Disintegration of concrete construction induced by acid mine drainage attack

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In this paper, microanalytical investigation was conducted on disintegrated field concrete that had been used to construct a weir within a coal mine in South Africa. The concrete was in contact with polluted mine water, commonly referred to as *acid mine drainage* (AMD). Accordingly, the concrete weir had been exposed to dynamic conditions associated with flowing AMD. Investigations were conducted by optical microscopy (OM), scanning electron microscopy (SEM) equipped with energy dispersive X-ray spectrometry (EDX), and X-ray diffraction (XRD). The field concrete samples examined consisted of soft broken concrete chunks and whitish powdery substance that had crystallized and formed a surface coating on the widely cracked locations of the deteriorated concrete. No evidence of sulphate attack or pyrite oxidation was found in the investigation; acid attack mechanism was diagnosed.

KEYWORDS: Acid mine drainage; Gypsum; Acid attack; Concrete damage; Map cracking

INTRODUCTION

The mine drainage, AMD refers to polluted, typically acidic mine water formed from oxidation of sulphidic ores from mining works, which at later stages undergo chemical reactions under atmospheric conditions. In recent years, AMD has become an important problem in South Africa and worldwide, creating major threats and concerns regarding its
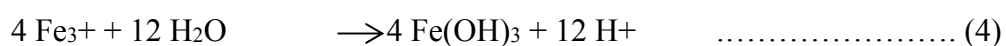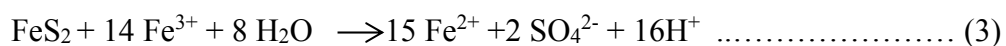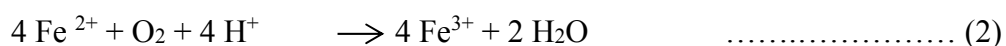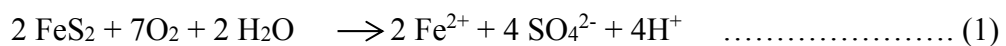
impacts on the environment and on infrastructure (IMC-AMD 2010). AMD typically occurs decades after mining activity has been abandoned at the mining site. But it is the discharge of AMD from its source of formation to the surrounding environment and water courses that amplifies the problem, resulting in damaging effects. For underground mines, AMD may pollute groundwater aquifers that usually provide quality water for urban supply, industrial and domestic consumption. Underground mines may also decant the polluted water to the surface as has been the case in the South African goldfields. Surface mines and tailings can also cause discharge of AMD at the earth's surface level, directly or indirectly impacting the environment and its inhabitants (McCarthy 2011).

Among other effects, AMD can be expected to cause impacts on engineering infrastructure including corrosion of plumbing and water conveyance systems, corrosion of pumps and water pumping equipment, deterioration of roads, bridges and other highway structures. It is in this regard that the observed degradation of the field concrete occurred as reported in (Azene & Ekolu 2012). In the literature, the problems resulting from the presence of sulphate bearing aggregates in concrete have generally been well-established and studied quite significantly. It is known that sulphate-bearing minerals of pyrites and pyrrhotites undergo oxidation, producing sulphuric acid and degradation within the cementitious matrix (Oberholster, du Toit & Pretonius 1984; Bromley 2015; Rodrigues, Duchesne, Fournier, Durand, Rivard & Shehata 2012; Tagnit-Hamou, Saric-Coric & Rivard 2005; Cody, Spry, Cody & Lee 1997; Thomas, Kettle & Morton 1989; Shayan 1988; Ayora, Chinchon, Aguado & Guirado 1998). However, there are hardly any research papers concerning an interaction between AMD and concrete. Perhaps rarity of these scenarios is related to the typically, remote location of AMD sources, being found in mines far removed from the areas of massive infrastructure. However, some concrete structures are also used at mine sites although to a relatively small scale. The closest past investigations of this kind, conducted on

AMD-concrete interactions, were laboratory experiments by Breitenbucher & Siebert (2008). They reported that solutions containing high sulphate concentrations and iron (II) sulphates exhibited acid attack at values in the range of 4pH. Although AMD has recently become quite a significant issue in South Africa, there is little or hardly any research so far done concerning its effect on infrastructure materials. This paper directly links degradation of concrete construction in the field to an attack by AMD from the mines.

Acid mine drainage

There are different forms of acids that may cause attack on concrete, ranging from weak acids such as acetic, carbonic, lactic, tannic, phosphoric acids to strong acids namely nitric, sulphuric, hydrochloric acids. In the current investigation, the acidic (mine) water under study is a by-product of pyritic oxidation typically emanating from abandoned mining works and resulting from exposure of the pyrites to oxygen and moisture. It may be emphasized that the formation of sulphuric acid (or the AMD) is a cyclic process of regeneration leading to its continuous discharge until the pyrites are exhausted or the support environmental conditions terminate. Understanding of AMD formation process was mainly recognized in the 1980-90's (Bromley 2015, Howie 1979, 1992, Newman 1998). This reaction process is explained by the following equations (1) to (4) (Bromley 2015, Blowes et al):

$$2\ FeS_2 + 7O_2 + 2\ H_2O \longrightarrow 2\ Fe^{2+} + 4\ SO_4^{2-} + 4H^+ \quad \ldots\ldots\ldots\ldots\ldots (1)$$

$$4\ Fe^{2+} + O_2 + 4\ H^+ \longrightarrow 4\ Fe^{3+} + 2\ H_2O \quad \ldots\ldots\ldots\ldots\ldots (2)$$

$$FeS_2 + 14\ Fe^{3+} + 8\ H_2O \longrightarrow 15\ Fe^{2+} + 2\ SO_4^{2-} + 16H^+ \quad \ldots\ldots\ldots\ldots\ldots (3)$$

$$4\ Fe3+ + 12\ H_2O \longrightarrow 4\ Fe(OH)_3 + 12\ H+ \quad \ldots\ldots\ldots\ldots\ldots (4)$$

Initially, pyrites react with oxygen and water to produce ferrous (iron II) oxide and sulphuric acid (sulphate and acidity) as shown in equation (1). With abundant presence of atmospheric oxygen and moisture, the ferrous ions convert to ferric iron, both forms existing in dissolved state (equation 2). The ferric oxide formed from equation (2), may further oxidise additional pyrites, creating a cycle of continuous acid generation given in equation (3). Additionally, a bacterial species *theobacillus ferrooxidans* is known to oxidise iron and sulphur in pyrites at a low pH < 3.5. At later stages, after the formation of AMD and during its discharge into the environment, hydrolysis may occur depending on the pH level of the solution. If the AMD is highly acidic with low pH < 3.5, then little or no hydrolysis may occur. At higher pH, the ferric (iron III) oxide will convert to ferric hydroxide which then precipitates out of solution as brownish-orange, rust-like product.

The stages defined by equations (1) to (3) represent the generic process by which AMD forms. In a typical case, the AMD formed seeps through various rock strata as it flows from its reaction sites to the general environment, and in the process dissolves metals from rocks and other materials within its pathway. These dissolved metals then become incorporated into the AMD chemical composition. Accordingly, AMD is typically characterized by high acidity, high content of heavy metals, high amount of dissolved solids and high sulphate concentrations. Such a chemical signature is more complex than the composition of mineral acids. For this reason, AMD can be viewed as an acid or acidic water of a unique category; it cannot therefore be expected to behave precisely as ordinary acids due to possible interactions that could result from its various dissolved ions.

Possible mechanisms of concrete attack by acid mine drainage

Considering the typical chemistry of AMD which consists of high acidity and high sulphate concentration, the postulated AMD damage attack on concrete may take the forms of acid attack and/or sulphate attack mechanisms.

Acid attack in concrete

When an acid comes in contact with concrete, the first line of attack arises from the reaction of the acid with portlandite (calcium hydroxide - CH) leading to the formation of calcium sulphate (i.e. gypsum) and water. In the case of sulphuric acid, the reaction may be written as (Zivica & Bajza 2001):

$$H_2SO_4 + Ca(OH)_2 \rightarrow CaSO_4 + 2H_2O$$
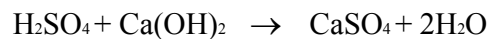
It is generally acknowledged that the second phase involving destruction of tobermorite or C-S-H will only follow after portlandite dissolution (Hill et al 2003, Sersale et al 1998). The second phase is a more advanced and severe acid attack above and beyond the effects arising from portlandite dissolution alone. It is essential to note here that the reaction product of acid attack is principally gypsum. However, other sulphate bearing reaction products may also be present in smaller quantities. Acid attack on concrete is generally exhibited at less than 6.5pH (Fattuhi & Hughes 1983) but becomes severe and more pronounced at 3 to 4 pH levels, which is the range of pH values that were determined for the AMD under this investigation (Azene & Ekolu 2012). According to the German standard DIN 4030 (2008), the degree of water aggressiveness is considered to be severe for a pH range of 4.5 to 5.5 and very severe for pH < 4.5 (Ekolu & Azene 2012, Earlie & Callaghan).

For groundwater, the conditions suggestive of potential acid attack are: water of pH ≤ 5.0, total acidity ≥ 25 mg per 100 g of soil, and a sufficient groundwater rate of replenishment (Earlie & Callaghan, Bearly 1980). The acid will typically attack and destroy the surface concrete but the latter will in turn tend to neutralize the acid due to high alkalinity of concrete

(Ekolu et al 2013, Makhloufia 2014). A fresh supply of acid will launch further attacks progressively into the interior of concrete (Woodson 2009, Attiogbe & Rizkalla 1988). It has been shown that an acid solution concentration of 1% H_2SO_4 can attack and cause significant corrosion damage within 1 to 12 months (Ash 1951). Most concrete structures also contain steel reinforcement which is protected by a thin layer of about 50 mm thickness of concrete cover. Erosion of the cover concrete would expose the reinforcement not only to acid attack but also to steel corrosion.

An extensive body of literature has shown that upon exposure of cementitious systems to acidic media over a prolonged period of time, the physical damage that ensues is characteristically associated with loss in mass, loss in compressive strength, increase in porosity and permeability (Fattuhi & Hughes 1983, Attiogbe & Rizkalla 1988, Fattuhi & Hughes 1988, Adesanya & Raheem 2010, Senhadji 2014). These properties of course are symptomatic of the underlying intrinsic degradation of chemical phases, which may only be determined through microanalysis. Indeed, studies using SEM/EDX and XRD show that the microstructural damage due to acid attack typically exhibits microcracking, often infilled predominantly by a whitish reaction product, gypsum (Senhadji 2014, Song et al 2005, Rendell & Jauberthie 1999, Tulliania et al 2002, Hasan 2009, Xie et al 2004).

Sulphate attack in concrete

External (as opposed to internal) sulphate damage would be the most likely form of sulphate attack relevant for the AMD scenario. From understanding of hydration reactions of cement, the most predominant phases present in healthy hardened concrete are monosulphate, tobermorite and portlandite along with unreacted cement compounds and unconverted ettringite. In the process of external sulphate attack, the sulphate ions from an external source (in this case, AMD water) penetrate into concrete. These ions then react with free and

abundantly available portlandite in the ground mass of concrete, forming gypsum which in turn converts monosulphate into ettringite (Thomas & Skalny 2006, Tian & Cohen 2000, Al-Amoudi Omar 2002) as given in the following chemical reaction:

$$C_3A.C\check{s}.H_{12} + 2C\check{s}H_2 + 16H \quad \rightarrow \quad C_3A.3C\check{s}.H_{32}$$

(monosulphate) (gypsum)   (ettringite)
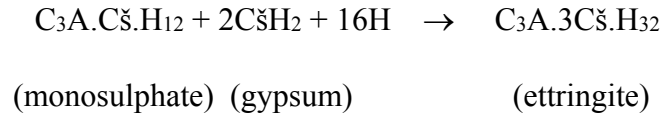
Hence in a cementitious system subject to sulphate attack, ettringite is the predominant reaction product (perhaps with some presence of gypsum), generating expansive pressures reported to be in the range of 8 MPa depending on the sulphate concentration (Müllauer 2013) . These high pressure levels by far exceed the tensile strength of concrete. Accordingly, the formation of gypsum and ettringite minerals is expansive, leading to disruption of the concrete and is characterized by mass increase, cracking and disintegration as well as compressive strength loss (Santhanam 2003, Ekolu & Ngwenya 2014a, 2014b, Ekolu 2014).

The common different types of sulphate salts known to cause attack in concrete are typically, Na_2SO_4 (Glaubers salt), $MgSO_4$ (Epsom salts) and $CaSO_4$ (Gypsum). For an AMD signature that has a high concentration of iron, the dominant sulphate compound would most likely be $FeSO_4$ (iron sulphate). But studies have shown that $FeSO_4$ may not be as damaging or expansively attacking as the alkaline-based sulphate compound forms (Breitenbucher & Siebert 2008). In those sources of AMD where alkalis such as sodium, potassium or magnesium may be present in significant concentrations, normal sulphate attack could be possible. It can therefore be surmised that the possibility of sulphate attack depends on the source (and therefore chemical composition) of the AMD.

BACKGROUND TO THIS INVESTIGATION

While conducting field survey in an abandoned coal mine, the authors observed severe exfoliation of a concrete weir that was in contact with AMD (Figure 1). A detailed

description of the field inspection undertaken was given in an earlier publication (Azene &

Ekolu 2012), at which an index assessment for AMD aggressiveness was conducted. This

paper presents microanalytical study of concrete samples that were taken from the field site

and subjected to examination with the aim of identifying the possible mechanism of attack.

The study was conducted using OM, XRD, and SEM with EDX.

[Insert Figure 1]

FIELD SAMPLES

The samples used in this investigation were the AMD water and the deteriorated concrete

specimens collected from the field site. As described in Azene & Ekolu (2012), severe

exfoliation had been exhibited in concrete above the water line, showing:

- A line of disintegration separating concrete above the water line from the foundation
  (Figure 1)

- Map cracking pattern, seemingly oriented longitudinally along the length of the wall
  lining. The deterioration and cracking occurred across the full thickness of the 250 mm
  concrete weir (Figure 1)

- Swelling and spalling of the concrete leading to falling out of disintegrated chunks of
  concrete

- Depositions of powdery salt crystals on the concrete surface. The surface depositions
  exhibited a white-yellowish discoloration

- Erosion of cement past matrix leaving protruding aggregates

Acid mine drainage water from the coal mine

Table 1 shows the chemical composition of AMD water collected from the source of attack on concrete. The crucial parameters of the AMD are its low pH of 3.0 and high sulphate concentration of 5200 ppm. This degree of water aggressiveness falls under *very severe* category (Neville 1981). It can be seen from the water chemistry that the main ion species responsible for aggressiveness in the AMD were the Cl^-, Fe^+ and SO_4^{2-} ions. Evidently, the concentrations of Cl^- and Fe^+ in the water are too low to be of concern, leaving the SO_4^{2-} to be the possible species with potential to inflict damaging attack especially considering the high sodium concentration. However, it was of interest in this study to determine whether the active mechanism was acid attack, sulphate attack or combined acid and sulphate attack processes. It may be noted that use of the term "acid" in AMD does not necessarily imply that all forms of AMD are acidic. Infact, some forms of AMD are not acidic at all, and have a neutral pH. So the potential for AMD attack on concrete, metals or any other materials, depends on its geological source which in turn relates to its chemical signature.

Table 1 Chemical composition of the acid mine drainage (Azene & Ekolu, 2012)

pH	EC mS/m	CaCO₃ mg/l	Cl mg/l	P mg/l	SO₄ mg/l	Fe mg/l	Ca mg/l	Mg mg/l	Mn mg/l	K mg/l	Na mg/l
3.0	907	66	32	<0.1	5200	23	990	247	14	32	1168

Exfoliated concrete and reaction products

The exfoliation of concrete was observed at upper layers of the weir, above the water-line as described in Azene & Ekolu (2012). The concrete was severely exfoliated to the extent that it softened and crumbled; and could be easily broken-off by hand. The crumbled pieces of concrete were collected and used for analytical studies. Another interesting feature of deterioration was the whitish powder crusts of a reaction product formed at the surface of the severely cracked concrete. Samples of the powder salts were also carefully collected for analytical investigation in the laboratory.

ANALYTICAL STUDIES AND DISCUSSIONS

The three main techniques that were used in microanalysis and petrographic examination of the deteriorated field concrete consisted of OM, XRD, and SEM/EDX. Different samples of the field concrete were prepared in the laboratory, and used for analytical studies.

Optical microscopy

Thin sections were prepared from the concrete chunk samples and examined using a research grade optical microscope with high resolution imaging capabilities of up to 400X magnification. Petrographic examination showed characteristics of a severely altered concrete matrix exhibiting distinct features of deterioration. Non-destructive testing of the concrete using the Schmidt hammer method (Neville 1981, Breccolotti et al 2013) found the compressive strengths to be in the range of 20 MPa for the concrete made with 22 mm aggregates. It is likely that a fairly high water- cement ratio in the range of 0.7 to 0.85 and low cement contents between 200 to 350 kg/m^3, were used in the concrete mixture.

Aggregates

Petrographic examination revealed the presence of predominantly quartz aggregates and opaque minerals, as the main types of aggregates used in the concrete mixtures. Figure 2a illustrates the typical quartz aggregates identified in the damaged concretes. Evidently the aggregates are circumvented by a network of cracks, as discussed later. Figure 2b gives a closer view of the aggregate surface features. It can be seen that the quartz particles are severely weathered, indicating a likely leaching away of surface material including cement paste and the associated phases. Leaching is a highly likely possibility given the exposure of the concrete to flowing AMD which then caused erosion of leachable phases both from the

cement matrix and aggregate surface. There was also an observation of fractured quartz aggregate particles as seen in Figure 2c. However, no infilling of the fracture was evident, indicating this damage to be of mechanical nature. A close up of the fractured particle, shown in Figure 2d shows a good bond between the particle and the cement paste but there appears to be concentration of unreacted pyrites lining along the aggregate rim and further into an opaque mineral aggregate. In Figure 3a, sulphate bearing minerals, most likely pyrite and pyrrhotite, can be seen distributed throughout the opaque mineral aggregate. This feature can be seen further at a higher magnification given in Figure 3b, clearly showing a widely disseminated (pale yellow) pyrite within the opaque aggregate particle.

Microcracking and expansive mineral phases

Thin sections were also examined for the presence of microcracks and expansive phases. Figure 4 gives microscopic images of microcracking observed in thin sections of the deteriorated concrete samples. In Figure 4(a) and (b), microcracks can be seen circumventing the aggregate particles, undertaking to follow aggregate rims, which in healthy concrete, is a typically weak interfacial transition zone (ITZ) comprising large depositions of calcium hydroxide relative to the CH present in the mortar matrix (Scrivener & Pratt 1994, Ollivier et al 1995, Harutyunyan et al 2000). The interconnected cracks run directly through the paste matrix, forming a multidirectional crack network. All the microcracks along the ITZ and paste matrix, are infilled with a mineral phase, later identified through SEM analysis, to be gypsum. It may be emphasized that this observation was not an isolated case but rather a characteristic feature. The visibly fibrous gypsum infilling, perpendicularly oriented to the crack walls indicates exertion of expansive pressure during the phase growth. In Figure 4(b), an infilled crack can be seen running through a severely weathered and sutured quartz particle as well as around its rim. This appears to be an isolated case where the particle may have

been fractured mechanically or due to weathering. In this case, the microcrack and its gypsum infilling opportunistically developed its path through the fractured particle. There is no evidence within or at the aggregate rims suggesting that the particle may be involved in an expansive reaction.

In Figure 5, a map cracking pattern is evident but also present are oriented parallel cracks, especially seen in Figure 5a. This combination of map and parallel microcracks is consistent with the cracking patterns observed during physical examination of the exfoliated concrete weir, as shown in Figure 1.

Scanning electron microscopy

The SEM examination allows characterization of the phase morphology which usually provides useful information in phase identification. The EDX gives elemental information and their relative proportions. This information is often used to confirm a distinct presence of specific phases. Concrete is a heterogeneous material with several inherent phases consisting of pores, unhydrated cement phases, hydration products and minerals, aggregates. Durability attack typically introduces new phases that are not normally present in substantial quantities within the hardened cementitious system. In microanalysis, such unusual phases can be identified and examined.

[Insert Figure 2]

[Insert Figure 3]

[Insert Figure 4]

[Insert Figure 5]

Figure 6a gives a backscattered electron image of deteriorated concrete taken from the field

site. The main mineral phase seen in the micrograph is gypsum. Also seen in the image is

contamination associated with clay and plant material intermixtures. The identified quartz

is a phase from the sand used in the concrete, confirming observations made by

petrographic examination. The dominant presence of gypsum in the pore structure is

unusual in normal concrete and represents a likely attack process. It is also evident that

gypsum forms the major groundmass product of the micrograph. Figure 6b shows the

associated EDX spectra for the various phases identified. It can be seen (Figure 6b) that the

EDX spectra for gypsum is mainly calcium (Ca), sulphur (S) and oxygen (O) which form

the main elemental composition of the mineral phase. Similarly, fine aggregate of quartz

consists predominantly of silica (SiO_2). The other spectra are for the clay and plant

contaminants found intermixed in the concrete. Further SEM analysis using another sample

taken from the deteriorated field concrete is given in Figure 7, also showing the electron

micrograph and the associated EDX spectra of the major phases observed. Again, the

electron micrograph shows an infilling of gypsum as the dominant product in the

groundmass of the matrix. The morphology of the gypsum consists of crumbled,

compacted crystals being perhaps an indication of the existence of expansive pressures

exerted against the crack walls. No other sulphate bearing phases such as ettringite or

thaumausite were observed. Also not observed were any rust product phases such as

goethite (FeO(OH)), Ferrihydrite (Fe(OH)$_3$) or heamatitie (½Fe$_2$O$_3$), which rules out possible involvement of pyrite oxidation in the attack.

X-ray diffraction

Samples broken-off from the mortar matrix of disintegrated concrete were dried and ground with mortar and pestle into fine powder passing 90 μm sieve. The powder samples were back-loaded into the sample holders and analysed. The XRD analysis determined the final reaction products and phases predominantly present in the cementitious system. Figure 8 shows the XRD patterns for the disintegrated concrete samples. The samples comprised phases that were identified to be quartz, gypsum and calcite. In both spectra shown, it is interesting to note that no portlandite was found among the phases identified. This implies that this phase is likely to have undergone conversion to calcite under carbonation, and/or to gypsum, the latter being the reaction product of CH with AMD. Furthermore, ettringite which is an opportunistic phase that is usually present in concrete, was generally not found. These changes in the matrix products of concrete are important indications of the conversion reactions that could have led to the observed disintegration of the concrete. Again, no trace of rust products such as goethite, ferrihydrite or hematite, were detected which also excludes the possible presence of pyrite oxidation as participant in attacking the cementitious system.

Discussion of the attack process

The AMD was shown to be of low pH of 3.0 and high sulphate concentration of 5200 ppm as given in Table 1. Accordingly, sulphate attack or acid attack processes on the concrete would be suspect, as discussed earlier. This high sulphate concentration of 5200 ppm of the AMD falls under *severe* classification (Ekolu & Azene 2012, Earlie & Callaghan). In the

XRD analysis, there was no evidence of CH being present in the concrete. In a normal healthy concrete matrix, CH is plentiful and is responsible for the high alkalinity of concrete, usually with pH ≥ 12.6.

[Insert Figure 6]

[Insert Figure 7]

[Insert Figure 8]

Upon exposure of the concrete to the low pH water of AMD, the CH must have undergone conversion to gypsum, while some calcium ions may have been leached out of concrete along with sodium and potassium alkalis, given the dynamic exposure conditions. Considering that the AMD on site was flowing at a substantial rate, there was continuous replenishment of fresh ions to reinforce the attack on concrete. Evidence from XRD analysis corroborates the observations from petrography and SEM/EDX examination, singling out gypsum as the sole reaction product found in the disintegrated concrete. In Figure 1, gypsum can be seen as the white powdery substance coating the surface of exfoliated concrete. It may also be noted that the reaction product was concentrated along large cracks, most likely leached from the concrete matrix by flowing water and deposited at the crack surface layers as water evaporated.

In summary, the evidence from microanalytical studies shows the acid attack mechanism to have been the likely cause of the observed degradation in the field concrete, following its exposure to AMD. These findings are also in agreement with the results of an experimental

work by Breitenbucher and Siebert (2008). The absence of ettringite or thaumausite excludes the possibility of sulphate attack. Similarly, there was no observation of rust phases of goethite, ferrihydrite or heamatite, indicating the absence of pyrite oxidation attack.

CONCLUSIONS

In the foregone investigation, exfoliated field concrete that had been used in a weir construction was examined. The concrete weir was in contact with acid mine drainage at its source of decant in an abandoned coal mine. Over time, the concrete had severely disintegrated. Microanalytical studies were conducted on the deteriorated concrete, by using optical microscopy, scanning electron microscopy and x-ray diffraction techniques. The main objective of the investigation was to determine the mechanism of attack that led to the concrete deterioration.

1. Petrographic examination found the concrete aggregates to be predominantly quartz particles and some opaque minerals. The quartz particles were found to have severely weathered and in some cases, there was evidence of mechanical fracturing. The opaque minerals were identified to be unreacted pyrites. Intense multi-directional microcracking was observed circumventing the quartz particles, by running along the interfacial transition zone and directly through the paste matrix. The microcracks were characterized by two patterns consisting of map cracking and parallel oriented cracking.

2. The observed microcracks contained an infilling by a mineral phase, identified by scanning electron microscopy and x-ray diffraction to be gypsum. The fibrous layers of the infilling, were visibly perpendicular to the crack walls. Besides, the gypsum crystals

exhibited crumbled morphology, suggesting exertion of pressure by the crystals during expansion.

3. No other sulphate bearing phases such as ettringite or thaumausite, that would typically exhibit similar concrete damage in form of sulphate attack etc., were observed or detected. Also, no rust products were found, which ruled out pyritic oxidation as a possible source of damage. Accordingly, gypsum was found to be the sole reaction product of attack, which points to acid attack as the mechanism responsible for the observed concrete disintegration.

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Figure 1 Disintegrated concrete weir at a site of acid mine drainage decant (Azene & Ekolu 2012)
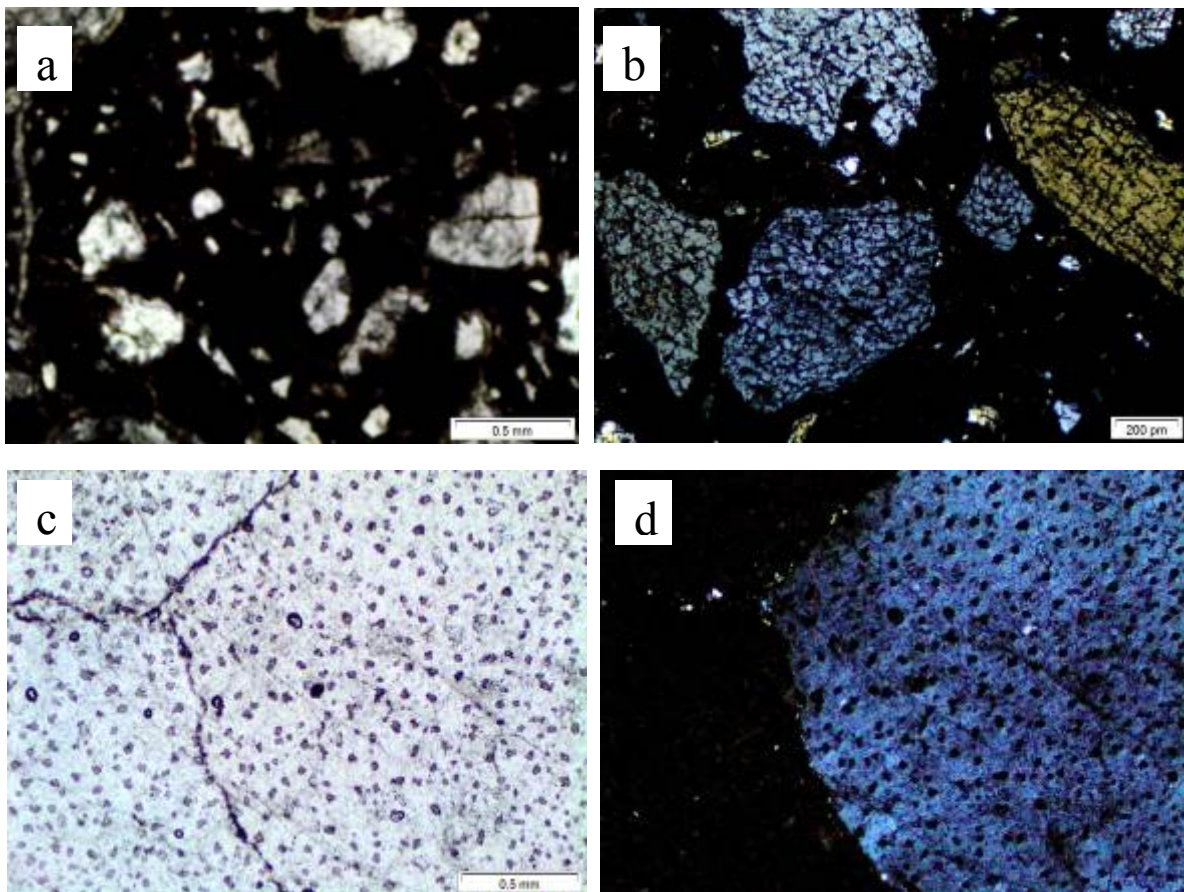

Figure 2 Photomicrographs of thin sections showing aggregate types and features under plane polarized light: (a) predominant presence of quartz particles, (b) severely weather quartz particles, (c) fractured aggregate devoid of infilling, (d) same as (c) but viewed at higher magnification.
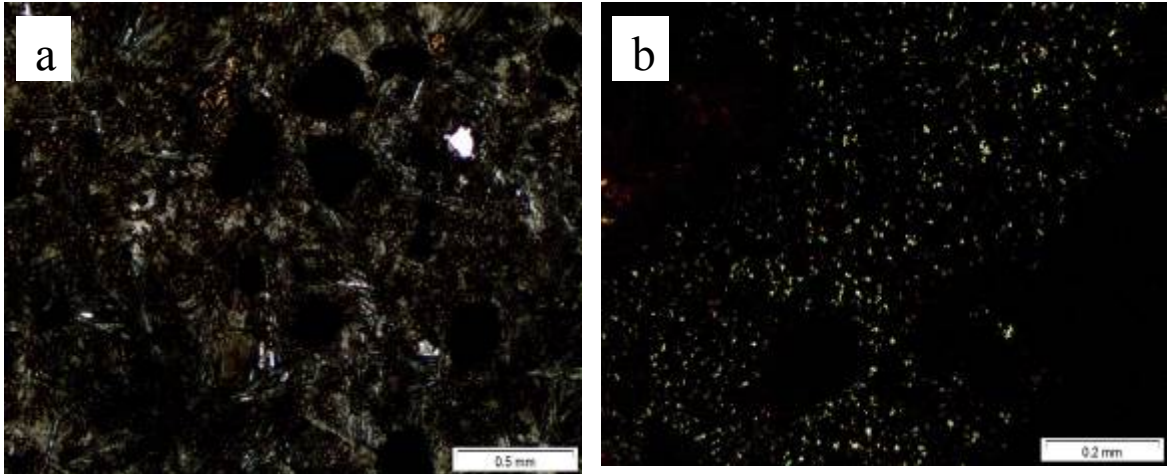
Figure 3 Photomicrographs of thin sections showing sulphate bearing minerals under plane polarized light: (a) opaque minerals, (b) a close up of (a) highlighting disseminated pyrites in an opaque particle under cross polarized light
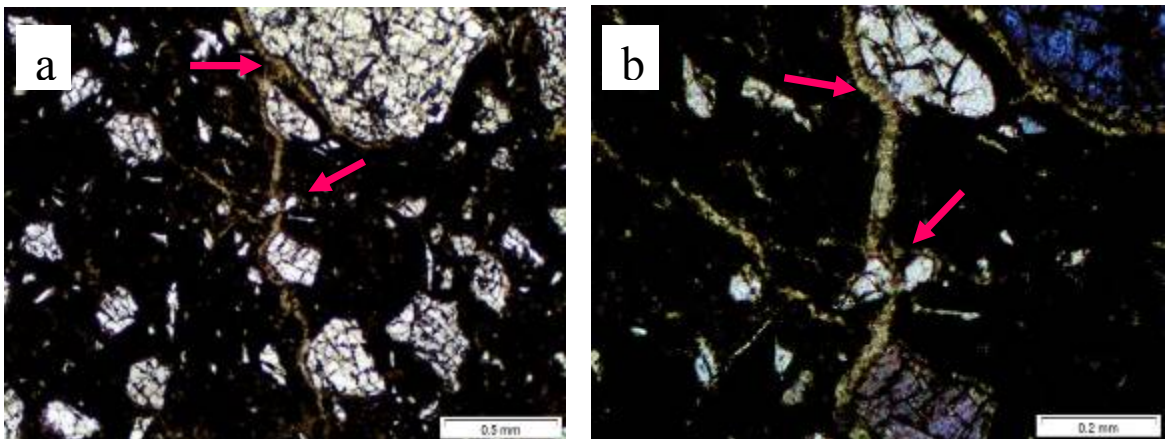
Figure 4 Photomicrographs of thin sections showing: (a) microcracks and infilling under plane polarized light, (b) a close up of (a) highlighting microcracking running through or over a sutured quartz particle in cross-polarized light
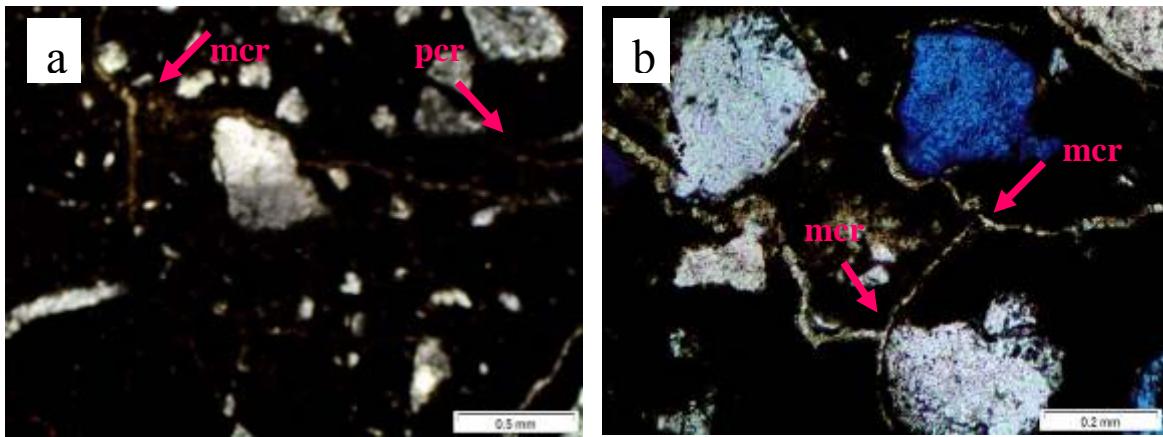
Figure 5 Photomicrographs of thin sections showing: (a) map patterns and parallel microcracks viewed under plane polarized light, (b) a close up highlighting multidirectional map cracking and infilling of cracks under cross polarized light: mcr – map cracks, pcr-parallel cracks
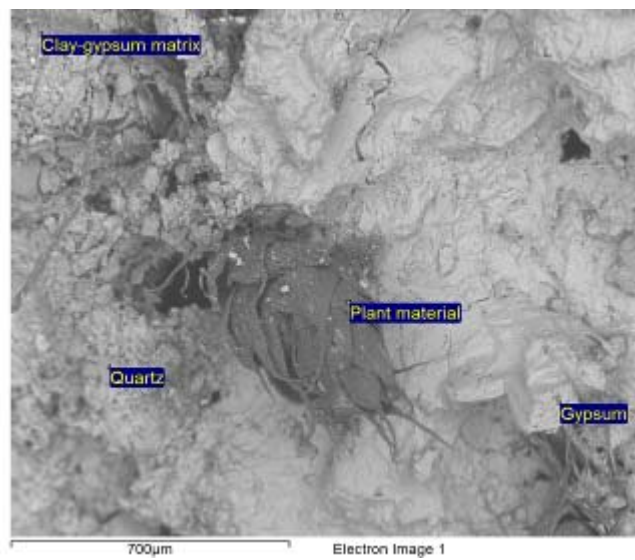
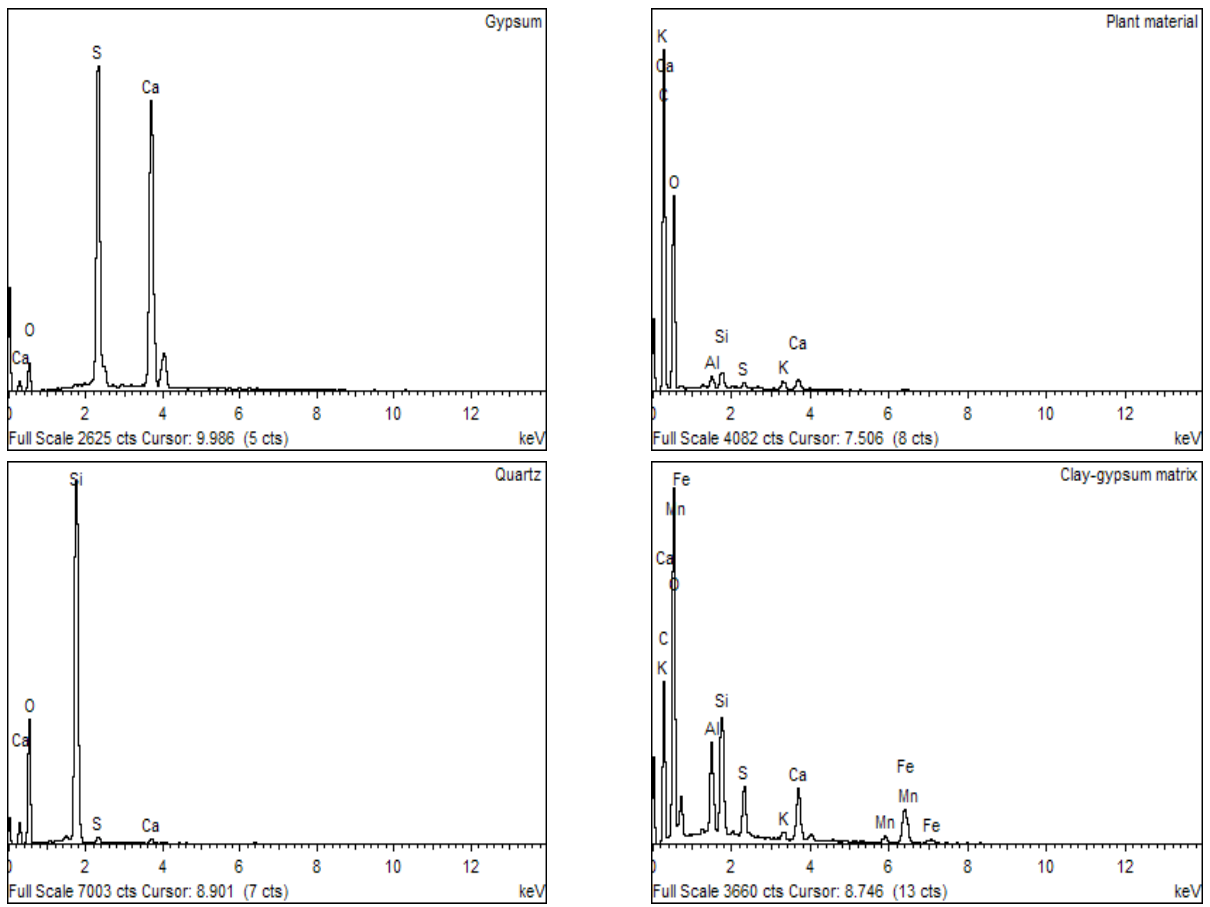**Figure 6a.** SEM image of the deteriorated concrete sample

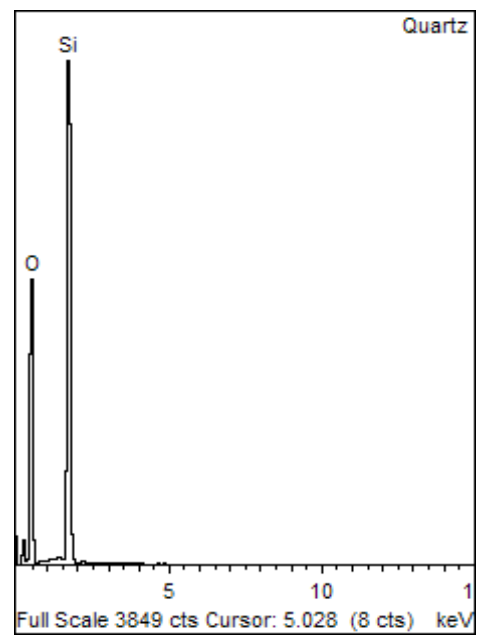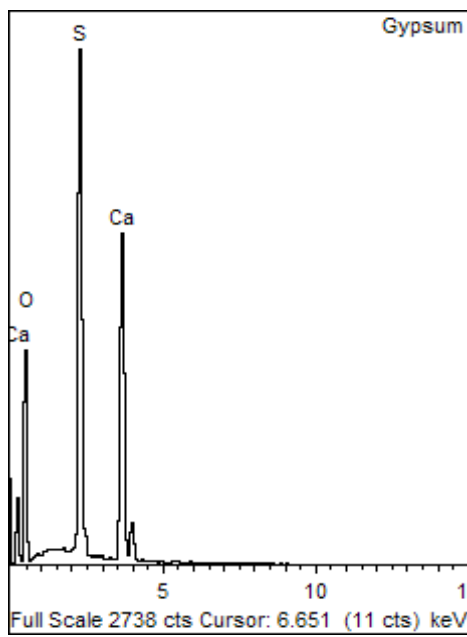**Figure 6b.** EDS spectra of various phases labeled in Figure 6a
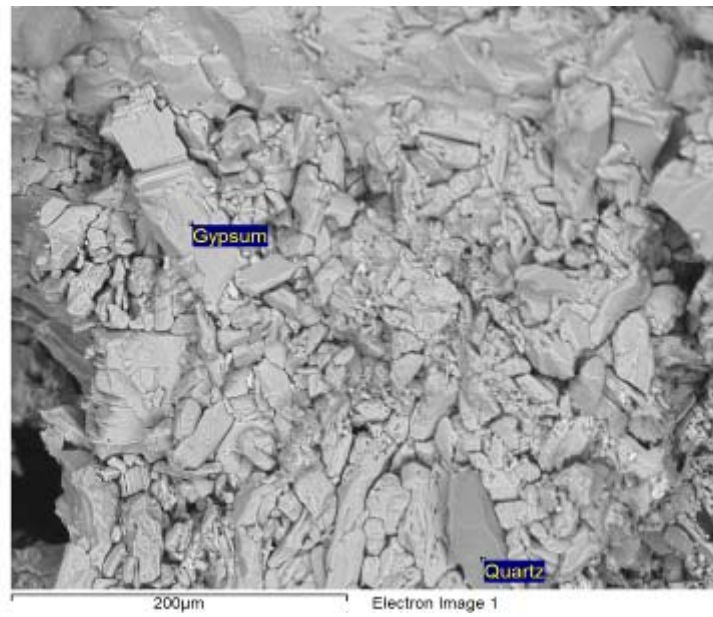
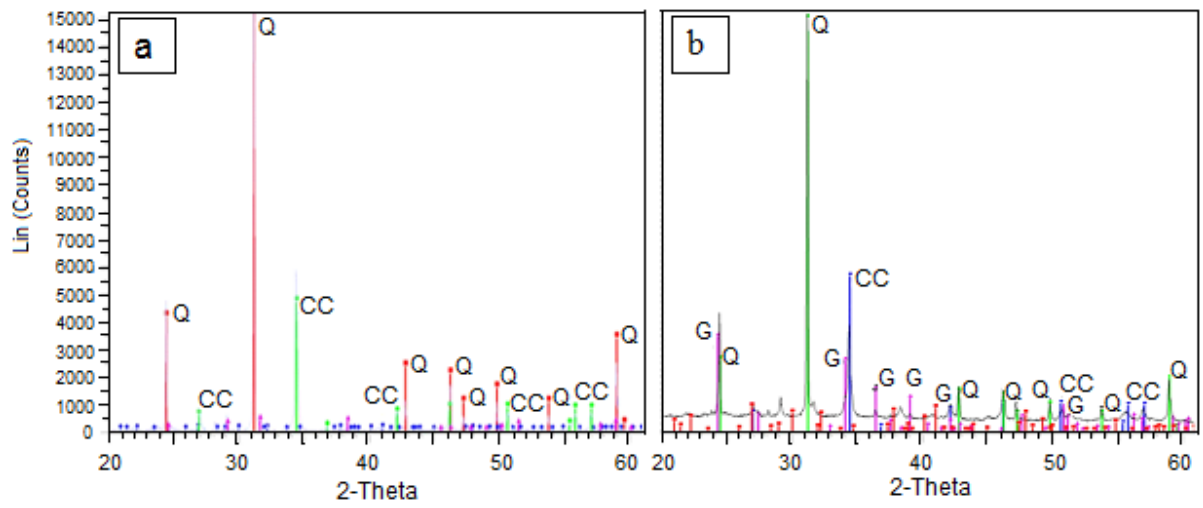**Figure 7** SEM image and EDS spectra of the deteriorated concrete

Figure 8 XRD pattern of disintegrated field concrete: Q - quartz, G - gypsum, CC - calcite