A compendium of concrete aggregates used in Southwest England
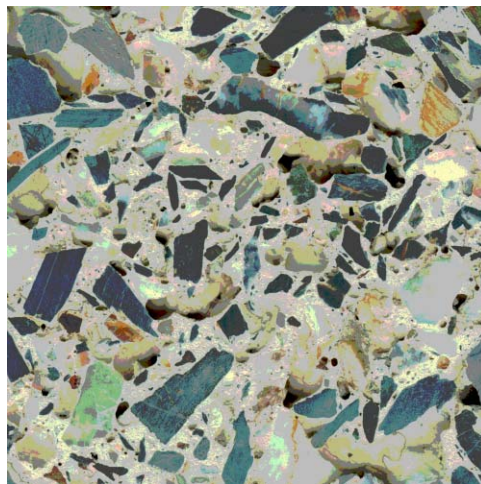
by

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1   Introduction

Since the decline in use of natural stone at the beginning of the century most domestic and small commercial properties in Cornwall and South Devon have been built with concrete blocks or mass concrete. Until the mid-1950's concrete blocks were often locally made, sometimes by individual builders, and shuttered concrete was mixed on site. Before the second world war concrete products were rarely transported more than 20 km. Because concrete was made where it was needed and as transport was difficult and costly, aggregates were sought locally. Now all blocks are factory produced and mass concrete is supplied ready-mixed from facilities where manufacture is strictly controlled.

In many parts of Cornwall and South Devon ample supplies of cheap and often suitably-graded aggregate were available as waste materials from the region's metalliferous mining industry. The use of mining and, more particularly, ore processing wastes as aggregates, is central to the problem of accelerated concrete degradation in the region. It is widely called "the *mundic* block problem". Mundic is an old Cornish word for the common mineral pyrite (FeS_2). Accelerated deterioration is generally associated with the *in situ* oxidation of pyrite (and other sulphide minerals) in mine waste aggregates and sulphuric acid attack on the cement. Deterioration is occasionally so severe that concrete becomes structurally unsafe and some properties have had to be demolished.

Mine wastes in Southwest England are geologically complex materials made up from mineralised veinstones (from lodes), altered wallrock and unaltered country rock in varying proportions. Mining wastes *sensu stricto* from shaft sinking, cross cutting and development are composed largely of unaltered country rocks. They are usually very coarse. The maximum fragment size is the largest piece of rock that could be manhandled into a wagon. Such wastes, unless they were re-crushed, would have been quite unsuitable for use as concrete aggregates. Most waste materials that were subsequently used as concrete aggregates were tailings products from various ore concentration processes. Ore concentration takes place in two stages. First, the mineralogically complex ore is crushed to achieve liberation. Then it is subjected to benefication when the valuable material is separated from the gangue to produce a concentrate. Mineral concentration processes work most efficiently with closely-graded feeds so careful screening and regrinding led to the province-wide generation of millions of tonnes of wastes which were often of a convenient size for use as concrete aggregates. Unlike coarse mining wastes, which are usually just ordinary rock, mineral processing wastes are composed mostly of veinstone or lode minerals and of fragments of altered wallrocks that border the mineral lodes.

Many kinds of tin, copper and arsenic processing wastes have been identified in concrete aggregates. Some are benign. The wastes from granite-hosted tin mineralisation are safe if used as aggregates because the ores have low sulphide mineral content, the gangue and altered wallrocks are made from quartz and stable silicate minerals (figure 1-1).

Exogranitic tin and copper mining wastes were abundant in many parts of Southwest England, notably in the Camborne - Redruth mineralised district. These ores were rich in sulphide

minerals, in veins and altered wallrock (figure 1-2). Fine-grained and potentially very reactive sulphide minerals were not recovered before the introduction of flotation separation techniques in the early part of the twentieth century. In the eighteenth and nineteenth centuries rich copper ores, with coarse chalcopyrite, were often broken by hand and sorted before grinding and further benefication. The waste, typically with 50mm - 100mm top size, contained some residual chalcopyrite and other sulphide minerals including pyrite and arsenopyrite. Hand-cobbed copper wastes were used as aggregate in low fines mass concrete in the Camborne - Redruth district. Poor construction and high sulphide mineral content have sometimes led to very serious degradation.

Figure 1-1. Processing waste from granite-hosted tin mineralisation at the former Geevor Mine, near St Just - a stable Group 1-6 aggregate.

Southwest England was never an important lead producing region but two former lead mines, East Wheal Rose, near St Newlyn East (figure 1-3), and Wheal Mary Ann, near Liskeard, are of enormous consequence in terms of deleterious aggregates. The lead ore, galena (PbS), occurred in narrow veins with quartz and, at Wheal Mary Ann, abundant fluorite. At both mines the wallrocks were graphitic mudstones and these were impregnated with fine-grained, disseminated pyrite during mineralisation (figure 1-4). Dense galena was separated from the lighter gangue and pyritic wallrocks in jigs. Before jigging the ore was crushed to give a product evenly graded between < 1mm and 10mm or 15mm. The techniques did not change through the lifetime of the mines so enormous quantities of similar waste accumulated at both sites. The material was perfectly graded for all-in concrete block aggregate and manufacturing plants were established at both mine sites in the 1920's. Concrete degradation results from oxidation of disseminated wallrock pyrite and aggregate expansion. East Wheal Rose jig tailings are the major cause of concrete degradation in Perranporth; those from Liskeard are responsible for nearly all degraded and potentially unsafe concrete in East Cornwall.
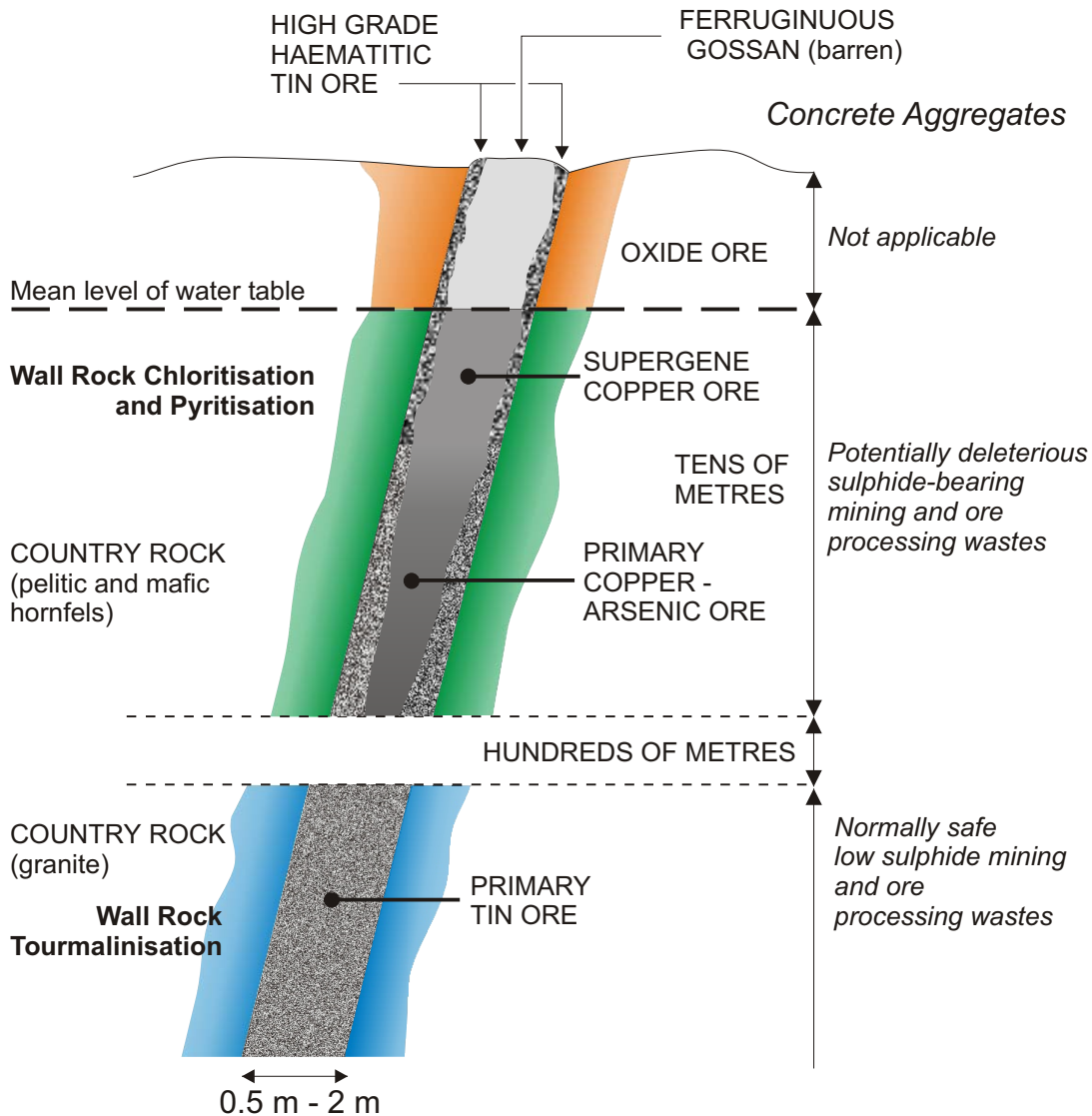
Figure 1-2. An idealised cross section through a high temperature tin - copper - arsenic lode like those in the Camborne - Redruth - St Day mineralised district. The lodes are vertically zoned with sulphide-deficient tin mineralisation at depth and sulphide-rich copper and arsenic mineralisation at higher levels. Lodes are generally narrow so the miners were often forced to extract altered wall rock and even unaltered country rock in addition to the vein material itself. Mining and processing wastes are necessarily complicated, consisting of veinstones, altered wall rock (often with disseminated sulphides) and unaltered host rocks.

Tin mining/processing waste.

Veinstones	*quartz + tourmaline + cassiterite (tin ore)*
Wall rock	*tourmalinised and haematised granite*
Host rock	*porphyritic muscovite-biotite granite*

Copper mining/processing waste.

Veinstones	*quartz + chlorite + fluorite + pyrite + chalcopyrite + arsenopyrite*
Wall rock	*chloritised pelitic and/or mafic hornfels with disseminated sulphides*
Host rock	*pelitic and/or mafic hornfels*

1-3

Figue 1-3. Strongly oxidised tailings at the former West Chiverton Mine, near St Newlyn East. Similar material from the nearby East Wheal Rose Lead Mine is responsible for most accelerated concrete degradation in the Perranporth area.

Lode (ore + gangue minerals)

Zone of wallrock alteration (host rock + pyrite deposited from fluids migrating outwards from lode fissure)

Host rock (graphitic mudstone)

Wide lode   Narrow lode

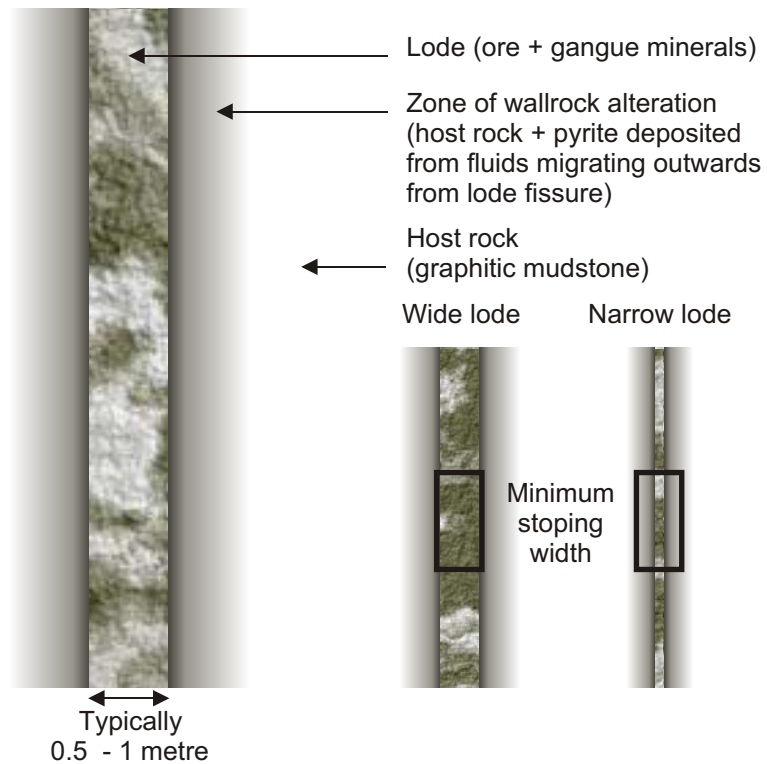Minimum stoping width

Typically 0.5 - 1 metre

Figure 1-4. Idealised cross section though a Cornish lead lode. From the standpoint of aggregate performance the dangerous materials are the altered wall rocks which often contain abundant very fine-grained, disseminated pyrite.

Not all pre-1950 concrete in the region was made with mine waste aggregates. Cornwall and South Devon have a huge variety of sedimentary, igneous and metamorphic rocks that are suitable for and have been used as concrete aggregates. In the past most of the granite plutons hosted quarries that produced aggregates. Mafic and ultramafic igneous rocks, including dolerites in East Cornwall and South Devon, the picrite at Clicker Tor near Liskeard, ophiolitic mafic and ultramafic rocks of the Lizard Complex and the metamorphosed dolerite of Penlee Quarry, at Newlyn in West Cornwall have all been important sources of aggregate. The Penlee dolerite is heavily mineralised. It carries more sulphide minerals than many mine wastes and its long term stability is still uncertain. Crushed slate, waste from the great quarry at Delabole, was widely used in North Cornwall while Devonian limestone is common in East Cornwall and South Devon.

Nowhere in Cornwall is more than 20 km from the sea; the region abounds with short rivers. Beach and river gravels and sands are still important locally. In the past beaches and rivers throughout the region yielded sand and gravel for concrete making. In the early part of the twentieth century, and in the Carnon valley till the 1970s, many river valleys were exploited for alluvial tin. Processed gravels were a cheap source of concrete aggregate. Beach and river gravels are usually stable, making excellent aggregates, but there are important exceptions. Some beach gravels derived from Upper Devonian rocks around the Camel estuary sometimes contain abundant pyritic mudstones - these materials can behave like pelite-hosted mine wastes. During the nineteenth and early twentieth centuries waste materials from the region's metal mines were commonly discharged directly into rivers. The waste-laden sediments were often worked for tin. The great mounds of processed sediment were attractive sources of concrete aggregate. Usually they were benign, but some gravels, heavily contaminated with hard rock mining waste, were rich in unoxidised sulphide minerals. They may be as unstable as sulphide-rich mine wastes.

Furnace clinkers are found throughout Cornwall and South Devon. There were major coal-burning power stations in Plymouth and at Hayle. These were important aggregate sources. There were also many smaller sources including gas works, commercial operations such as laundries, and innumerable steam raising furnaces on the region's mines. Clinkers usually make safe aggregates but there are important exceptions. An electricity generating plant which operated in Falmouth during the 1920s and 1930s burned domestic and commercial waste to augment coal. The resulting clinker, employed locally as an aggregate, is compositionally complex and usually unstable.

The regions's most important natural resource is china clay. It was formed in granites, by destruction of feldspars reacting with heated, descending meteoric water. The reserves are enormous - probably in excess of 10 billion tonnes. The major by-product of hydraulic china clay extraction is quartz-rich sand that is stable and ideally graded for concrete making (figure 1-5). Mountains of this waste dominate the landscape in Mid Cornwall. It is scarcely surprising, and very fortunate, that china clay waste is the most important concrete aggregate in the whole region.

Figure 1-5. Hydraulic mining of china clay from the strongly kaolinised St Austell granite. Waste materials from this important industry are quartz-rich sands. They are very stable and usually have ideal natural grading for concrete aggregates. China clay waste is the most widely used concrete aggregate in the region.

This compendium has been assembled primarily as an aid to the identification of concrete aggregates used in the region, though section 2 provides a brief outline of degradation mechanisms associated with different types of mine wastes. The aggregates are illustrated in section 3. The classification is that set out in the Royal Institution of Chartered Surveyors Guidelines (The *'Mundic'* Problem - A Guidance Note, Second Edition, RICS Books, London, 1997). The plates show carefully ground surfaces of concrete, usually prepared from 50 mm or 75 mm diameter diamond drill cores. They are the kind of specimens normally used for Stage 1 examination and classification under RICS Guidelines. Most aggregates used in the region are illustrated, though new materials, some of them potentially unstable, appear from time to time. They are usually found in "one off" houses built near convenient and probably free aggregate from old mine burrows. New aggregates are also encountered as more concrete testing is carried out in South Devon.

Section 4 comprises distribution maps of the principal aggregate types. These should be treated as only as general guides. Mine waste aggregates are sometimes found in areas far removed from the main mineralised districts. They may have been won from some small and now forgotten mine of which no surface evidence remains. More probably, the use of free aggregate outweighed transport costs so that even on the difficult roads of the 1920s and 1930s it paid to carry cheap blocks for long distances.
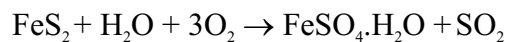
2   DEGRADATION MECHANISMS
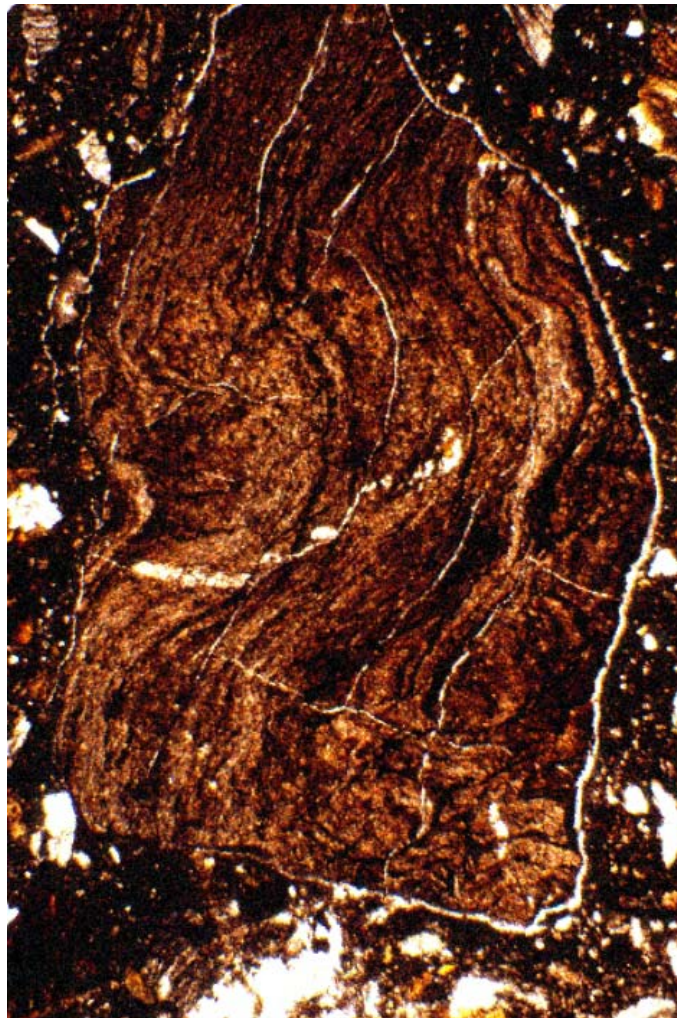
2   Degradation mechanisms

Mundic degradation is overwhelmingly associated with the oxidation of sulphide minerals, mainly pyrite, in mine waste and other mineralised aggregates. Howie (1979, 1992) and Newman (1998) recognised three mechanisms for pyrite oxidation.

1   Oxidation by a sequence of chemical reactions. The overall reaction at high relative humidity (RH) is usually given as:

$$2FeS_2 + 2H_2O + 7O_2 \rightarrow 2FeSO_4 + 2H_2SO_4$$
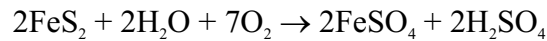
At low to moderate RH the following reaction also occurs:

$$FeS_2 + H_2O + 3O_2 \rightarrow FeSO_4.H_2O + SO_2$$

Both reactions involve expansion and because the oxidation products are hygroscopic they may be facilitated by absorption of water.

2.   Bacteriological oxidation. The oxidation of pyrite and other sulphide minerals by *Thiobacilli* and similar genera have been extensively studied because of their economic significance in ore leaching (Smith and Schumate, 1970; Jorgensen, 1983; Pugh *et al,* 1984; Williams, 1990). Direct bacterial attack at sulphide surfaces probably does occur though two other processes may also be important. *Thiobacilli* may remove sulphur films, that would otherwise inhibit further oxidation, from pyrite surfaces. The *Thiobacilli* and some of their congeners can also catalyse the oxidation of Fe(II) to Fe(III). Ferric ion is, itself, an extremely important oxidising agent.

$$7Fe_2(SO_4)_3 + FeS_2 + 8H_2O \rightarrow 15FeSO_4 + 8H_2SO_4$$
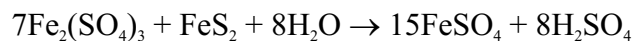
Two groups of bacteria are capable of facilitating the oxidation of pyrite in acid and near neutral environments. The *Thiobacilli* and related genera are effective only under acid conditions. In concrete low pH domains are probably restricted to individual aggregate fragments exposed at the surface or projecting into large voids. Neutral pH bacteria include many genera (Lundgren and Dean, 1979) that may be capable of facilitating pyrite oxidation in concrete with carbonated cement.

3.   Electrochemical oxidation. Howie (1992), Peters (1984) and Williams (1990) have discussed electrochemical mechanisms for pyrite oxidation. Howie, discussing the deterioration of museum specimens, noted that framboidal pyrite (Rust, 1935; Wilkin and Barnes, 1997) in organic matrices was very susceptible to oxidation. Bang (1994) proposed that each pyrite framboid behaves as a galvanic system when moisture enters it by capillary action. Pyrite is oxidised anodically creating acid conditions that lead to the chemical and mechanical breakdown of the framboids. Electrochemical breakdown may be an important mechanism in concrete made with lead ore processing waste where some pyrite is present as framboidal grains in dark, graphitic mudstones.

Newman (1998), reviewing previous literature, suggested that surface area, availability of water, temperature, pH, oxygen concentration and the presence of certain trace elements may

influence the rate of pyrite oxidation.

Experimental studies (Smith and Schumate, 1970; Howie, 1979, 1992) suggest that surface area of pyrite strongly influences its oxidation rate. Pugh *et al* (1984) reported a twofold increase in reaction rate in framboidal compared with massive pyrite. Khawaja (1975) demonstrated a very close relationship between crystal size and oxidation rate though Caruccio (1972) had ground coarse pyrite to 0.5 µm and found that it showed no signs of oxidation even after three weeks. He concluded that grain size was not the single controlling factor in pyrite oxidation.

Morth and Smith (1966) and Smith and Schumate (1970) reported that at constant RH the oxidation rate doubled for a 10°C rise in temperature. In Cornwall mean January and July temperatures are 6.8°C and 16.0°C respectively. Pyrite oxidation may be faster under warm summer conditions than in winter. Kim (1964), Morth and Smith (1966) and Smith and Schumate (1970) demonstrated that oxidation rate increases as a function of RH. They also suggested that water may be necessary to remove oxidation products from the pyrite surface, permitting the reaction to proceed. It is also important because above RH of approximately 60% ferrous sulphate can hydrate with resultant volumetric expansion of 256%. Mean minimum RH in Cornwall is about 60% in January, falling to 30% in July. Seasonal variation in relative humidity may work in the opposite direction to that of temperature, favouring more rapid pyrite oxidation during the wetter winter months.

Pyrite oxidation is pH dependent (Smith and Schumate, 1970; Waller,1987; Howie, 1992). Under strongly alkaline conditions oxidation products tend to build up on mineral surfaces, inhibiting further reaction. This is of critical importance in concrete. In uncarbonated cement the pH of pore fluids is greater than 12. Pyrite remains stable. On carbonation the pH falls below 9 and pyrite oxidation proceeds rapidly. Morth and Smith (1966) and Smith and Schumate (1970) demonstrated experimentally that oxidation rate increased as the oxygen concentration in water at the reaction site was raised.

Many authors have proposed that oxidation rate is influenced by trace element concentrations. Caruccio (1972) suggested that pyrite was stabilised by the presence of titanium and very prone to oxidation if it contained high concentrations of silver. Other authors, e.g., Smith and Schumate (1970), argued that the presence of particular trace elements in pyrite did not appear to influence oxidation rates. It is interesting that concrete made with strongly mineralised dolerite aggregate, from the former Penlee Quarry at Newlyn, usually remains stable. Strong pyrite oxidation is rare. The pyrite is reputed to contain much higher levels of cobalt and nickel than that associated with fissure lode mineralisation (Prof. K.F.G Hosking, personal communication), suggesting that trace element concentrations may influence oxidation rates.

An idealised section through the foundation and wall of a typical domestic property is shown in figure 2-1. There are many variations, particularly in older houses, such as absence of a damp proof membrane or solid walls built with mass concrete or concrete blocks.
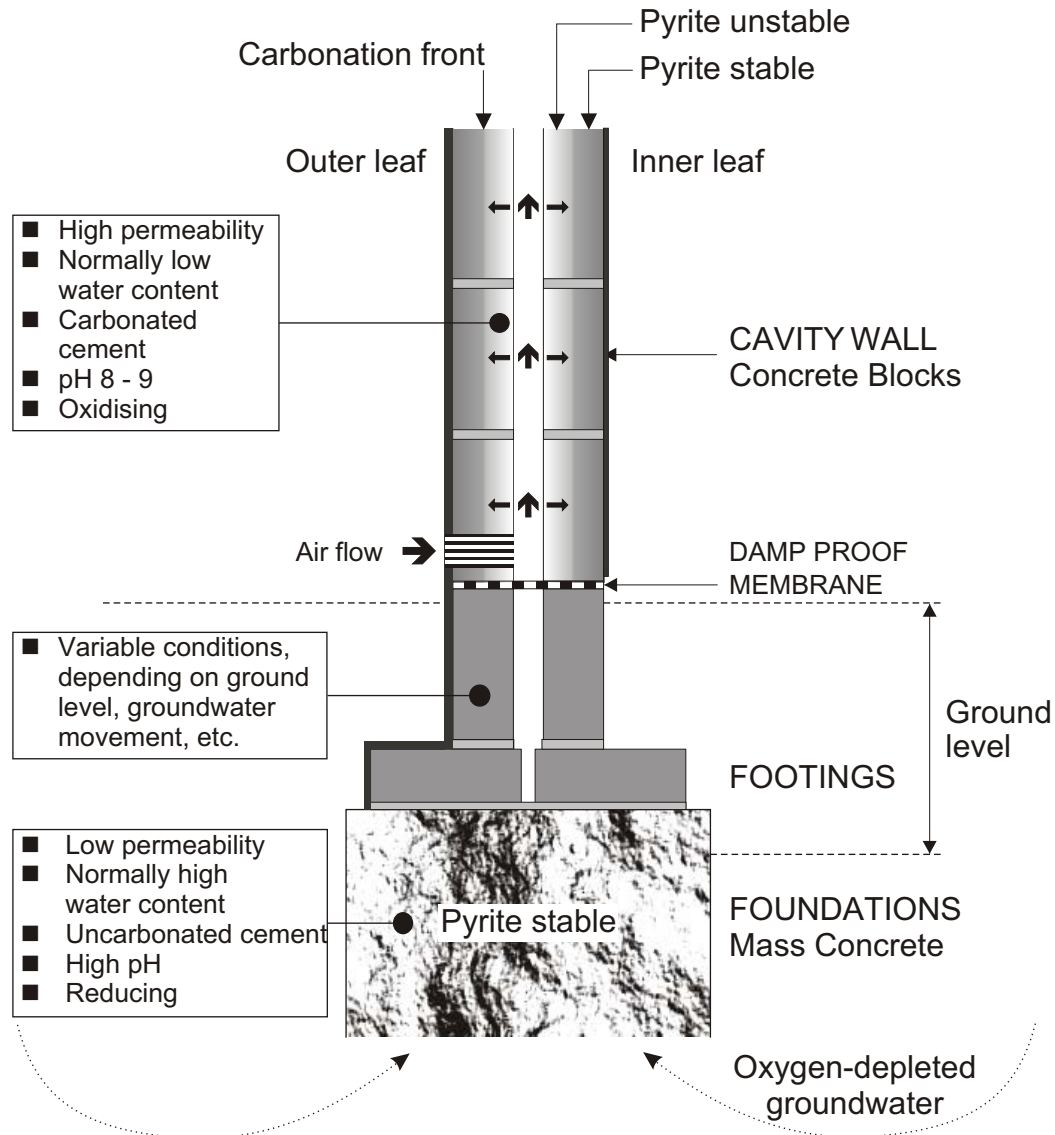

Figure 2-1. Physiochemical conditions in foundations and walls.

Physiochemical conditions are strongly contrasted in different structural elements (figure 2-1). The pH of pore fluids in concrete with uncarbonated cement is > 12.5. When the cement is fully carbonated it falls to about 8.5. Mass concrete used in foundations and even in some walls, has cement:aggregate ratios and macroscopic pore volumes comparable to those of modern structural concrete. Carbonation depth is often only a few millimetres, even after many years. Foundation concrete is often saturated with groundwater from which oxygen has been removed by reaction with Fe(II) minerals and organic matter in soil. Pyrite in wet mass concrete foundations usually shows only superficial oxidation. The stability of pyrite in contact with uncarbonated cement paste may be a result of oxygen depletion or build up of a layer of oxidation products that are insoluble under alkaline conditions, effectively rendering the pyrite passive (figures 2-2, 2-3). Additionally, it is possible that pyrite oxidation is

facilitated by the action of sulphur bacteria that are dormant under alkaline conditions.
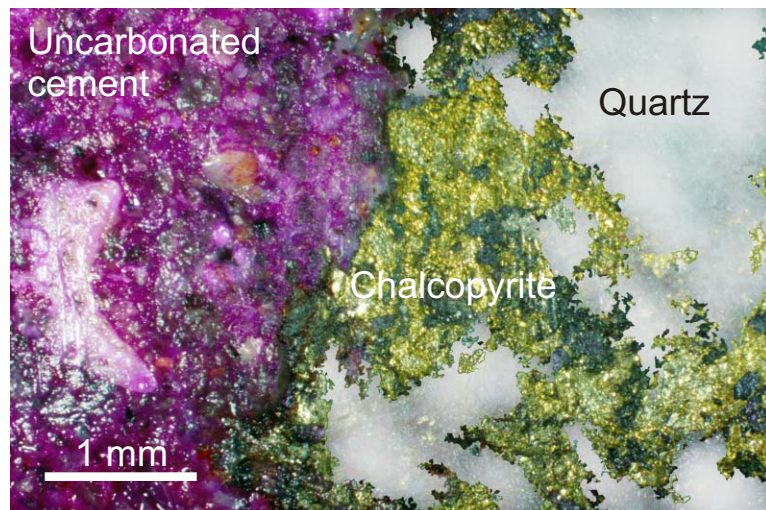

Figure 2-2. Concrete with uncarbonated cement. Sulphide minerals are protected from oxidation by strongly alkaline conditions. The uncarbonated cement is stained pink with phenolphthalein indicator solution.
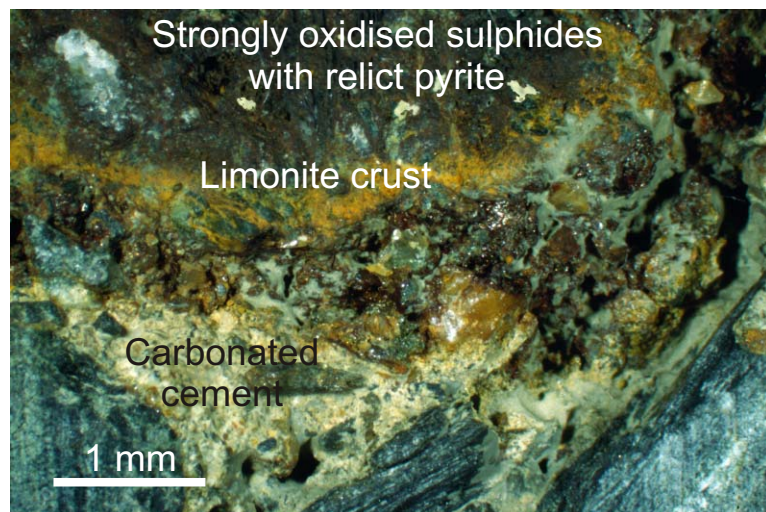

Figure 2-3. Concrete with carbonated cement. Sulphide minerals are readily oxidised under near neutral conditions. Cement next to the sulphidic aggregate is strongly impregnated with iron oxides and gypsum.

Low strength concrete blocks and much poorly-constructed mass concrete in the region have cement:aggregate ratios between 1:6 and 1:15. Void volume is typically 5% - 10% and can be as high as 20%. The concrete has a 'honeycomb' structure. In such materials carbonation might be expected to proceed very rapidly because air can circulate freely through the strongly interconnected voids, but it is not always complete in blockwork walls, even after 70 - 80 years. In cavity wall construction, where the outer leaf is protected by sound render and the inner leaf is covered by mortar or plaster, carbonation usually begins at the cavity (figure 2-4). Moisture-laden air flowing through the cavity diffuses into the blockwork. Carbonation fronts migrate from the cavity towards the protected surfaces of the blocks. In single block walls protected externally by sound render the progress of carbonation depends mainly on the

2-4

nature of the internal covering. If the inner surface of the blockwork is exposed carbonation proceeds from the inner face towards the external render. If both surfaces are protected by mortar render or if the inner surface is covered in gypsum plaster carbonation normally proceeds inwards leaving a 'core' of uncarbonated cement.
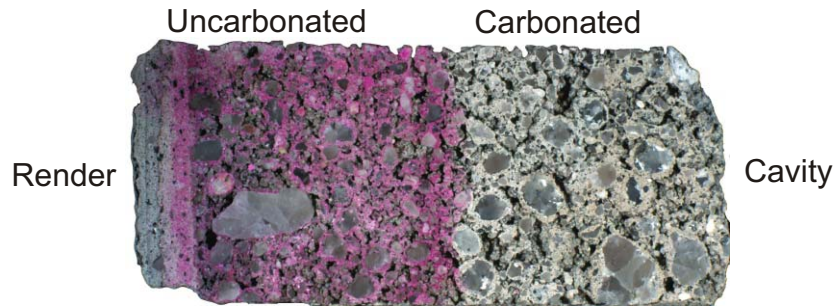

Figure 2-4. Partial carbonation of concrete block from the outer leaf of a cavity wall. Carbonation begins at the cavity and proceeds towards the external rendered surface. The specimen has been treated with phenolphthalein indicator solution to show the distribution of uncarbonated and carbonated cement.

Sometimes in blockwork rendered externally and internally carbonation is very patchy, possibly as a result of air movement along partly open mortar joints. Carbonation penetration is also influenced locally by the presence of cracked or porous render. In porous concrete blocks pyrite oxidation is initially slow and superficial while the cement paste remains uncarbonated. Rapid pyrite oxidation follows carbonation of the cement paste. Degradation begins at the cavity (figure 2-5). Debris spalls from the inner faces of the blockwork and accumulates in the bottom of the cavity. It is only when pyrite oxidation has penetrated deep into the blockwork that characteristic cracking appears in external render.
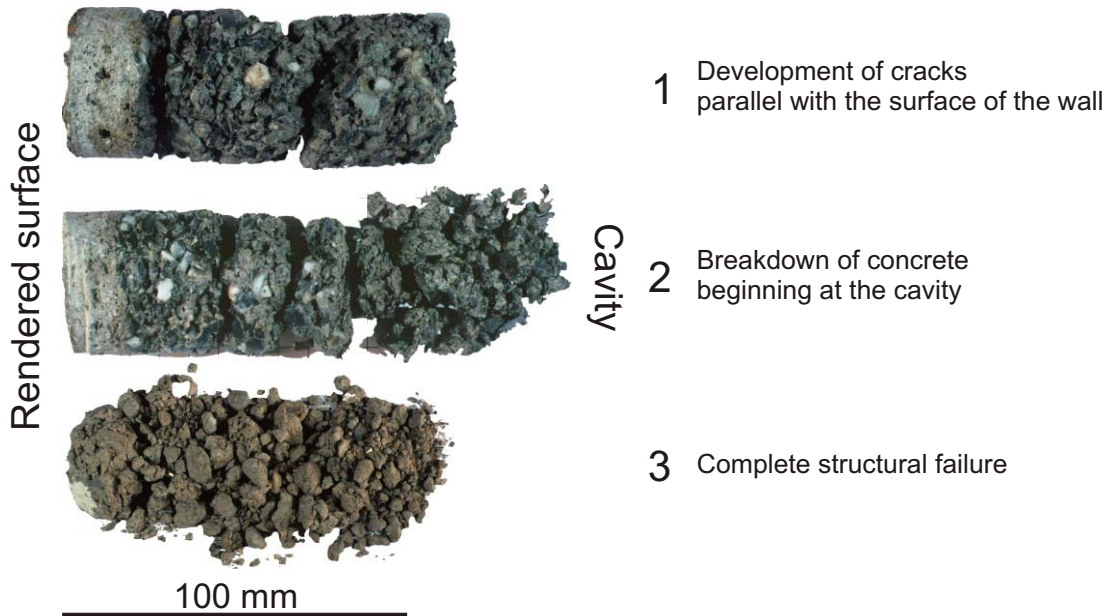

Figure 2-5. Progressive degradation of concrete made with lead ore processing waste from Wheal Mary Ann Mine, near Liskeard.

The relative importance of molecular, bacteriological and electrolytic oxidation has not yet been established but two main degradation mechanisms are recognised, each associated with specific types of pyritic aggregate (Bromley and Pettifer, 1997; Bromley and Sibbick, 1999). The first is associated mainly with hypothermal, exogranitic tin - copper - arsenic wastes like those which characterise the Camborne - Redruth mineralised district. Degradation is caused by oxidation of liberated and easily accessed pyrite and other sulphide minerals in tailings products and re-crushed mining wastes and direct sulphate attack on carbonated cement paste (figures 2-6, 2-7).
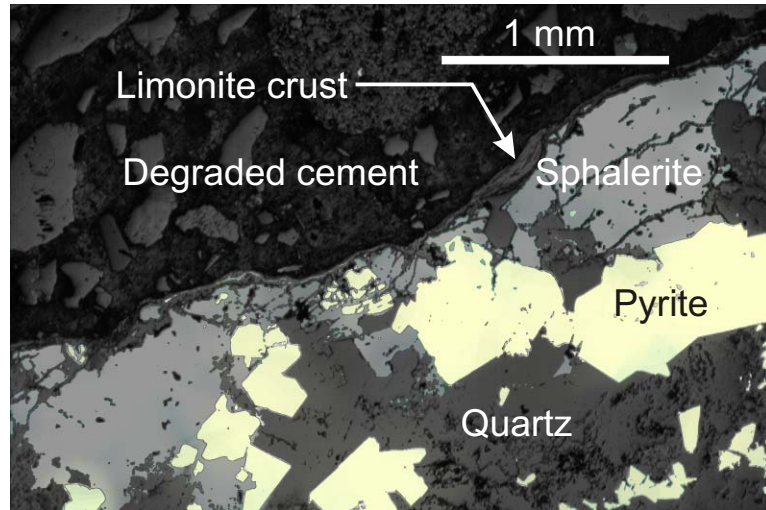
Figure 2-6. Polished specimen viewed under the microscope showing part of a large sulphide-bearing aggregate fragment in contact with degraded cement. A limonite (iron oxide) crust encloses the aggregate fragment.
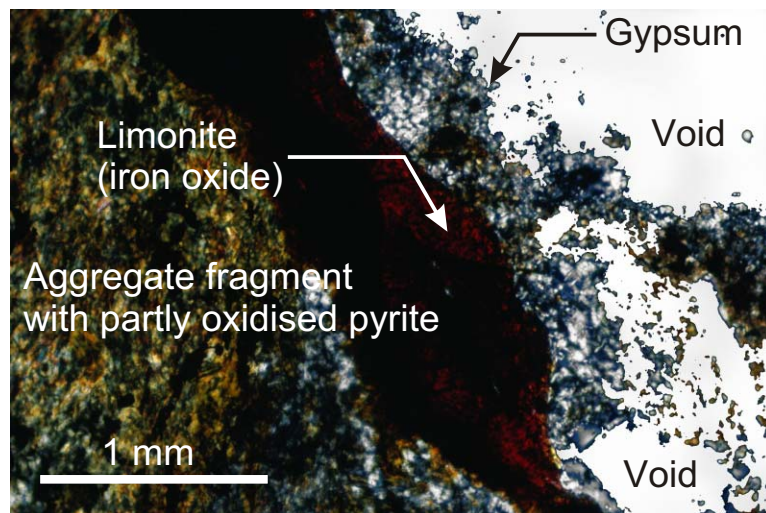
Figure 2-7. Microscope thin section showing strongly oxidised pyrite in contact with friable cement that has partly collapsed into an air void. Calcium carbonate in the cement has been converted to gypsum by reaction with sulphuric acid. The acid forms as pyrite is oxidised.

In low strength, high voidage concrete (low fines mass concrete and blockwork) degradation results mainly from sulphide oxidation and direct sulphate attack on the cement. Secondary gypsum grows at aggregate - cement interfaces and in the carbonated cement matrix. Degradation is caused by rupture of cement-aggregate bonds, disintegration of cement 'bridges' between aggregate fragments and pore volume collapse. Initial pyrite concentrations of at least 0.5% are generally required for major degradation to occur.

The second mechanism is associated with the use of mesothermal, mudstone-hosted lead ore processing wastes like those used in the Perranporth area and East Cornwall. These aggregates carry little liberated sulphide but have abundant graphitic mudstone wallrock with fine-grained, disseminated, sometimes framboidal pyrite (figure 2-8). Degradation results from oxidation of fine pyrite and bulk expansion of the mudstone aggregate. Expansion is caused by growth of secondary minerals in lensoid veinlets parallel with bedding and/or cleavage in the mudstone and at the interface between the aggregate and the cement (figures 2-9, 2-10, 2-11). Gypsum is the most important secondary mineral (figure 2-12). Water-soluble phases including Fe(II) sulphates and potash alum, formed by direct sulphate attack on phyllosilicates in the mudstone, are also found. Expansion of mudstone aggregate leads to propagation of open microfractures in the cement matrix (figure 2-13). Paucity of secondary sulphates in matrix cracks and absence of replacement gypsum indicate that direct sulphate attack on the cement is of minor importance. Degradation proceeds slowly and serious effects may not be apparent even after 50-60 years. Initial pyrite contents less than 0.2% may be enough to cause major damage.
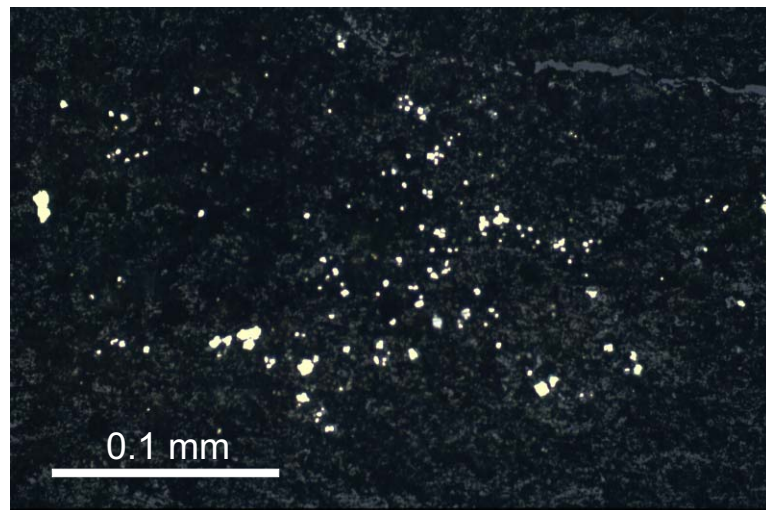
Figure 2-8. Lead ore processing waste from Wheal Mary Ann Mine, Menheniot, near Liskeard. Microscope polished specimen showing mudstone aggregate fragment with very fine-grained, disseminated pyrite (pale yellow).Graphite is medium grey. It is typical of material from the zone of wallrock alteration, adjacent to the lode.
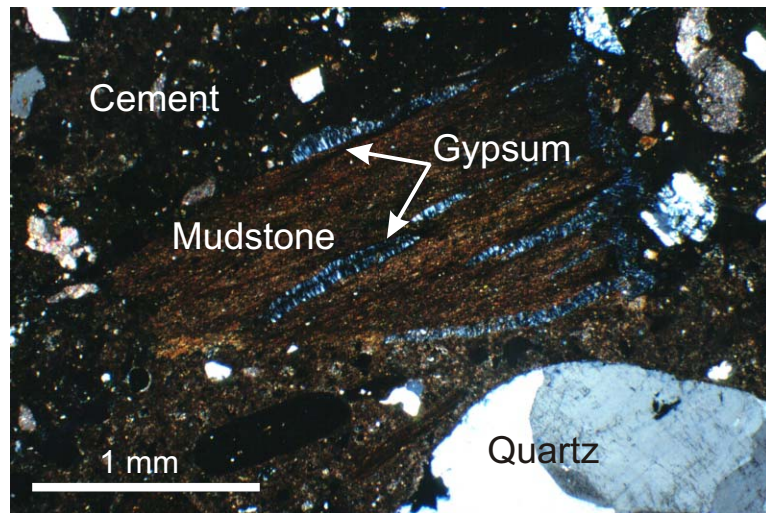
Figure 2-9. Microscope thin section of concrete made with lead ore processing waste aggregate from Wheal Mary Ann Mine, near Liskeard. Lensoid veinlets of very fine-grained fibrous gypsum have grown along cleavage planes and at interfaces between the aggregate and the cement.
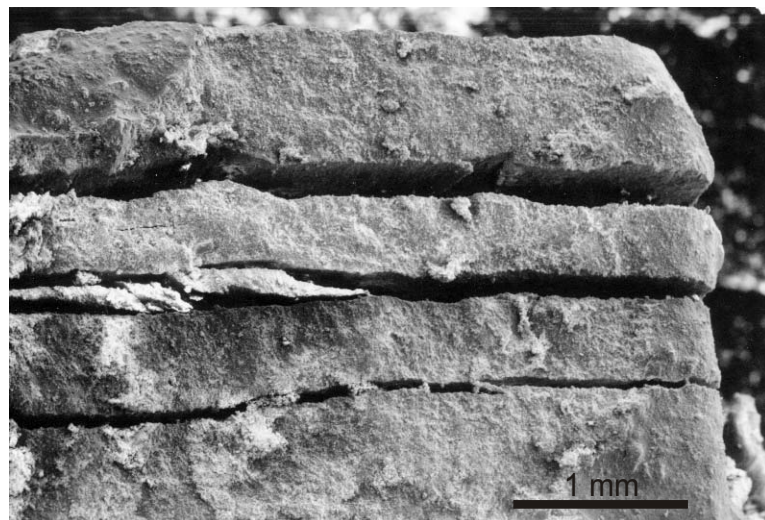
Figure 2-10. Photomicrograph taken under the scanning electron microscope (secondary electron image), showing a mudstone aggregate fragment in concrete made with lead ore processing waste aggregate from Wheal Mary Ann Mine. The mudstone shows severe cleavage-parallel spalling caused by growth of secondary sulphate minerals. The secondary phases include gypsum, potassium alum and hydrated ferrous sulphate. Gypsum forms by reaction between soluble sulphate ions (oxidation product of pyrite) and calcium-rich pore fluids in the cement. The alum is probably formed by sulphate attack on phyllosilicate minerals in the mudstone. Ferrous sulphate is a primary oxidation product of pyrite.

Figure 2-11. Strongly exfoliated mudstone aggregate in mass concrete. Ruined mill building at West Wheal Kitty Mine, near St Agnes.
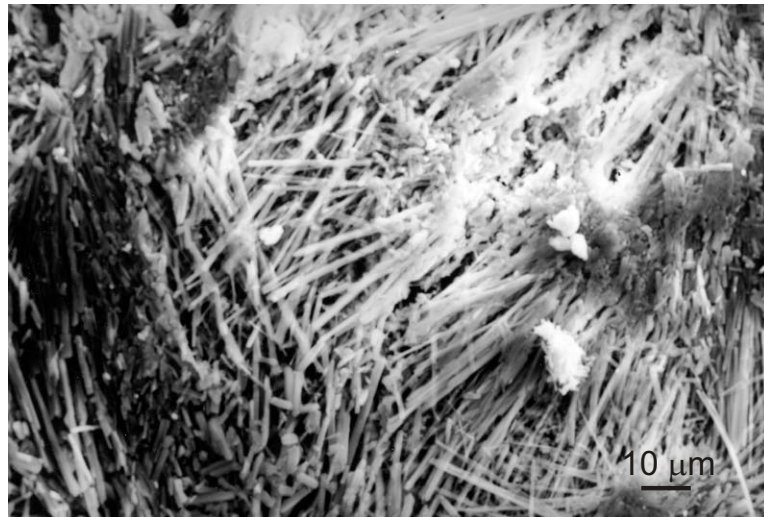
Figure 2-12. Photomicrograph taken under the scanning electron microscope (secondary electron image) showing very fine-grained fibrous gypsum growing on the surface of a pyritic mudstone aggregate fragment.
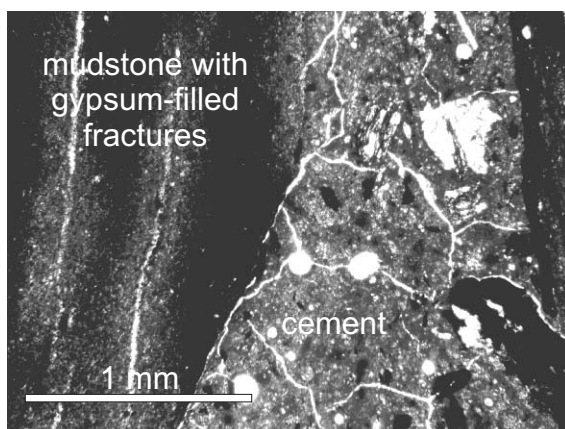
Figure 2-13. Photomicrograph of thin section showing microcrack propagation in the cement surrounding an expanded mudstone aggregate fragment. The aggregate is the lead ore processing waste from the former East Wheal Rose Mine, near St Newlyn East. This material is responsible for most concrete degradation in the Perranporth area.

External evidence of aggregate-related deterioration only appears when degradation has reached an advanced stage and affected the full thickness of the wall. Serious cracking may develop in the render cover and sometimes large pieces of render become detached from the walls. Advanced degradation of concrete made with coarse tin - copper -arsenic wastes usually causes the development of branching irregular open cracks in render overlying blockwork and mass concrete. This type of deterioration is characteristic of the Camborne - Redruth area (figures 2-14, 2-15).

Figure 2-14. Irregular branching cracks (many recently repaired) in render overlying seriously degraded blockwork. The aggregate is a sulphide-rich copper-arsenic mining waste typical of the northern part of the Camborne - Redruth mineralised district. House near Camborne.

Figure 2-15. Wide branching cracks in render overlying severely degraded mass concrete. The aggregate is a very coarse, low fines copper mining waste. Commercial property in Camborne.

Degradation of concrete blocks made with lead ore processing waste, rich in pyritic mudstone, is usually characterised by quasi-rectilinear cracks that follow mortar joints between the underlying blocks (figure 2-16). Lead ore processing wastes are unknown in mass concrete walls.

Figure 2-16. Severe cracking in render overlying blockwork. The cracks commonly follow mortar joints between blocks in the underlying wall. This type of render cracking is characteristic of degradation of blockwork made with lead ore processing wastes in the Perranporth area and East Cornwall. House at Perranporth (now demolished).

Crack patterns in render overlying degraded concrete seem to depend more on the nature of the aggregate than the structure of the wall. The reasons for this are not fully understood and further investigation is required. They may be related to contrasted degradation mechanisms. Direct sulphate attack on the cement and pore volume collapse, which is characteristic of sulphide-rich tin-copper arsenic wastes in West Cornwall, does not appear to be accompanied by bulk expansion of the concrete (Lane *et al.,* 1999). Alteration of pyritic mudstones - the failure mechanism of lead ore processing waste aggregates - does lead to bulk expansion of the concrete.

It is usually difficult to study concrete deterioration in the field, except occasionally when houses are being demolished, or in dark and cramped conditions under floors or in roof voids. However, the many disused mine buildings in the region provide useful examples of aggregate-related concrete degradation. Mass concrete and locally-made blocks have been used in mine buildings since the last years of the nineteenth century. Most of these can be accurately dated. The range of aggregates used is the same as that found in domestic properties. Figure 2-17 shows a mass concrete pillar at the former Levant Mine at Pendeen. It

was probably built during the early 1920s. Though it is in an exposed position near the top of a cliff the concrete remains completely sound. Even the chamfered corners of the pillar are preserved in sharp outline. The aggregate is a stable granite hosted mine waste with no sulphide minerals.

Figure 2-18 shows concrete pillars at Wheal Kitty Mine, near St Agnes. They are in the remains of a processing plant built in 1925 - 1926. Here, the local mine waste is made up mainly of fine-grained pelitic hornfels that often carries fine-grained, disseminated pyrite. The concrete is strongly degraded due to oxidation of the pyrite and spalling and expansion of the aggregate. Similar aggregates in domestic properties are responsible for much accelerated concrete degradation in the St Agnes - Perranporth area and in East Cornwall

Figure 2-17. Mass concrete pillar at Levant Mine, near St Just in Penwith.

Figure 2-18. Mass concrete pillars in ruined mill buildings at West Wheal Kitty Mine, near St Agnes.

3 AGGREGATE DISTRIBUTION MAPS

SIMPLIFIED GEOLOGICAL MAP
OF CORNWALL AND SOUTH DEVON

DEVON

LAUNCESTON

BODMIN MOOR
GRANITE

KIT HILL
GRANITE

HINGSTON DOWN
GRANITE

Wadebridge

Callington

Bodmin

Liskeard

PLYMOUTH

CLIGGA HEAD
GRANITE

ST. AUSTELL
GRANITE

St. Austell

ST. AGNES
GRANITE

CORNWALL

Truro

Camborne

CARNMENELLIS
GRANITE

Penzance

Falmouth

LAND'S END
GRANITE

ST. MICHAEL'S
MOUNT GRANITE

GODOLPHIN-
TREGONNING
GRANITE

LIZARD
COMPLEX

Limit of metamorphic
aureole

Mineral lodes

Porphyry dykes

Granite

Devonian and Carboniferous
sedimentary rocks

Lizard Complex (Ophiolite)

0   10   20   30

KILOMETRES

DISTRIBUTION OF MINING WASTES
IN CORNWALL

0   10   20

kilometres

N

Bodmin

Liskeard

Newquay

Perranporth

St Austell

St Ives

Truro

Redruth

Camborne

Penzance

Falmouth

Main areas of tin - copper
mining and processing wastes

Main areas of lead mining
and processing wastes

Site of concrete former block plant using
lead ore processing waste aggregate

3 - 1

The main areas of use of granite aggregates
in Cornwall
(RICS Group 1-2)

Delabole • Camelford
•Launceston

Padstow • Wadebridge
•Bodmin

Callington • •Gunnislake

•Liskeard
Menheniot
Looe

Newquay•
St Newlyn East•
Lostwithiel•
St Blazey•
Fowey•
Perranporth• St Austell•
Polperro•
St Agnes•
Mevagissey•
N

St Ives• Portreath•
Truro•
Carbis Bay• Redruth•
Hayle• Camborne•
St Just Penryn•
Penzance• Marazion• Falmouth
Newlyn•
Helston•

Coarse-grained granite

Fine-grained granite

Mullion•
Coverack•

0   10   20
kilometres

The main areas of use of
dolerite and related aggregates
in Cornwall
(RICS Group 1-3)

Delabole• Camelford
•Launceston

Padstow• Wadebridge•
Bodmin•

Callington• •Gunnislake

Liskeard•
Menheniot•
Looe•
Polperro•

Newquay•
St Newlyn East•
Lostwithiel•
St Blazey•
Perranporth• Fowey•
St Austell•
St Agnes•
Mevagissey•
N

Portreath•
St Ives• Truro•
Carbis Bay• Redruth•
Hayle• Camborne•
St Just Penryn•
Penzance• Marazion• Falmouth•
Newlyn•
Helston•

Source of aggregate

Various Dolerites
East Cornwall - South Devon

Serpentinised Picrite
Clicker Tor Quarry, Menheniot

Metagabbro - Metadolerite
East Lizard Peninsula

Metamorphosed Dolerite
Penlee Quarry, Newlyn

Mullion•
Coverack•

0   10   20
kilometres

3 - 2

The main areas of use of some beach gravel aggregates in Cornwall (RICS Group 1-5)

Source of aggregate

- Camel Estuary
- Ganel Estuary
- Portreath Beach
- Porthmeor Beach, St Ives
- Mount's Bay
- Lizard Peninsula
- Ruan Lanihorne
- Charlestown Harbour
- Fowey - Polperro - Looe

The main areas of use of some river gravel aggregates in Cornwall (RICS Group 1-5)

Source of aggregate

- River Camel
- Porth Valley, North of Newquay
- Stream north of Canonstown
- Red River
- Carnon Valley Gravels
- River Fal, Ladock
- River Fowey
- River Lhyner

3 - 3

The main areas of use of sulphide- bearing
tin - copper - arsenic
mining and ore processing wastes
in Cornwall
(RICS Group 2-2)

N

Launceston
Camelford
Delabole
Padstow
Wadebridge
Bodmin
Callington Gunnislake
Newquay
Liskeard
St Newlyn East
Lostwithiel
Menheniot
Looe
St Blazey
Perranporth
Fowey
St Agnes
St Austell
Polperro
Portreath
Mevagissey
St Ives
Truro
Carbis Bay
Redruth
Hayle
Camborne
St Just
Penryn
Penzance
Falmouth
Newlyn
Marazion
Helston
Mullion
Coverack

0   10   20
kilometres

The main areas of use of
lead ore processing waste aggregates
in Cornwall
(RICS Group 2-2)

N

Launceston
Camelford
Delabole
Padstow
Wadebridge
Bodmin
Callington Gunnislake
Newquay
Liskeard
St Newlyn East
Menheniot
Looe
Lostwithiel
St Blazey
Perranporth
Fowey
St Agnes
St Austell
Polperro
Portreath
Mevagissey
St Ives
Truro
Carbis Bay
Redruth
Hayle
Camborne
St Just
Penryn
Penzance
Falmouth
Newlyn
Marazion
Helston
Mullion
Coverack

Source of aggregate

East Wheal Rose, St Newlyn East

Wheal Mary Ann, Menheniot

0   10   20
kilometres
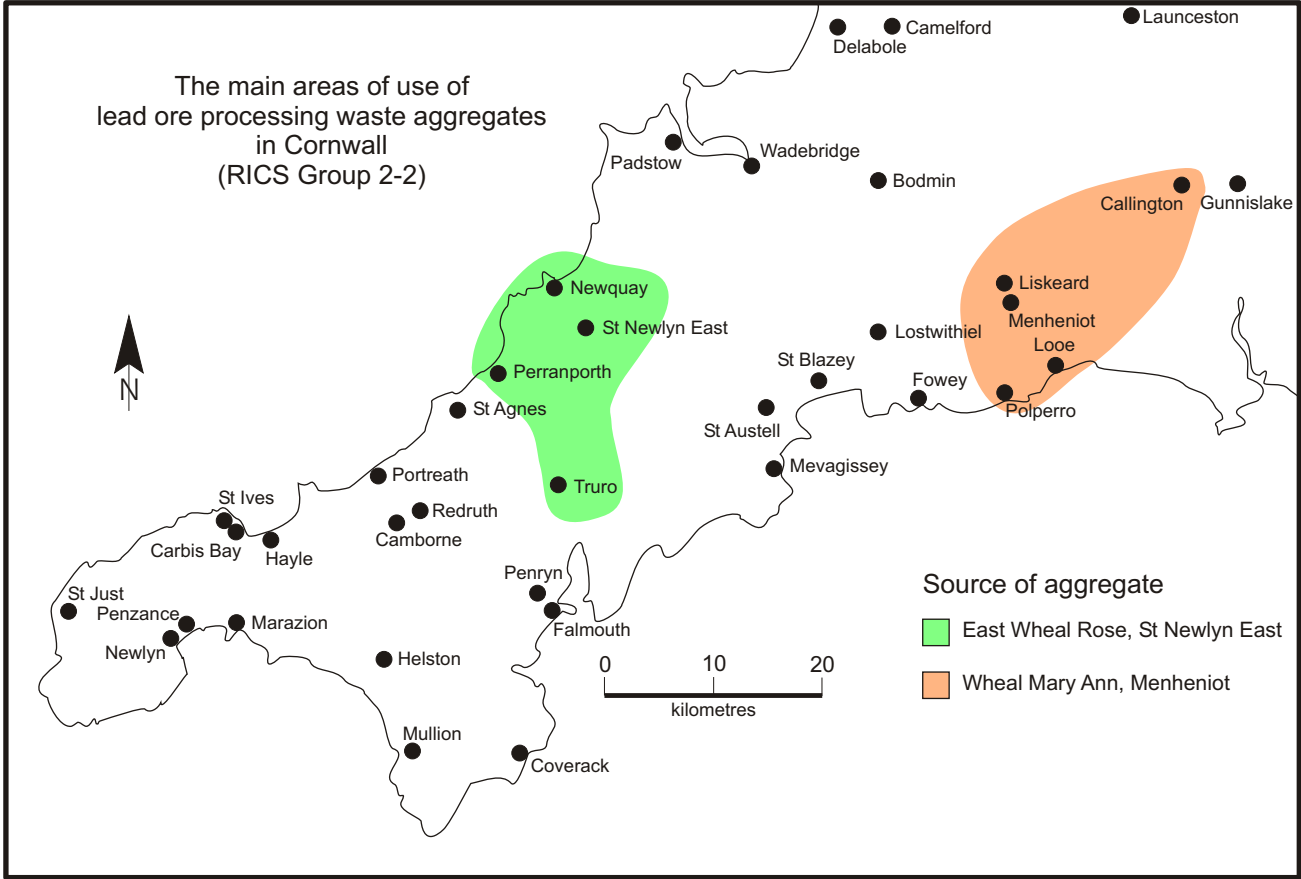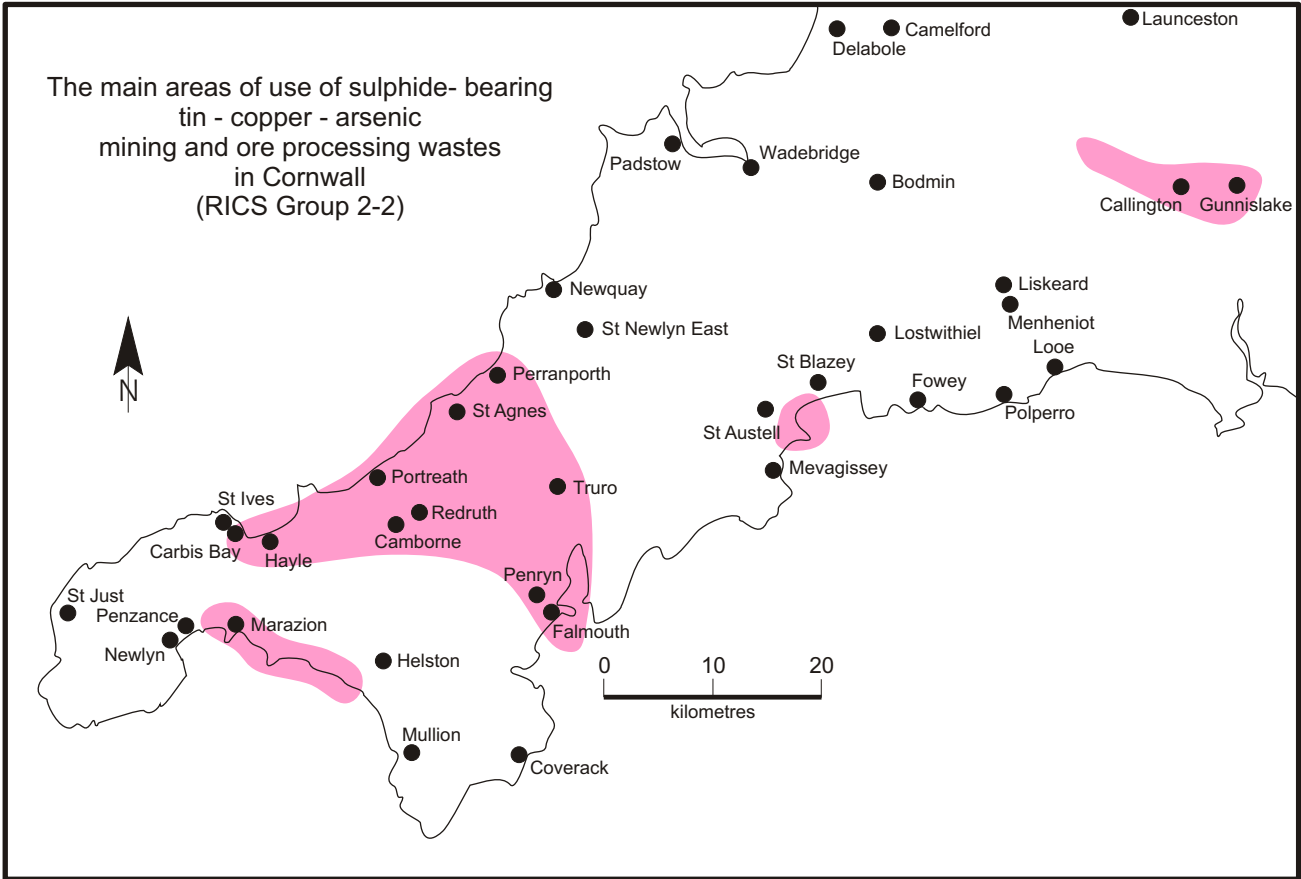
3 - 4

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