatory extinction in quartz is no longer accepted as a method for predicting the reactivity of quartz-bearing rocks (Grattan-Bellew 1992). A method based on the estimation of total grain boundary areas of the quartz crystals appears to provide some correlation with reactivity in some metamorphic rocks (Wigum 1996).

XRD: 33-1161: 4.257-22, 3.342-100, 1.8179-14, 1.5418-9.

Thermal analysis: Gives a sharp exothermic peak at 573°C due to the α to β inversion.

Chalcedony

SiO₂ Av. $n = 1.537$ Cryptocrystalline
(1.530–1.539)

Birefringence: Weak, maximum colour is first-order grey.

Form: Fibrous, often spherulitic, may also show mosaic type structure (Plate 67).

Extinction: Usually parallel to length of fibres and rarely at 30°. Aggregate structures may fail to extinguish. Fibres usually length slow but may also be length fast.

Colour: Colourless in thin-section.

Occurrence: Present as the main constituent of flints, cherts, jaspers and as a cementing agent in quartzites.

Comment: Formerly considered as a distinct mineral but electron microscopy has shown chalcedony to consist of minute quartz crystals. Chalcedony is considered to be a reactive mineral with cement alkalis but work by Rayment (1992) has shown that other disordered forms of quartz are the reactive species in flints and cherts.

XRD: Gives same pattern as quartz.

Cristobalite

SiO₂ Uniaxial –ve Pseudo-isometric (tetragonal)
 $\epsilon = 1.484$ $\omega = 1.487$

Interference figure: Crystals are usually too small to obtain a figure.

Birefringence: Variable. Cristobalite formed below 1470°C is practically isotropic. When formed at higher temperatures both the synthetic and natural cristobalite have grey interference colours giving a characteristic mosaic effect.

Form: When formed below 1470°C cristobalite is minutely crystalline and appears as an isotropic groundmass. Cristobalite exposed for long periods to higher temperatures exhibits a characteristic curved fracture, resembling overlapping roof tiles. Cristobalite crystallising from a glass may be dendritic, fernlike, needles or laths. In volcanic rocks it is found in minute square crystals or aggregates in cavities. It also occurs intergrown with the feldspar fibres in spherulites (Plate 67).

Twinning and extinction: Complex lamellar twinning is common with cristobalite formed at high temperature. Twinning is less common in natural cristobalite. Elongated crystals may show extinction at any angle.

Colour: Colourless in thin-section.

Occurrence: In silica and semi-silica bricks around the periphery of quartz crystals and along cracks. Found in some high-temperature contact rocks and widely found as a late-forming metastable mineral in volcanic rocks. Often forms in cavities but is also present as small pools in the groundmass.

Comment: As little as 2 per cent of cristobalite has been shown to be expansively reactive with cement alkalis (Kennerley and St John 1988) and its presence results in pessimum proportions in alkali-aggregate reaction. Thus its detection is important when examining aggregates. It can be difficult to detect in basalts and requires the field diaphragm to be closed down to detect its negative relief and low refractive index. Chemical detection of the silica minerals such as cristobalite indicates that greater amounts are often present

than detected in thin-section (Katayama *et al.* 1989). Synthetic cristobalite has been proposed as a reference aggregate in the ASTM C227 mortar bar test by Lumley (1989).

XRD: 39-1425: 4.040-100, 3.136-8, 2.841-9, 2.487-13.

Thermal analysis: See Mackenzie (1970).

Tridymite

SiO₂ Biaxial +ve Orthorhombic

synthetic $\alpha = 1.469$ $\beta = 1.470$ $\gamma = 1.473$.

natural $\alpha = 1.477$ $\beta = 1.478$ $\gamma = 1.481$. Indices may vary slightly.

Interference figure: Readily obtained unless crystals are very small which is usually the case in rocks.

Birefringence: Very weak. The maximum polarisation colour is grey.

Form: Wedged or arrowhead crystals are common but may be absent as tridymite may also crystallise as laths (Plate 67).

Twinning: Twinning is very characteristic in both wedge and lath forms.

Colour: Colourless in thin-section.

Axial angle: Minimum $2V = 35^\circ$ with angles of up to 72° having been measured.

Occurrence: Tridymite is the principal constituent of silica brick with cristobalite as an associate. Natural tridymite occurs as a metastable mineral in a well-crystallised form in the cavities of acid and intermediate volcanic rocks and less frequently in basalt. In the groundmass it is usually microscopic. Tridymite in general is much more abundant than cristobalite in volcanic rocks and in cases can form up to 25 per cent of the rock (Fronde1 1962). May be associated or altered to quartz or cristobalite.

Comment: Tridymite is usually much easier to detect in thin-section than cristobalite because of its distinctive shape and twinning although greater amounts are usually present than observed in thin-section. Hornibrook *et al.* (1943) and Schuman and Hornibrook (1943) tested firebrick composed principally of tridymite and found it gave an expansion of 0.68 per cent comparable to that found with opal. This means that like cristobalite and opaline materials, tridymite contributes to the effect of pessimum proportion and that only small percentages are required to cause expansion.

XRD: Natural orthorhombic 42-1401: 4.28-93, 4.08-100, 3.80-68, 3.242-48.

Thermal analysis: See Mackenzie (1970).

Opal

SiO₂.nH₂O Isotropic

Water content commonly 4-9 per cent but can range up to more than 20 per cent.

Water content (per cent) 3.5 6.33 8.97 28.04

Refractive index 1.459 1.453 1.447 1.409

Birefringence: Usually nil but may show very weak birefringence due to strain.

Form: Often massive without any structure and can be present as a cementing material in sandstone (Plate 67). It is often found as rounded crusts, in veinlets and as a cavity filling or lining. It can replace wood and feldspars.

Colour: Colourless to pale grey or brown in thin-section.

Occurrence: Occurs as the main mineral in opaline shales and opal rock. Opal is a secondary mineraloid in volcanic rocks where it is commonly associated with quartz, chalcedony and tridymite. It is the principal constituent of diatomite and siliceous sinter.

Comment: Opal is a mineraloid consisting of submicroscopic cristobalite with a disordered structure and excess water (Fron del 1962). Its detection in concrete aggregates is important as amounts as small as 1 per cent can cause damaging expansion due to alkali-aggregate reaction.

XRD: Gem quality opal 38-448: 4.08-100, 2.86-10, 2.51-60.

Thermal analysis: Similar to cristobalite (Mackenzie 1970).

Fused silica glass including lechatelierite: $n = 1.458$.

Ignited silica hydrogel: $n = 1.48 - 1.485$ isotropic.

Soluble silicates

Optical details of the anhydrous soluble silicates are given by Vail (1952). Details of some of the crystalline hydrated potassium and sodium silicates are given in Winchell and Winchell (1964). These soluble silicates are either orthorhombic or monoclinic with indices varying from 1.45 to 1.50 and birefringence from 0.007 to 0.009.

Alkali-silica gel

Sodium/potassium silicate gel $n = 1.45-1.51$, mean ~ 1.48 .

The composition of the gel is variable and has been reported as: $\text{Na}_2\text{O} = 1-25$ per cent, $\text{K}_2\text{O} = 0.5-19$ per cent, $\text{CaO} = 0.5-23$ per cent, $\text{SiO}_2 = 29-85$ per cent, ignition loss 10-25 per cent (Idorn 1961, Buck and Mather 1978). Older gels, gels remote from the site of reaction and crystallised gels may contain significant concentrations of Ca^{++} ions within the gel/crystal structure.

Relief: Fairly low negative relief.

Birefringence: True gel is isotropic but portions of gel often convert to birefringent material (crystalline gel) with a first-order white colour. May be carbonated near surfaces when it will show higher-order interference colours more typical of carbonates.

Form: Gel often contains conchoidal drying cracks especially where it lines cracks and pores. Has the appearance of a viscous material that has flowed and may be layered. Commonly present as tongues of gel extruding from the mouths of cracks in aggregates. Hardened cement paste saturated with gel at the margins of aggregates and cracks appear darkened under cross polars (Plate 65).

Colour: Can vary from colourless to yellow, brown and almost black. The colour does not appear to be related to crystallisation of the gel.

Occurrence: The product formed by the interaction of pore solution alkalis with siliceous or alumino-siliceous components in the aggregates. Commonly observed where expansion and cracking of concrete has occurred.

Comment: Alkali-silica gel is easy to recognise in cracks and pores where it may be associated with ettringite. It is difficult to observe in the texture of aggregates. Where tongues of gel plug mouths of aggregate cracks, the tongue often sits on an area of finely crystalline birefringent material showing yellow and red colours of possibly the first order. This finely crystalline material, not to be confused with crystallised gel, may be an intermediate product and is claimed to be of the same composition as the adjacent alkali-silica gel (Andersen and Thaulow 1990).

XRD: Indeterminate. Some data given by Buck and Mather (1978).

Relief: Indices are close to the standard mountant index of 1.54 or epoxy indices of about 1.57–58. On rotation of stage relief is close to nil in one position.

Birefringence: In standard sections gives first-order red and second-order blue. In thinner sections of concrete more commonly gives first-order yellow, orange and red. Small crystals, such as occur in hydrated lime, appear white. In some hardened pastes the yellow birefringence of small crystals of calcium hydroxide can be confused with the golden birefringence of small aggregates of carbonation.

Form: Crystals occur as minute plates naturally. In hardened cement paste calcium hydroxide when observed by electron microscopy occurs as hexagonal plates, tablets and rods as well as irregular shapes. In thin-sections of concrete calcium hydroxide is observed filling or partially filling void space and is usually irregular in form. Sizes range from microcrystalline to crystals as large as 50 μm in size (Section 5.3).

Cleavage: Perfect basal cleavage which is rarely observed in thin-sections of concrete.

Colour: Colourless

Occurrence: Very rare mineral found in some limestone contacts. Calcium hydroxide is ubiquitous in hardened cement paste and is the principal constituent of slaked and hydraulic limes.

Comment: In hardened cement paste calcium hydroxide is one of the few minerals which is not submicroscopic. The observation of calcium hydroxide is an important diagnostic tool in petrography. In slaked lime, microscopic examination can give information on impurities but the crystals of calcium hydroxide are too small to be readily observed. In hydraulic limes the hydraulic components are best observed in polished section.

XRD: 4-733: 4.9-74, 2.628-100, 1.927-42, 1.796-36.

Thermal analysis: Endotherm 500–600°C (Ramachandran 1969).

Calcium oxide (lime, burnt or quick lime)

CaO	Isotropic $n = 1.838$	Cubic
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Form: Usually rounded grains in cement clinker and dolomite bricks. In calcined limestone, calcium oxide essentially retains the shape of the crushed limestone particles and will tend to be polycrystalline. Electron microscopy shows burnt lime to consist of agglomerates 0.5–5 μm in size consisting of minute equant to globular shaped particles.

Cleavage: Perfect cubic cleavage but only apparent if material has been subjected to a high temperature.

Colour: Colourless but often stained yellow or brown by interaction with iron oxide.

Occurrence: Very rare mineral found in some high-temperature limestone contacts. Present in cement clinker, dolomite brick and is the major constituent of burnt lime.

Comment: Calcium oxide is not observable in thin-sections of concrete. In cement clinker it is best observed in polished section (Campbell 1986). The appearance of various lime powders in oil immersion is given by McKenzie (1994). It can be identified in powders and distinguished from periclase and spinel by White's Test (White 1909), which is outlined by Rigby (1948).

XRD: 31-1497: 2.4059-100, 2.777-36, 1.7009-54.

Indices increase with iron and titanium content.

Interference figure: $+2V = 45-50^\circ$.

Relief: Moderately high.

Birefringence: Maximum interference colour is yellow. Usually white to grey.

Form: Most characteristic form is needles or laths.

Extinction: Parallel extinction. Needles are length slow.

Colour: Colourless.

Occurrence: Rare natural mineral found in some high-temperature contact rocks. Mullite is constituent of some porcelains. Crystallises out when slag reacts with fired clay materials. Can often be seen as fine needles crystallising out in the glass spheres in fly ash.

Comment: Mullite needles may be too small to be observed under the optical microscope.

XRD: 15-776: 5.39-50, 3.428-95, 3.390-100, 2.206-60.

Grinding and polishing compounds

Diamond

C	Isometric $n = 2.414$	Cubic
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Relief: High positive relief.

Form: Cubes, octahedrons, etc.

Colour: Colourless, white, yellow, orange, red, green, blue brown, black.

Occurrence: Natural gemstone. Also manufactured.

Comment: Most diamond grinding and lapping compounds are made from synthetic diamond. Diamond particles are observed in polished and thin-sections which have not been adequately cleaned during preparation. They stand out very clearly because of their high relief and colour.

XRD: 6-675: 2.06-100, 1.261-25, 1.075-16, 0.816-16.

Silicon carbide

SiC	Uniaxial + ve $\varepsilon = 2.689-2.697$ $\omega = 2.647-2.654$	Hexagonal
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Relief: Very high positive relief.

Birefringence: Strong with strong dispersion.

Form: Grinding powder often has splintered appearance with conchoidal fracture showing radiating stress lines.

Colour: Colourless, green, blue or black. Industrial silicon carbide is usually colourless or bluish. Blue crystals are pleochroic.

Occurrence: Rare natural mineral known as moissanite. Manufactured for grinding media which can consist of mixtures of cubic to hexagonal silicon carbide in a number of polytypes.

Comment: Silicon carbide particles are observed in polished and thin-sections which have not been adequately cleaned during preparation. They stand out very clearly because of their high relief and iridescent colours.

XRD: Variable. See 29-1126 through to 29-1131.

Aluminium oxide (corundum, α -alumina, γ -alumina)

Al_2O_3 Corundum, α -alumina	Uniaxial –ve $\varepsilon = 1.760$ $\omega = 1.768$	Hexagonal
$\gamma\text{Al}_2\text{O}_3$	Isometric $n = 1.696$	Cubic

Interference figure: Readily obtainable.

Relief: Very high positive relief.

Birefringence: First-order white for corundum.

Form: Natural corundum is often hexagonal in shape. Synthetic corundum consists of angular and irregular shaped aggregates with some signs of conchoidal fracture. γ -alumina appears as irregular aggregations of fine particles.

Twinning: Simple or multiple twinning in corundum.

Colour: Colourless, white or grey.

Occurrence: Found particularly in some contact rocks in low silica environments where it may be called sapphire or ruby. Industrially synthesised for grinding media. Principal constituent of fused alumina brick and other products. γ -alumina is a synthetic precipitated product used as a polishing compound.

Comment: Synthetic corundum is widely used for grinding and polishing of cement clinker and concrete specimens. During grinding the corundum particles fissure and gradually break down to finer particles which makes it an ideal grinding agent. Unless specimens are carefully cleaned residual corundum particles may remain embedded in surfaces. It is not uncommon to find some corundum at the edges of the specimen embedded in the mounting media. γ -alumina is restricted to polishing compounds in the submicron range and is unlikely to interfere with optical examination.

XRD: Corundum: 13-373: 2.41-50, 2.12-50, 1.96-35, 1.395-100.

γ -alumina: 43-1484: 2.551-98, 2.086-100, 1.602-96, 1.374-57.

Cerium dioxide (cerianite, ceria polishing compound)

CeO_2	Isometric $n \approx 2.2$	Cubic
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Relief: Very high positive relief.

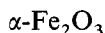
Form: As irregular shaped aggregates.

Colour: Yellow to brown.

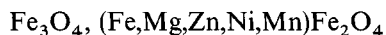
Occurrence: Extracted from bastnasite.

Comment: The polishing compounds are a mixture of cerium dioxide and lanthanum and praseodymium oxides together with other impurities. It is coloured brown by the other rare earth oxides (Kilbourn 1993). Used extensively for polishing glass and may be used to polish cement clinker. Is difficult to remove from surfaces of clinker and is observed as aggregations of orange-brown fine particles.

XRD: Cerianite: 43-1002: 3.124-100, 2.706-27, 1.913-46, 1.632-44.

Pigments and colorants*Red (hematite, red ochres, burnt sienna, burnt umber)*Uniaxial – ve
 $\omega = 3.22\text{--}2.90 \quad \varepsilon = 2.94\text{--}2.69$

Hexagonal

Relief: Extremely high.**Form:** Basal plates, rhombohedrons, platy, fibrous or massive.**Colour:** Opaque unless crystals are very thin. Thin scales are coloured blood red, red-brown, orange or yellow. May be slightly pleochroic. Steel-grey with metallic lustre in reflected light with a tendency to a marginal red.**Occurrence:** A very important iron ore. Rather common as microscopic inclusions and alteration products in many minerals and rocks, colouring them red.**Comment:** Hematite is the principal coloured mineral in Spanish and Persian and other red ochres and in burnt sienna and umber. Many of these are impure mixtures especially some of the siennas and umbers which may contain clays and manganese oxide. For industrial use and in concrete red ochre is made synthetically where the quality is uniform and the colour shade is controlled by particle shape and size (Schiek 1982). Both synthetic and natural red iron oxides are classified as CI pigment red 101.**XRD:** 33-664; 2.74-100, 2.519-70, 1.841-40, 1.694-45.*Black (magnetite, carbon black)*Isometric
 $n = 2.42$ varies with substitution

Cubic

Many natural magnetites are substituted.

Relief: Very high.**Form:** Octahedral or granular. Rarely cubes.**Colour:** Opaque. Appears black in thin-section. Grey metallic lustre in reflected light.**Occurrence:** Widespread in igneous and metamorphic rocks and important in many black ironsands.**Comment:** Is also synthesised for use as a pigment. Black colour may be tinged with red unless some manganese is present. Both natural and synthetic iron oxides are classified as CI pigment black 11. Present in slag and fly ash.**XRD:** 19-629; 2.967-30, 2.532-100, 1.616-30, 1.485-40.

C (carbon black)

Amorphous
OpaqueCarbon black produced from oil feedstock varies in particle size from 0.5–4 μm in size. Particles less than 0.5 μm are rounded but other particles are sharply angular or sliverlike without apparent agglomerates (McCrone and Delly 1973).**Comment:** Carbon black is a superior pigment to iron black and is classified as CI pigment black 6.

Yellow (goethite, lepidocrocite)

FeO(OH) Uniaxial –ve Orthorhombic
 α -FeO(OH) (goethite) $\alpha = 2.275\text{--}2.15$ $\beta = 2.409\text{--}2.22$ $\gamma = 2.415\text{--}2.23$
 γ -FeO(OH) (lepidocrocite) $\alpha = 1.94$ $\beta = 2.20$ $\gamma = 2.51$

Interference figure: Goethite $-2V = 23^\circ$ with strong dispersion. Lepidocrocite $-2V = 83^\circ$.

Relief: Very high.

Birefringence: Goethite crystals are length slow.

Form: Goethite, prismatic or striated or tabular or fibrous. Lepidocrocite scaly.

Extinction: Parallel.

Colour: Goethite has strong variable pleochroism from yellow to orange yellow. Lepidocrocite also pleochroic ranging from colourless to yellow through to red orange.

Occurrence: Goethite is a common mineral, present in limonite iron ore and is the usual weathering product of siderite, pyrite, magnetite, glauconite and iron silicates. Lepidocrocite is often found associated with goethite. Goethite is the principal constituent of yellow ochre and raw sienna.

Comment: Limonite is the general term used for undifferentiated iron weathering products and usually consists of goethite and/or lepidocrocite. However, optically it usually appears isotropic with a refractive index of 2.0 to 2.1. The yellow colour of ochres and synthetic iron oxide is due to the presence of one of these hydrated iron oxides. The natural siennas are classified as CI pigment brown 7 and ferrite yellow as CI pigment yellow 42.

XRD: Goethite: 29-713: 4.183-100, 2.693-35, 2.450-50, 1.792-20.

Lepidocrocite: 8-98: 6.26-100, 3.29-90, 2.47-80, 1.937-70.

For further X-ray data see also Brindley and Brown (1980).

Thermal analysis: See Mackenzie (1970).

Green (eskolaite, green cinnabar, phthalocyanine green)

Cr₂O₃ (eskolaite) Uniaxial –ve Hexagonal
 $n = \text{about } 2.5$

Relief: Very high.

Birefringence: Thin plates are anisotropic but polarisation colours are masked by natural green colour.

Form: Equant, tabular or scales.

Cleavage: Parallel to the faces of the rhomb.

Colour: In thick sections is opaque. Thin-sections exhibit a bright emerald green colour.

Occurrence: Natural mineral known as green cinnabar. Occurs in refractory mixes containing chromic oxide.

Comment: Synthetic chromic oxide is the principal green colorant used with cement.

XRD: Eskolaite: 38-1479: 2.665-100, 2.480-93, 1.6274-87, 1.4316-39.

C₃₁H_xCu.15-16Cl (phthalocyanine green) n about 1.40, laths (Gettens and Stout 1966). A chlorinated derivative of phthalocyanine blue classified as C.I. pigment green 7. Variations also listed as CI pigment green 42 and 43 are now listed as CI pigment green 7 and pigment green 36. CI pigment green 36 is a polybromochloro derivative of different shade. The systematic name is polychloro-tetrabenztetraazaporphyrin.

XRD: CI pigment green 7: 36-1870: 14.8-83, 13.2-57, 5.21-40, 3.34-100.

Blue (cobalt blue, phthalocyanine blue)

Co₃Al₂O₃ (cobalt blue) Isometric Cubic
 $n > 1.78$ (red) $n = 1.74$ (blue)

This is CI pigment blue 28.

XRD: 38-816: 2.439-100, 2.021-21, 1.557-36, 1.429-42.

C₃₂H₁₆Cu (copper phthalocyanine blue) Biaxial Monoclinic
 n about 1.38, laths (Gettens and Stout 1966).

This is classified as CI pigment blue 15 and forms α and β modifications which are slightly different in shade and stability. There are a number of variations of this pigment classified as 15.1, 15.2 and 15.3 which are phthalocyanine substituted with other ions such as nickel and cobalt. The systematic name is copper tetrabenzotetraazaporphyrin.

XRD: 22-1686: 13.2-100, 21.1-100, 8.93-40, 5.71-40.

White (Anatase, rutile)

α -TiO₂ (rutile) Uniaxial +ve Tetragonal
 $\omega = 2.609$ – 2.616 $\varepsilon = 2.895$ – 2.903

β -TiO₂ (anatase) Uniaxial –ve Tetragonal
 $\omega = 2.561$ – 2.562 $\varepsilon = 2.488$ – 2.489

Interference figure: Both rutile and anatase may give anomalous biaxial figures with a small 2V.

Relief: Highest relief of any rock-forming mineral.

Birefringence: Extreme birefringence which does not show well on account of total reflection.

Form: Small prismatic to acicular crystals.

Cleavage: Parallel to length of crystals.

Twinning: Common.

Extinction: Parallel.

Colour: Yellowish to reddish brown in thin-section. In reflected light shows adamantine lustre.

Occurrence: Widely distributed accessory minerals in metamorphic rocks and occur as detrital minerals. Rutile is much more widespread than anatase.

Comment: The synthetic pigment grades of rutile and anatase appear as dark agglomerates of very fine particles which under crossed polars appear white with some reddish brown coloration in the larger agglomerates. Individual fine particles exhibit brownian motion and may show some visible birefringence.

XRD: Rutile: 21-1276: 3.247-100, 2.487-50, 2.188-25, 1.687-60.

Anatase: 21-1272: 3.52-100, 2.378-20, 1.892-55, 1.700-20.

Magnesium oxychloride cement hydrates (Sorel cement)

Formed by mixing calcined magnesite and calcium chloride solution. A range of hydrates are possible with 3Mg(OH)₂.MgCl₂.nH₂O and 5Mg(OH)₂.MgCl₂.nH₂O usual hydration products at ambient temperatures. The 5-form is metastable and converts to the 3-form. Also these hydrates are unstable in air and slowly convert to the magnesium chlorocar-

bonate, $\text{Mg}(\text{OH})_2 \cdot \text{MgCl}_2 \cdot 2\text{MgCO}_3 \cdot 6\text{H}_2\text{O}$. Formation of the calcium oxychloride, $3\text{Ca}(\text{OH})_2 \cdot \text{CaCl}_2 \cdot 11\text{H}_2\text{O}$ also occurs in this system. At higher temperatures more crystalline 9-form and 2-form hydrates occur. Data given is from Demediuk *et al.* (1955), Cole and Demediuk (1955) and Newman (1955).

Optical data: The 3-form occurs as a gel-like aggregate of possibly monoclinic, minute crystals which are irregular in shape. The mean refractive index lies between 1.505 and 1.510 and the birefringence is very low. The 5-form tends to be more crystalline forming well-shaped needles about $10 \mu\text{m}$ long. The mean refractive index is about 1.525 and the birefringence is weak. The needles have parallel extinction and are length fast. The calcium oxychloride is possibly the $\text{Ca}_4\text{O}_3\text{Cl}_2 \cdot 15\text{H}_2\text{O}$ listed by Winchell and Winchell (1964). Colourless, orthorhombic, acicular crystals with basal cleavage. $\alpha = 1.481$, $\beta = 1.536$, $\gamma = 1.543$, $-2V = 44^\circ$.

XRD: 3-form: 8.03-s, 3.83-s, 2.431-ms, 1.985-ms.

5-form: 7.57-s, 4.14-ms, 2.64-m, 2.420-s.

From Cole and Demediuk (1955). Data variable with hydration. JPCDS data difficult to correlate.

$\text{Ca}_4\text{Cl}_2\text{O}_3 \cdot 15\text{H}_2\text{O}$: 2-280: 4.08-100, 2.75-80, 2.61-80, 2.50-70.

Thermal analysis: See Cole and Demediuk (1955).