DESIGN OF QUEENSLAND ROAD INFRASTRUCTURE FOR HIGH RISK ENVIRONMENTS

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Abstract

This paper examines the current issues facing Queensland Main Roads in relation to designing road infrastructure to withstand aggressive ground conditions. Probably the two most common conditions that need to be considered for concrete structures are acid sulphate soils and sodic soils which cover 45% of Queensland. Sodic soils may cover a wide range of pH values from 3.5 to 11.5 and have associated salinity issues depending on the attached anion species. Concrete can be designed to withstand these harsh conditions and in some cases extra steps are taken such as coating piles and using polythene sheeting to protect concrete from very low pH ground conditions. As well as concrete, this paper will address the risks to road surfacings and pavements posed by problem soils including sodic, acid sulphate and saline soils. In these areas of concern it will describe what to look for, types of damage to expect and appropriate treatments. It is important that designers are made aware of the prevailing ground conditions early in the design phase so suitable strategies can be selected to ensure durable pavements and concrete structures are produced.

Keywords: bridges, pavements, concrete, durability, life cycle performance, acid attack, sodic soils, sulfate attack, chlorides

Introduction

The first section of this paper looks at the current performance of the bridge network in Queensland regarding long term performance and the issues to be faced in high risk environments. The second part looks at the performance of road surfacings and pavements in similar environments.

Discussion of Current Performance of Existing Bridge Network

In relation to Queensland's concrete bridges some 2500 in number the average life before major repairs are needed would be in the order of 50 years with probably only 1% or less of structures reaching a 100 year life. The range of distress mechanisms that have been encountered consist of:

(i)   Carbonation induced corrosion distress
(ii)   External chloride ion attack of 20 to 32 MPa Grade concretes
(iii) Aggressive Ground Conditions
  - Acid sulfate attack generated in coastal areas below 10 m AHD level.
  - Sodic (dispersive) soils – sodium rich
(iv)   Alkali-silica reaction degradation in 40 to 50 MPa concrete due to reactive aggregates and aggressive environments
(v)   Fire damage due to bush fires and petrochemical fires
(vi)   Abrasion damage due to sand loads in rivers
(vii) Impact loads due to vehicles or barges/ships

Probably the dominant two issues have been (ii) and (iv). Optimised and improved concrete technology is needed to have an appreciable affect on (i) to (vii) inclusive. Hence, Road Authorities need to invest their first dollars available in understanding their local concretes and optimising the durability performance of the concrete and then look at other potential strategies. Fig. 1 shows a schematic representation of the actual histogram of bridge performance and the desired position. The average design life needs to shift to 125 years at least to guarantee a 1% failure criterion at 100 years. The Austroads Bridge Design Code (1992) requires a design life of 100 years.

Figure 1. Schematic view of bridge service and design lives

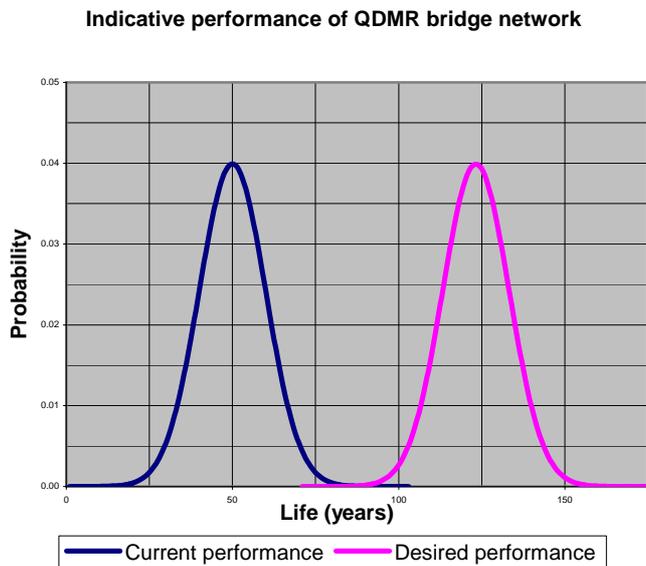Indicative performance of QDMR bridge network

Figure 2. View of Lamington Bridge built in 1896 now 107 years old

The definition of design life in the Austroads Bridge Design Code does not mean that the bridge reaches its end of life at that age or that no maintenance is needed during its life. A regular normal maintenance plan should be undertaken to counter any localised distress due to construction defects or the affects of wear and abrasion. Fig. 2 shows a view of one of the few concrete bridges in Queensland which has met and exceeded the aims of the 1992 Bridge Code even though it was built in 1896 some 96 years before the Code was published.

Genetic Origin of Soils and Rocks

Sodic (dispersive) Soils

Understanding the genetic origin of soils is important in relation to unlocking the possible chemical compositions that are to be expected in a given area. About 1/3 of the soils covering Australia are sodic in nature. The occurrence of sodic soils in Australia is related to their genetic origin from the process of weathering rock compared to the alternative of extracting sodium from saline ground conditions. Sodic soils have been defined by others (Northcote and Skene 1972) as having an exchangeable sodium percentage (ESP > 6) in the top metre of soil. In contrast saline soils have a sodium chloride concentration 0.1 to 0.2% in the surface or > 0.3% in the subsoil. Queensland has a general absence of saline soils except in the south west corner as described by (Northcote and Skene 1972). Queensland lacks current or historic saline lakes and soils compared with the Western Murray Basin (Shaw 1995). In sodic soils, much of the chlorine has been washed away, leaving behind sodium ions (sodium atoms with a positive charge) attached to tiny clay particles in the soil. As a result, these clay particles lose their tendency to stick together when wet – leading to unstable soils which may erode, hence the term dispersive soils.
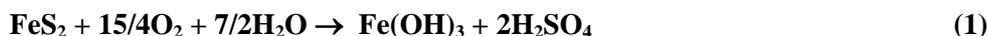
Acid Sulfate Soils and Sulfate in Source Rock and Groundwater

Acid Sulfate Soils

Bannerman – 1996 described the formation of acid sulfate soils in sediments of marine origin in coastal embayments where the ground surface elevation is less than 10m above sea level. In these soils and sediments flooded by brackish water, bacteria that decompose organic matter reduce sulfates from the water and iron oxides from the sediments. The end product is usually pyrites that accumulates in the organic remains. The primary source of the sulfur and iron originally would have been volcanoes. Subsequently this material has been leached out into the oceans and now remains in the soils. The action of anaerobic bacteria reduces the sulfates to microcrystalline sulfide. The environmental conditions under which these microorganisms normally operate are:

    (i)   Temperatures from 20 to 30 degrees Celsius
    (ii)   pH from 6 to 8
    (iii)   Soil Resistivities from 500 to 20,000 ohm.cm

The oxygen concentration of the soil moisture generally will determine its redox (oxidation/reduction) potential. Low redox values may provide an indication that conditions are conductive to anaerobic microbiological activity. If the soil is exposed, the action of oxidising bacteria can lead to the production of sulfuric acid as shown in equation 1.

$$FeS_2 + 15/4O_2 + 7/2H_2O \rightarrow Fe(OH)_3 + 2H_2SO_4 \qquad (1)$$

Dry pyrite exposed to air does not appear to oxidise. Equation 1 shows that both water and oxygen are needed similar to a corrosion reaction of steel in concrete. Bacterial action greatly speeds up the oxidation reaction as the solid pyrite is converted to sulfate and iron. For each mole of pyrite oxidsed two moles of sulphuric acid are produced. The soil may have a self-buffering capacity due to calcium carbonate, shells, other carbonates or reaction with fine sediments. The lowest reported pH produced by pyritic oxidation of soil is around 1.3. When the pH drops the characteristic smell of hydrogen sulifde gas is an indication of the acidic conditions. Fig. 3 shows the equilibrium condition for hydrogen and sulfide with varying pH. As the pH drops the equilibrium diagram shows that all the sulfide will exist in the gaseous phase.
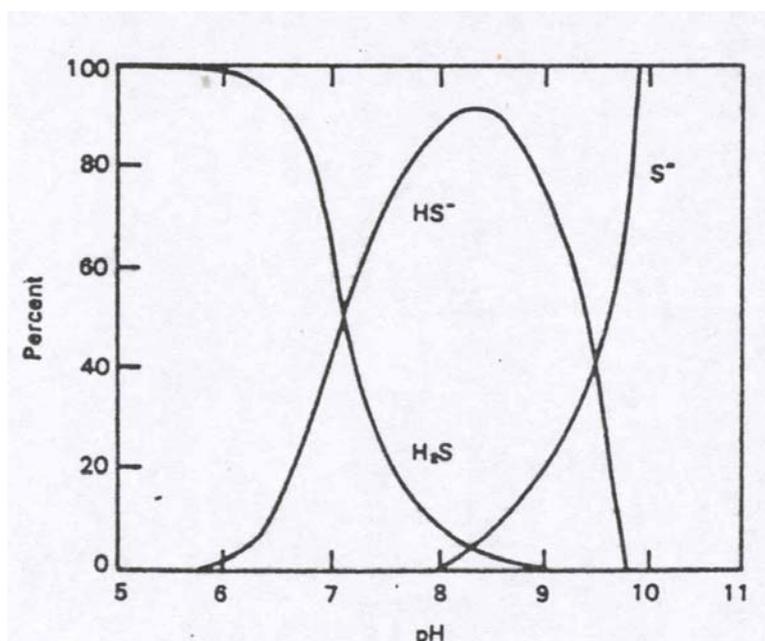

Figure 3. Effect of pH on hydrogen sulfide equilibrium

Sulfate in Source Rocks
Some metamorphic and sedimentary source materials used for the production of crushed rock and aggregates may contain sulphides which can oxidise when exposed to the atmosphere to form deleterious and highly soluble acid salts. If crushed rock with a high sulfide content is used as a pavement material the dissolved acid salts will migrate to the asphalt/crushed rock interface where crystallisation will result in debonding of the surface layer. For concrete mix designs AS2758.1 requires that the total SO_3 content of the mix does not exceed 5% by mass of cement. Since approximately 3% of this allowance will already have been taken up by the gypsum in the cement this allows 2% for sulfide from all other sources. It should be noted that the only way to control this type of impurity is to ban the known sources. A good example of pyrite staining can be seen on the Cultural Centre building in Brisbane. Fig. 4 shows a view of the pyrite staining on the concrete walls. The oxidisation process is a lot slower due to the larger crystal size of the pyrite and the lack of bacterial action.
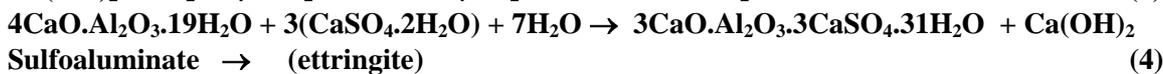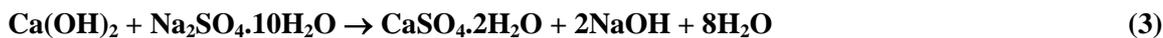
Sulfate in Groundwater
An additional source of sulfate in groundwater may come form the use of fertilisers such as ammonium sulfate. An assessment of the land use activity is required for a complete understanding of the origin of sulfate in the local soils and groundwaters.

Figure 4. View of pyrite staining on wall panel

Sulfate Attack on Concrete Structures

All soluble sulfates have a deleterious action on Portland cement concrete. Calcium sulfate only reacts with the hydrated calcium aluminates to form calcium sulfoaluminate. However, sodium sulfate reacts with the free calcium hydroxide in the set concrete to form calcium sulfate which proceeds to react with the aluminates. The reactions are as follows:

$$Ca(OH)_2 + Na_2SO_4.10H_2O \rightarrow CaSO_4.2H_2O + 2NaOH + 8H_2O \qquad (3)$$
$$4CaO.Al_2O_3.19H_2O + 3(CaSO_4.2H_2O) + 7H_2O \rightarrow 3CaO.Al_2O_3.3CaSO_4.31H_2O + Ca(OH)_2$$

Sulfoaluminate $\rightarrow$ (ettringite) (4)

Ettringite has a large amount of crystalline water and hence produces expansive disruptive forces within the concrete. The effect of sulfate attack maybe minimised by choosing a cement with a controlled aluminate content, using blended cement and selecting a suitable water cement ratio and compressive strength grade.

Risks to Pavements

The main properties required of paving materials are strength; durability; permeable; and volume stability. During construction pavement materials should also be workable and economic; and the surfacing should be wear resistant and impermeable. Any chemical properties of paving materials which adversely affect the above required properties pose a risk to the long term performance of the pavement. Salty, sodic and acid soils when used in pavements pose particular risks which are briefly described in this section.

Salt in Pavements

The level of damage that salt will cause to a road depends upon the type and concentration of salt/s present (DSNR, 2003) . The ability of a particular salt to cause damage depends on its solubility and crystallisation properties, which determine the concentration at which the salt will crystallise.

Salt dissolved in water enters the pores of the aggregate, reacting with compounds of calcium, aluminium, iron and magnesium, forming crystals of different chemical compounds that have larger volumes. This crystallisation at increased volume exerts pressure on the aggregate causing cracks to develop allowing more moisture to enter. As moisture levels fluctuate, the change in conditions drives a cycle with the salts crystallising, dissolving and re-crystallising. Further growth of the salt crystals can crack the aggregate causing it to disintegrate. This breakdown makes the grading finer and may increase the aggregate's plasticity and lower the strength of the base course by reducing aggregate interlock.

Another effect of salt in fine-grained materials is that they can affect the tightness of surface finish of the base. As the water evaporates and the salt crystals form they can fluff up the surface effectively decompacting it. A thin salt and soil crust can also form as plates, which detach from the base making it very difficult to seal.

The best approach is to prevent the salt or the salt bearing water from entering the pavement. The testing of materials, including construction water where salt is suspected, is recommended. Where salt is concentrated in the top of the base, it could be swept or trimmed off to the level where the concentrations are lower before sealing. Further guidance is given in the later section dealing with Risks to Bituminous Surfacings.

Sodicity

The dispersive nature of sodic soils makes them unsuitable paving materials or additives to crushed rock which is to be used as a base course. Where they are used there is a high risk of tunnelling within the pavement and as well as edge erosion. If water penetrates the sealed surface of a sodic pavement, local failures are likely to include a depression and seal failure. Where no other materials are available, sodic soils would need to be protected from water entry.

In areas where the subgrade is a sodic soil, the risk to the pavement comes from the loss of support it suffers when the tunnelling or erosion occurs in the subgrade. The likely method of failure would be the pavement falling into the hole left in the subgrade.

Sodic material should be not be used in pavements where possible. Little is written about their use in pavements but, given that the agricultural treatment for sodicity involves gypsum, lime stabilisation may be one way to reduce sodicity. Prevention of water entry into the pavement is essential so sealing the shoulders and encasing the pavement and /or subgrade edge will help. Polymer waterproofing additives may also prove valuable in circumstances where sodic soils have to be used in a low volume road pavement. Suitable treatments and specification limits for sodicity of materials used in pavements or embankments need to be developed by road authorities where these materials are prevalent.

Sulphate Acidity

Road builders have encountered aggregate which releases sulphuric acid from one of two sources:
  (i)   The first is where fines coating the stone is a pyritic material,
  (ii) The second is where the aggregates inherently contain pyritic mineralisation.

In the first case, the stone is coated with pyrite bearing soil or more likely sediment. Usually this arises when aggregate is excavated from old marine deposits. Once the stone and sediment are exposed to air, the pyrite oxidises and later releases the acid, either in the stockpile or in the pavement. In some cases, the sediment not only coats the stone but is also located in fissures within the aggregate which are then exposed during crushing.

Where it is intended to construct pavements using sulphide/sulphate bearing base or subbase materials, VicRoads (Geopave, 1996), restrict the amount of deleterious soluble acid salt present in the crushed rock by the application of pH and conductivity limits as shown in Table 1.

Table 1. VicRoads base specification limits

Test	Test value
pH (units)	6.0(min)
Conductivity (uS/cm)	1500 (max)

There is also an option to use material not meeting these requirements if such is combined with quicklime so that the resultant material has a minimum pH of 10. However, Main Roads recommends that in addition to the above, testing for the total potential acid and total actual acid be carried out.

Acid sulphate soils and aggregates should not be used in pavements where possible. Where an increase in strength is not needed treatment with agricultural lime is recommended, as it is less soluble than hydrated lime. Testing is essential to determine the quantity of lime to be mixed into the material. Further information is provided in the Main Roads Technical Note on Acid Sulphate Soils.

Risks to Bituminous Surfacings

Eighty percent of the Queensland State controlled road network has a bituminous surfacing with 25,367km spray sealed and 1,759km of asphalt. This critical component of the pavement structure must remain waterproof for the pavement to perform. The following paragraphs describe how sodic, acid sulphate and saline materials can damage these surfacings and the measures that can be taken to minimise this damage.

Salts Under Pavement Surfacings

Soluble salts, predominately chlorides but also sulphates, carbonates and nitrates are the main cause damage to seals from salt. In the presence of water, these salts migrate towards the surface of the pavements and depending the permeability of the seal may accumulate at the base/seal interface. The pressure from salt crystallisation and vapour movements builds up beneath the seal until it is sufficient to deform it. Initially, deformation may appear as blisters. If the blisters burst, the waterproof layer is damaged allowing the infiltration of surface water also increasing the evaporation rate. This accelerates the crystallisation process, speeding up decay of the pavement and usually causing cracking. Where traffic is low, curling of the surfacing may also occur. Once the blisters or cracks have broken through, white efflorescence or dark brown staining may be observed after rain. This is the saline discharge from the pavement crystallising as it dries on the surface.

Generally, the most effective treatment is to apply a substantial seal as soon as possible. Light treatments including primes and primer seals are particularly vulnerable to salt damage, (Austroads, 2002). In cases of light damage from salt attack, rolling may flatten blistering and the surface may be resealed if necessary. For severe damage to a seal the pavement and any visible salt should be boxed out to a depth of powdering and patched before resealing. In areas of extreme damage, resealing using a polymer modified binder should be considered.

The following table shows the treatments which were recommended after the trial to provide satisfactory performance for various levels of dissolved salts in a pavement.

Table 2. Recommended treatments (Januszke, and Booth, 1984)

Salt Level	Treatment
0 – 1.5%	As for normal pavement
1.5 – 2.5%	Primerseal followed as quickly as possible by the final seal.
2.5 – 3.0%	A sacrifical primed surface swept, then followed by a primerseal and final seal may be satisfactory, otherwise treat as for >3.0%.
> 3%	Special investigations will usually be needed and techniques developed. Emulsion prime followed by a C170 light seal and 2 coat seal could be considered.

Sodicity

Bituminous surfacings placed on non-saline sodic soils should perform normally. As sodic soils are fine grained, they may require greater waterproofing and seal strength to avoid leaking and softening the sodic soil with delamination of the seal from the fine surface.

One approach used in the past has been to apply two primes and a two coat seal to ensure good performance while, more recently, fabric seals have been applied to fine base courses to ensure adequate strength. The choice of treatments may be influenced by base course material and traffic levels.

Sulphate Acidity

Pyritic-bearing paving materials also generate soluble salts which can concentrate under and disrupt the surfacing in the same way as described above in the salinity section. The pavement show blistering and cracking and usually exuded a white to yellow acidic substance from the cracks.

If the damaged surfacing is asphalt, it should be milled off and the base mixed with lime and the asphalt replaced. Where the damage is minor, this may be repaired as a patch or with a strain relieving membrane interlayer and asphalt overlay applied to waterproof and strengthen the surfacing.

If the damaged surfacing is a seal, it could be removed and the base treated by mixing with lime. If the damage is minor, removing the damaged areas of seal and resealing with a strain alleviating membrane to waterproof and strengthen the surfacing may be sufficient.

Conclusions

The following conclusions are made about the information and discussion presented in this paper:

(i)   A detailed analysis of the ground conditions is essential for the design/manufacture of durable concrete structures and pavements which will live in those environments over 100 years.

(ii)   Both the soil and groundwater need to be analysed for assessment of the current conditions and prediction of possible future aggressive durability loads on the structures (changes in land use that may impact on the performance of the structure need to be considered at the design stage).

(iii)   From the information presented the major controlling factors in the soil and water will be the pH, sulfate ion content and chloride ion content. Guidelines have been supplied (Carse 2003) for the input of these parameters and selection of suitable mix designs. Additional testing of the oxidation/reduction potentials in the soil may give an indication of active anaerobic bacteria being present.

(iv)   Improvement is needed between the amount of information that needs to be collected at a specific site and communication to the Bridge Design Section to ensure a high level of confidence in the range of field conditions that will occur. Only in this manner can suitable designs be selected for a guaranteed 100 year minimum design life.

(v)   The principal way to avoid poor pavement performance arising from saline, sodic or acid sulphate soils is to exclude them from the pavement and subgrade if possible, but this can only be achieved if they are identified during the planning stage of a road project. Road authorities need to have investigation protocols that identify and classify problem soils.

(vi)   The salt content of pavement construction water should also be monitored when drawn from a suspect source.

(vii)   Further investigation is needed to determine acceptable limits of sodicity for paving and embankment materials.

Acknowledgements

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