

Geomaterials: aggregates, building stone and earthworks: papers from 50 years of QJEGH

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Abstract

Numerous papers encompassed within the broad subject of geomaterials have been published in QJEGH over the past 50 years. These have been compiled and divided here into three main categories: aggregates, building stone and earthworks. The aim of this review is to provide a comprehensive summary of the relevant papers published in QJEGH with a view to identifying the main areas of interest historically, now and in the future. Some clear trends are evident from the survey and review, for example: a steady interest in building stone and in particular its deterioration; a decline in papers on earthworks and an increase in ground improvement (also covered here). It is also noted that methods of characterizing geomaterials are becoming more sophisticated with advancing technology. The review makes relevant links with other Special Publications from the Geological Society, including also Engineering Geology Special Publications.

I INTRODUCTION

In order to mark the 50th Anniversary of Quarterly Journal of Engineering Geology and Hydrogeology, a number of summary papers have been compiled to provide summaries of some of the main areas covered within the journal (Winter and Bromhead, 2017). This paper is one of these. The intention within this review is to gather together papers encompassed within a broad subject area concerning the use of geological materials in construction. Geological materials cover an enormous spectrum of sizes ranging from clay particles at the nanometre scale to rock masses at scales of tens of metres. Between these size extremes there are silts, sands, gravels, cobbles and boulders. These various sizes may have resulted from natural processes such as weathering or may have been produced by operations such as quarrying and mining. It is perhaps useful to recap that quarrying relates to the removal of material (e.g. rock, sand and gravel, clay) that is almost entirely utilised, while mining is a process where a specific material is sought (e.g. coal, minerals, ore) that only occupies part of the overall volume of the mass excavated, thus producing a great deal of surplus material. The material from quarrying is often used directly or with minimal sorting (e.g. building stone, aggregates) while that from mining is often processed (e.g. crushed, washed and sorted) to extract the material sought and to utilise the remaining surplus. There are numerous applications in building and engineering construction for the various

sizes, regardless of whether they are natural or man produced. At the large scale, rock blocks can be shaped, often directly in the quarry, into dimension stone for building and armourstone for coastal defence. Boulders and cobbles are frequently needed in dam and embankment construction and sometimes slope stabilization (e.g. gabions). Sands and gravels are used as aggregates in railway ballast, concrete and road pavements. At the small scale, silts and clays are frequently used in earth dams, embankments and earthworks in general (and also in the manufacture of bricks). Regardless of size, the materials need to be characterized according to common factors such as strength and stiffness (from an engineering perspective), appearance (for aesthetic considerations) and perhaps less obvious but more important, durability and resistance to weathering.

The papers within the broad area of geomaterials have been divided here into main categories of aggregates, building stone and earthworks. Within each category, further subdivisions are made where necessary, for example there are several papers on armourstone and these have been included within the main category of aggregates. There are also several papers on concrete, bricks and lime mortar but these are not discussed within the current review as they are considered to be artificial materials where all their individual components are controlled. The other geomaterials discussed in this paper are truly products of nature or at least largely so. A summary of the number of papers published in QJEGH found within the various categories is given in Table 1.

Category	Time span	No. of QJEGH papers	Comments
General	1991-2012	7	Covering the overall term geomaterials
Aggregates	1968-2014	59	A wide variety of aggregate types (e.g. road and concrete aggregates and armourstone) are covered, as well as resources, characterization, testing and performance.
Building stone	1986 – 2015	44	Dealt with in terms of characterization, testing, weathering and quality.
Earthworks	1967-2015	58	Mine waste, ground improvement and the use of geotextiles in fills are also included.

Concrete and bricks	1980-2006	15	Not covered in this review paper.
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Table 1. Summary of paper numbers found within designated categories.

It is appropriate to mention other closely associated publications that have direct links to the subject matter of this review: seven Geological Society Special Publications and five Engineering Geology Special Publications. These are discussed in the final section of the paper.

II GEOMATERIALS

Prior to covering the three main areas (aggregates, building stone and earthworks) some general papers on geomaterials are discussed. Also within the second sub-section, a brief summary is given of other materials that might be considered under the heading of geomaterials but that are not included as part of this paper.

General papers

Three general papers on geomaterials are published in a single QJEG issue (vol. 24, no. 1): ‘Geomaterials in construction: an introduction’ by Hawkins (1991); ‘Geomaterials’ by Fookes (1991) and ‘Sandstones as geomaterials’ by Hawkins and McConnell (1991). The first paper by Hawkins explains that this entire QJEG (as it was at the time) issue is dedicated to papers presented at the November 1989 conference on ‘Geological Materials in Construction: Developments in Geomaterials Research and Practice’ held to celebrate the 10th anniversary of the geomaterials research and graduate training centre at Queen Mary and Westfield College (London, UK), with papers, primarily on aggregates, by staff (current or past) as well as students. Fookes’ paper ‘Geomaterials’, which includes both aggregates and construction stone, discusses durability and the factors which influence it, as well as engineering tests which can give good indications of potential durability.

On the same subject of weathering and durability, another pertinent paper is ‘Petrography of geomaterials: a review’ by Ingham (2011). This reviews the use of petrographic techniques for the study of geomaterials in the construction industry throughout the world, as well as discussing methods and standards and their application in various stages of the life-cycle of structures. A book by the same author ‘Geomaterials under the microscope’ is reviewed by Paige-Green (2012) and highly recommended to those working in this field. Another general geotmaterials

paper within QJEG relating to longevity is by Taylor-Firth and Laycock (1999), ‘Weathering simulation for durability assessment of the in-service performance of construction materials’.

Other ‘geomaterials’

In collating papers for this review of the QJEGH over its first 50 years, a number of papers were encountered covering concrete (twelve papers between 1980 and 2003), bricks (two in 1988 and 2006) and one on lime mortars (2002), with none on other ceramics. These, along with other processed products, are considered to be outside the main emphasis of this review paper and so are not mentioned further. One paper that does not fit within the categories given in this paper but seems relevant, in terms of being considered as a geomaterial, concerns ‘The Cornish greenstones: their physical properties and use in engineering’ by Hawkes and Cratchley (1970). This dealt with the relationship between the properties of these stones and their past and present use in construction and engineering.

III AGGREGATES

The papers in this section have been divided into sub-groups: sampling, characterization and testing; road and pavement aggregates; aggregates used in construction; and armourstone. It seems fitting to mention here three papers related to aggregate resources, which are relevant throughout this section. Fox (1991) discusses ‘The future of aggregate extraction and evaluation in Europe’ giving estimated production figures (1985-1989) for the UK, France and W. Germany, and exploring sources of aggregates to meet growing demands, such as marine aggregates and the concept of “Mammoth or Superquarries”. Crimes et al. (1994) describe comprehensively ‘Techniques used in aggregate resource analyses of four areas in the UK’ and Wardrop (1999) reported on ‘A study on the accuracy of sand and gravel reserve estimates’.

Sampling, characterization and testing

From the early 1970s, aggregate sampling, characterization, testing and performance, start to be discussed. Aggregates can be characterized in numerous ways, depending on factors such as their origin, nature and intended use, for example, in the following section on road and pavement aggregates, skid resistance and polishing are important attributes that should be quantified. Four early papers published are: ‘Studies of inter-particle void characteristics’ by Lees (1970); ‘Effect of deicing agents and sulphate solutions on concrete aggregate’ by Gillott (1978); ‘An osmotic method for determining rock and aggregate suction characteristics with applications to frost heave studies’ by Jones and Hurt (1978); and a paper relating results from Los Angeles abrasion

and Schmidt hammer strength tests on aggregates from Jeddah by Kazi and Al-Mansour (1980). Most of the papers in this class are published between 1987 and 2000 (Latham and Poole, 1987a; Czarnecki and Gillott, 1989; Bullas, 1990; Sims and Miglio, 1992; Irfan, 1994; Akpokodje and Hudec, 1994; West, 1994; Howarth, 2000).

Sampling techniques prior to testing are dealt with in very few papers. These include a Technical Note on ‘Selecting appropriate numbers of increments for bulk samples of aggregates’ by Pike (1992) which looks at BS 812:1989 (Part 102), compares it with standards in most other European countries and develops and tests a method to determine the appropriate number of sample increments to determine a representative sample. Other papers are those by Sims and Miglio (1992) and by Howarth (2000), both of which are already mentioned above.

Road and pavement aggregates

The first papers on road aggregates are published in the QJEG (as it was then known) in the late 1960s and the 1970s, with the first being ‘A study of the mechanism governing the polishing of stone in road surfaces’ by Maclean (1968). This paper studies the polishing of aggregate by traffic, and sets out to develop laboratory apparatus and tests to reproduce wear at the road surface. This paper concludes that “it is not always possible to predict the polishing characteristics of a rock from its petrography”. Subsequently, the role of aggregates in skidding is written up in the 1970s by Williams and Lees (1970), Cameron (1972), Hartley (1974) and Lees and Kennedy (1975), although it should be noted that this last paper is more general than just discussing skidding. Three similarly related papers appear much later: ‘Petrographical comparison of old and new control stones for the accelerated polishing test’ by West and Sibbick (1988); ‘Observations on aspects of skid-resistance of greywacke aggregate’ (Perry et al., 2001) and ‘Skid resistance performance of natural New Zealand aggregates using dynamic friction tester’ (Wilson and Black, 2009).

Other papers within this category are provided by: Fish (1972), giving a general overview on ‘Road materials and quarrying’; Jones (1980), focussing on ‘Frost heave of roads’; Wylde (1982) discusses ‘Texture changes in crushed basalt road base’; and Hussain et al. (2014), who investigate ‘The effect of moisture and relative proportions of clay minerals on the performance of unbound granular base courses’.

Aggregates used in the building and construction industry

The paper by Gillott (1978) opens up the field of aggregates used in the building and construction industry and is the first of numerous papers (1978–2013) on aggregates in concrete or construction in general, some of which have been mentioned already.

Many of the papers relate to aggregates from outside the UK such as that by Kazi and Al-Mansour (1980), concerning aggregates from Jeddah, the paper ‘The influence of serpentinite and other rocks on the stability of concretes in the Middle East’ by French and Crammond (1980) and ‘Properties of aggregates affecting concrete in North America’ by Gillott (1980). In fact this whole issue (vol. 13, no. 4) is concerned with concrete aggregates, and includes papers presented at an Ordinary General Meeting of the Geological Society in February 1979 (see introduction by French, 1980a). Papers are also given by: Fookes (1980) on the influence of natural aggregates on the performance and durability of concrete; French (1980b) on reactions between aggregates and cement paste; Poole and Sotiropoulos (1980) on reactions between dolomitic aggregate and alkali pore fluids in concrete; and Moore and Gribble (1980) on the suitability of aggregates from weathered Peterhead granites. The issue ends with a discussion of papers covered within it by Sims (1980).

Sims (1986) also provides a summary of a report by the UK’s Geological Society Engineering Group Working Party on ‘Sand, gravel and crushed rock aggregates for construction purposes’. Al-Jassar and Hawkins (1991) discuss the ‘Carboniferous Limestone of the Bristol area’ with respect to their use as aggregates in concrete, while Harrison (1993) covers a much greater area in ‘High-purity limestones in England and Wales’ with regard to both aggregate and cement production. Other later papers on non-UK aggregates include those from: Hong Kong (Irfan, 1994); Nigeria (Akpokodje and Hudec, 1994); Trinidad (Eglinton et al., 1994); East Bohemia (Martinec et al., 2008); New Zealand (Wilson and Black, 2009); and a Technical Note on ‘Particle size distribution of dune sand from Libya’ (Charman and West, 2011).

Several of the papers above concentrate on reactions between aggregates used in concrete and cement constituents. Further work on this subject is provided by Rübner et al. (2008) who discuss the ‘Use of municipal solid waste incinerator bottom ash as aggregate in concrete’ and three later papers. Fernandes (2013) reviews the ‘Alkali–silica reactivity of some common rock types. A global petrographic atlas’, while Braithwaite and Heath (2013) focus on ‘Alkali–carbonate reactions and ‘dedolomitization’ in concrete’. At a smaller scale and focussing on lime rather than cement as a binder, Arizzi and Cultrone (2013) investigate ‘The influence of aggregate

texture, morphology and grading on the carbonation of non-hydraulic (aerial) lime-based mortars’.

There are two book reviews related to aggregates in construction. The book reviewed by Woodbridge (2003), ‘Aggregates: sand, gravel and crushed rock aggregates for construction purposes’ seems completely devoted to the subject while that by Rosenbaum (2007), ‘Urban geology in Wales: 2’ has a section on marine aggregates.

Armourstone

As there have been a significant number of papers published on this topic, a separate section is included here within the overall subject of aggregates. It seems fitting that they be covered at the end of this section, given their very large size while still in essence being clasts! The first paper ‘Some preliminary considerations on the selection and durability of rock and concrete materials for breakwaters and coastal protection works’ by Fookes and Poole (1981) aims at relating physical parameters of the rock to its performance in a marine environment, as well as suggesting methods for assessing suitability. Other papers dealing with selection parameters have been contributed by: Dibb et al. (1983a) on ‘Controls of size and shape of natural armourstone’; Clark (1988) on ‘The use of Portland Stone rock armour in coastal protection and sea defence works’; Wang et al. (1991) on ‘Predictions of block size distribution for quarrying’; Poole (1991) on ‘Rock quality in coastal engineering’; Clark and Palmer (1991) on ‘The problem of quality control and selection of armourstone’; and most recently Latham et al. (2006) on ‘The specification of armourstone gradings and EN 13383 (2002)’.

The performance and durability of armourstone are discussed by: Dibb et al. (1983b) on ‘The identification of critical factors affecting rock durability in marine environments’; Latham and Poole (1987b) on ‘A pilot study of an abrasion test for breakwater armourstone’; and by Latham (1991) on a ‘Degradation model for rock armour in coastal engineering’. Four of the above papers were published in a single issue in 1991 (vol. 24, no. 1). Further, more general information may be obtained from the book reviewed by Lott (2000) ‘Stone: Building stone, rock fill and armourstone in construction’.

IV BUILDING STONE

This section has been divided into the following sub-groups: characterization and testing; weathering and durability; and deterioration and restoration of stone (including recording).

However, inevitably there are often papers that overlap across more than one sub-group. The interest in building stone in terms of papers published within QJEGH began primarily in the mid-1980s and has steadily increased since then. The interest in this subject is also reflected by the seven Geological Society Special Publications that have been published between 2002 and 2015. Further details are provided in a later section.

Characterization and testing

There are two primary areas in terms of characterization and testing. One relates to dimension stone to be used in new construction and the other to stone existing in historic structures. The need to understand the properties of stone used to construct historic heritage buildings and structures is a vital component to their future preservation. The assessment of the durability of the stone (and other materials) used within them is necessary if they are to be successfully safeguarded, especially with more modern issues of surface breakdown through causes such as pollution from traffic and industry. The first paper in QJEGH on building stone is by Laurie et al. (1986) and concentrates on ‘The restoration of buildings constructed with Menorcan limestone’, discussing a phased analytical approach to help understand the deterioration of quarry and building limestone and dolomite in Menorca. Previous methods of treatment of weathered stone on the case study discussed, an 18th century building in Menorca, are also studied. Recommendations for treatment and repair, based on local and UK experience, are suggested. A Technical Note by Raymahashay and Sharma (1993) is also concerned with problems associated with historic buildings, focussing on the ‘Decay of building stones: a mineralogical model for Konark Sun Temple, India’. So too is the photographic feature on ‘Troglodyte dwellings of the Loire Valley, France’ by Forster and Forster (1996).

Other papers with a focus on characterization are provided by various authors covering building stones mainly from Europe but also elsewhere: Cassar and Vella (2003) – Malta; Sousa (2010) – Portugal (note that this paper covers the ‘Evaluation of joints in granitic outcrops for dimension stone exploitation’); Cnudde et al. (2013) – Belgium; Diana et al. (2014) – Malta again; and in the same issue Cuccuru et al. (2014) – Cagliari (Italy). Several of papers within the 2013 thematic set mentioned below can also be included.

Weathering and durability

Specific studies on stone durability of dimension stone in construction have appeared over the years with the first by Fookes et al. (1988) on ‘Rock weathering in engineering time’. Here the

authors develop a Rock Durability scheme, to predict the long-term performance of a stone in use, and conclude that combination of different tests (physical and mechanical) and a consideration of environmental factors, are needed to assess durability.

Two other notable papers on this subject include ‘Quality and durability of stone for construction’ by Sims (1991), and ‘Rapid prediction of Building Research Establishment limestone durability class from porosity and saturation’ by Moh’d et al. (1996). Other papers on the theme include papers by Valdeon et al. (1996); Ordóñez et al. (1997); Taylor-Firth and Laycock (1999); Cassar and Vella, (2003); and Cultrone et al. (2012), and Diana et al. (2014). The subject of weathering and durability is closely related to conservation (covered below) and several of the papers mentioned in the 2013 thematic set (vol. 46, no. 4) are relevant.

Deterioration and conservation of stone

Thirty two papers appear between 1988 and 2014 on the study of building stone, focussing on aspects such as weathering, durability (and how to record and classify it) and treatment methods.

Jefferson (1993) produced a seminal paper on ‘Building stone: the geological dimension’, where a short historical overview of the use of stone in building in the UK is given along with a wide range of aspects including the rock types used for such purposes, the wider issues of stone extraction and its various uses in buildings, stone tests and durability, and case studies of different quarries associated with specific historic buildings, and the geologist’s role in the conservation and restoration of stone buildings.

A photographic feature on ‘The survey and recording of historic monuments’ by Emerick (1995), includes examples from Fountains Abbey, Yorkshire on photogrammetry and the mapping of weathering forms. Following immediately in the same issue is an extensive commentary on ‘The description and classification of weathered rocks for engineering purposes’, a general paper covering soils and foundations as well as stone, given in the report produced by the Geological Society Engineering Group working Party (1995). This is followed by other papers on weathering by: Price (1995) and Pye and Mottershead (1995).

Another flurry of papers on weathering and deterioration of stone follow in vol. 31, no. 4 soon after with nine out of the total of eleven papers being devoted to the subject. There are two papers on bio-deterioration by Wakefield and Jones (1998) and Young and Urquhart (1998): the first

ever in QJEG, reflecting the more widespread interest in this aspect of deterioration as an important factor in stone deterioration. Another paper on ‘Characterization of freshly quarried and decayed Doultong limestone’ by Jones et al. (1998) focusses on Wells Cathedral, Somerset UK, where the elaborately sculptured West Front had recently been restored. There also appears a study on the ‘Influence of climatically induced cycles in physical weathering’ by Halsey et al. (1998). Other notable papers within the issue are those by Trudgill and Viles (1998); Mottershead (1998); Viles and Moses (1998); Williams and Robinson (1998); and Turkington (1998).

Another two papers further associated with durability and weathering concentrate on the effects frost action on building stone. Ingham (2005) investigates ‘Predicting the frost resistance of building stone’ by comparing an accelerated test with indirect methods of assessing stone durability. The other paper entitled ‘A new laboratory rock test based on freeze-thaw using a steel chamber’ by Binal (2009), seeks to relate laboratory testing to real outdoor performance.

In 2013 (vol. 46, no. 4), a thematic set ‘The Stone Cycle and Conservation of Historic Buildings’ is published in QJEGH. Following an introduction by Cassar et al. (2013), four invited papers are presented, two on durability by Viles (2013) and Přikryl (2013), one on condition assessment (Smith et al., 2013), and the other on stone for conservation and repair in Britain (Lott, 2013). Other reviewed papers within this issue discuss stone and stone-related problems and solutions in regions of Europe: Madrid, Spain (Fort et al., 2013); the Netherlands (Quist et al., 2013); and Syracuse (Southern Italy) (Calia et al., 2013). Other topics dealt with are the site assessment of façades and the environment (Siedel, 2013; Erkal et al., 2013 and; Zurakowska and Hughes, 2013) and the study of stone decay (McCabe et al., 2013 and; Alves et al., 2013).

Papers on conservation continue to appear in later issues, including: ‘Assessment of new protective treatments for porous limestone combining water-repellency and anti-colonization properties’ by Eyssautier-Chuine et al. (2014) and ‘Laboratory testing of non-standard original historic building materials and related implications for conservation’ by Erkal and D’Ayla (2015).

V EARTHWORKS AND FILLS

Geological materials used as fill and in earthworks form the subject of occasional papers in QJEGH. In this section the papers have been broadly divided into the following related sub-

groups: fills; mine (and colliery) waste; ground improvement using additives; and ground reinforcement and the use of liners for waste storage.

Fills

The first paper in the first issue of the journal relates to fill used in dam construction. Kennard et al. (1967) discuss the use of shales in fill at the Balderhead dam in Yorkshire, UK. In the next issue Hitchin (1968) describes the 'Materials surveys and investigation for the Kainji Dam project, Northern Nigeria'. Subsequently there are essentially no further papers specifically concerning fill in earth and rockfill dams as the need for dam building, especially in the UK, diminished. It is more than twenty years later that Atkinson et al. (1990) consider the erosion resistance of embankment dam fills in their paper.

Papers on the characterization, testing and suitability of soils and rock for fills and earthworks (perhaps more associated with embankments and roads) are considered next. The earliest of these was by McGown (1971) on 'The classification for engineering purposes of tills from moraines and associated landforms'. Papers following a similar vein are provided by: Horner (1983); Maharaj (1993) – relating to road construction in Jamaica; Winter et al. (1998) on 'The effect of large particles on acceptability determination for earthworks compaction'; Czerewko et al. (2003) on 'The development of a new testing protocol for sulphur compounds in structural backfills'; Winter (2004) on the applicability of glacially derived soils as fill; Irfan (1999) on 'Characterization of weathered volcanic rocks in Hong Kong' for engineering fill purposes; and Barrientos et al. (2010) on the use of granite sawdust produced by the dimension stone industry as fill or liner material.

Classic tests for fills often involve Proctor and CBR (California Bearing Ratio) tests. The results from such tests (and others) and the conclusions from them and the acceptability and suitability of the fills under investigation are covered in another group of papers. These are summarised as follows: Ola (1980) on 'Permeability of three compacted tropical soils'; Parsons (1981) on 'The assessment of soils and soft rocks for embankment construction'; Arumala and Akpokodje (1987) on 'Soil properties and pavement performance in the Niger delta; Al-Khafaji (1987) on 'A simple approach to the estimation of soil compaction parameters'; Ogunsanwo (1989) on 'CBR and shear strengths of compacted lateritic soils from southwestern Nigeria'; Al-Khafaji (1993) on 'Estimation of soil compaction parameters by means of Atterberg limits'; Razouki and Al-Shefi (2002) on 'Effects and observations of surcharge load on the laboratory CBR and

resilient modulus values of roadbed soil’; Lindh and Winter (2003) on ‘Sample preparation effects on the compaction properties of Swedish fine-grained tills’ – they also describe aspects of testing and compare different national standard test methods; and Najser et al. (2010) on ‘Mechanisms controlling the behaviour of double-porosity clay fills’.

Mine waste

Some properties concerning mine waste are given in Bishop’s paper (1973) to the Regional Meeting on Slope Stability held in Bristol the previous year. Coal mine waste also appear in other papers, for example Kettle (1983) and Siddle et al. (1996). This area of technical interest develops after the disastrous slide in colliery waste at Aberfan in 1966, as considerable professional attention is devoted to stabilising old tips of mine and colliery waste, but in particular with the decline in mechanised coal mining of the UK, the work in this area has declined considerably. Two other papers discussing colliery waste are provided by Thomas et al. (1989) and Indraratna (1994).

The problem of pyrite-induced swelling occurs sometimes with structures built on certain compacted fills. In the context of mine waste Gandy and Younger (2003) describe pyrite oxidation within mine spoil while Wilson (1987) discusses the swelling of pyritic shale experienced in Wales. Hawkins and Pinches (1987) describe a related problem of gypsum induced heave in underfloor fill. A directly related group of papers are also included in this section, the first by Pye and Miller (1990) discusses ‘Chemical and biochemical weathering of pyritic mudrocks in a shale embankment’. A more recent group of papers describes how pyrite-induced swelling affected a large number of recently constructed houses in Ireland: Matheson and Quigley (2015); Matheson and Jones (2015); and McCabe et al. (2015).

Ground improvement using additives

Traditionally the primary method of improving the ground was by compaction or consolidation, i.e. without the use of additives. The paper mentioned earlier by Najser et al. (2010) describes such an application, considering the behaviour of excavated and redeposited or ‘lumpy’ soils. In recent years there has been an increasing use of additives and associated processes to improve ground conditions. This subject has also been included in this section under the broad heading of earthworks.

The three common additives are cement, lime and flyash and there are a number of papers covering their use. The first of these is by Dunn and Obi (1969) who focus on ‘Some engineering properties of cement-stabilized Keuper Marl’ (now referred to as Mercia Mudstone). Almost ten years later Ola (1978) writes on ‘Geotechnical properties and behaviour of stabilized Nigerian lateritic soils’ and then in 1986 on the ‘Engineering properties and behaviour of stabilized compressed tropical soils’. At about this time there are another two papers again from Africa by Akpokodje who describes in 1985 ‘The stabilization of some arid zone soils with cement and lime’ and concluded that cement is more effective than lime and also note that neither are useful for stabilising gypsiferous soils. He follows up this paper with another in 1986 on ‘A method of reducing the cement content of two stabilized Niger delta soils’ in which he explains how up to 50% saving in cement can be made according to the method of mixing.

Further papers follow looking at the effectiveness of stabilisation, using a variety of processes on a variety of soils: Indraratna et al. (1991), ‘Stabilization of a dispersive soil by blending with fly ash’; Stamatopoulos et al. (1992), ‘Treatment of expansive soils to reduce swell potential and increase strength’; Eze and Suoware (1993), ‘Geotechnical evaluation of untreated and cement-treated Ajali Sandstone from southeastern Nigeria’; Fang et al. (1994), ‘Mechanical properties of jet grouted soilcrete’; Indraratna et al. (1995), ‘Effect of fly ash with lime and cement on the behaviour of a soft clay’; Al-Amoudi et al. (1995), ‘Stabilization of an arid, saline sabkha soil using additives’; Hughes and Glendinning (2004), ‘Deep dry mix ground improvement of a soft peaty clay using blast furnace slag and red gypsum’; Chinkulkijniwat and Horpibulsuk (2012), ‘Field strength development of repaired pavement using the recycling technique’ – this is achieved using cement stabilisation of the coarse grained soil; and most recently Chen et al. (2015), ‘Observations of stress-dependent microstructural changes in cement-stabilized soil’.

Prikryl et al (2005) describe the use of tyre bales as lightweight fill and Horpibulsuk et al. (2014) assess ‘Factors influencing unit weight and strength of lightweight cemented clay’, but otherwise, lightweight fills get little mention.

Ground reinforcement and the use of liners for waste storage

Most of the papers covered in this sub-section were published in a single quite early issue of the journal (vol. 15, no. 3).

Ground reinforcement

All but one of the following appear in the third issue of 1982. As the use of geofabrics and geotextiles is increasing at that time there is a particular interest in the polymeric materials themselves and the paper by McGown and Andrawes (1982), 'An approach to laboratory testing of geotextiles' is one of the first well referenced studies. Milligan (1982) uses 'Some scale model tests to investigate the use of reinforcement to improve the performance of fill on soft soil', the complex soil-reinforcement interaction being difficult to analyse without laboratory or field data to back up the results. In a similar vein but at a larger scale, DuBois et al. (1982) describes 'A fabric reinforced trial embankment'.

The other two papers in this issue report on 'The performance of impermeable and permeable reinforcement in clay subject to undrained loading' (Ingold and Miller, 1982) and 'The design of a two-layer permeable membrane/webbing filter system for a marine causeway wave defence system in the Gulf of Arabia' (Rankilor, 1982). It is more than a decade later that another paper in this area appears by Al-Omari et al. (1995), 'Effect of stiffness and amount of reinforcement on strength of sand'. This subject is now much better understood and standardised.

Liners

The use of liners for sealing municipal and industrial waste in the ground is an area of considerable research from the 1980s with a view to minimising contaminant transfer into the surrounding ground. The liners were sometimes comprised plastic clays alone such as the cases described by Murray et al. (1992), 'Clay linings to landfill sites' and Yong et al. (1999), 'Competency assessment of two clay soils from South Wales for landfill liner contaminant attenuation'. Often a geomembrane was also incorporated to provide a fully impermeable barrier as discussed in the papers by French et al. (1982), 'Results of preliminary experiments on the influence of fabrics on the migration of groundwater and water-soluble minerals in the capillary fringe' and Henderson (1982), 'The potential use of a degradable erosion control membrane in the United Kingdom'. There have not been any further papers since 1999, perhaps because there is now a much greater concerted research effort into investigating barriers for nuclear waste storage. In considering this scenario there a greater focus is on the soil mechanics aspects of partial saturation and temperature, although understanding the geology of the host ground is still an essential component of such schemes.

VI SPECIAL PUBLICATIONS

The Geological Society has also published closely related Special Publications and Engineering Geology Special Publications. These are discussed in this section.

Engineering Geology Special Publications

A number of Engineering Geology Special Publications (EGSPs) with relevance to this paper have been published by the Geological Society during the years 1985 – 2006. As already mentioned, Sims (1986) announced in QJEG the establishment of a working party in 1978 by the Engineering Group of the Geological Society (EGGS) and provided a summary paper concerning its first publication, entitled *Aggregates: Sand, Gravel and Crushed Rock Aggregates for Construction Purposes* (Collis & Fox 1985). This is the first Engineering Geology Special Publication, followed by a second edition in 1993 (EGSP 9, Smith & Collis 1993), and a third edition in 2001 (EGSP 17, Smith et al. 2001).

In the preface to the third edition mentioned above, Professor Fookes, Chairman of the Working Party, mentions two other reports produced by the group: *Stone: Building Stone, Rock Fill and Armourstone in Construction* (Smith 1999, No. 16) and *Clay Materials Used in Construction* (Reeves et al. 2006, No. 21). The second book is reviewed in QJEGH by Lott (2000), who points out that the book contains an immense amount of information related to the British stone industry, with 33 specialists covering a range of fields, useful to both specialists and non-specialists, and especially non-geologists. These two EGSPs along with EGSP 17 form a trilogy on geological materials in construction. EGSP 21, besides dealing with the geology of clay and clay deposits, and their investigation (including exploration and analysis), includes six chapters on the application of clay materials in engineering geology, and also considers earthworks, another of the topics dealt with in the present paper.

Another two EGSPs by the Geological Society Engineering Group include *Engineering Geology of Construction* (Eddleston et al. 1995, No. 10) where a paper of particular relevance is ‘Petrographical examination of road construction materials’ (West 1995). This paper concludes that this technique can provide the most and best information when specific objectives are determined, rather than when general information is sought. The need to have standardized rock nomenclature when describing rocks petrographically is mentioned.

An EGSP that also has direct relevance to this current paper is *Advances in Aggregates and Armourstone Evaluation* (Latham 1998, No. 13). Of special relevance is Section 3, ‘Aggregate testing and the use of alternative aggregates’, which contains six papers. In the foreword to the

publication, the editor in fact comments on the wide variety of topics presented in this section. These range from testing for aggregate wear (two papers), to a study of the Polished Stone Value for aggregates in the gritstone trade group, to a statistical study of aggregate testing data, to a study of concrete using waste (slate and china clay waste and pulverized fly ash), and to a Technical Note on a new method of abrasion testing. The other two sections in this book are Section 1 on ‘Marine sand and gravel geology and resources’ and Section 2 on ‘Armourstone evaluation and shingle performance assessment’.

Geological Society Special Publications

The interest in dimension stone, particularly when used in heritage buildings, and particularly its characterization, deterioration and conservation, is evident from seven Geological Society Special Publications (2002 – 2015). These supplement well the papers published in QJEG and QJEGH. The first in the series is on Natural Stone, Weathering Phenomena, Conservation Strategies and Case Studies (Siegesmund et al. 2002). Here it is pertinent to note that the editors, in their introduction, state that ‘Knowledge of the properties of geomaterials, of their weathering processes and of subsequent material changes is a basic requirement to understand the complex mechanisms involved in producing the eventual deterioration’ and ‘Before attempting any restoration project on monuments and historical buildings, characterization of the stone must be carried out, and the causes of stone deterioration need to be established in order to eliminate or mitigate them effectively.’ These are in effect not only principles that underline correct and ethical conservation strategies, but also are running themes through another four Geological Society Special Publications. These are Building Stone Decay: From Diagnosis to Conservation (Přikryl & Smith 2007), Natural Stone Resources for Historical Monuments (Přikryl & Török 2010), Limestone in the Built Environment: Present-Day Challenges for the Preservation of the Past (Smith et al. 2010) and Stone in Historic Buildings: Characterization and Performance (Cassar et al. 2014). The other two of relevance to the present paper, but perhaps to a lesser degree, are Geomaterials in Cultural Heritage (Maggetti & Messiga 2006) and Global Heritage Stone: Towards International Recognition of Building and Ornamental Stones (Pereira et al. 2015).

VII CONCLUSIONS

This review paper refers to the vast number (almost 200 in total) of papers published over the past fifty years in QJEG and QJEGH (name change from the year 2000 onwards) and other

special publications concerning the broad subject of geomaterials: aggregates, building stones and earthworks. In the early papers there was more of a focus on material properties needed for civil engineering construction (earthworks and aggregates) and the need to think about the geology in the associated projects. The link between engineering and geology is still a crucial component in the successful design of civil engineering works, the importance of which the journal continues to promote in its publications. Hydrogeology is a major consideration within both of these areas (geology and engineering) and the continued influx of papers on this subject led to the augmentation of the title of the journal in 2000.

The number of papers on building stone has also increased greatly since the mid-1980s with a greater awareness of the importance of understanding the materials from which many of our heritage buildings are constructed for their future preservation. Closely linked with this is the need to understand, and where possible control, the effects of pollution, in dealing with industry- and traffic-induced contamination of both the ground and the built environment above it. There have therefore been more papers concerning this subject area in recent years. Also evident in the more recent years are papers reporting on methodologies using advanced technology that is becoming increasingly available.

Thus, some clear trends which come out of the survey and review include: a steady interest in aggregates; an increasing interest in building stone and in particular its deterioration and conservation; and a decline in papers on earthworks from a traditional perspective (especially relating to dam construction) although within this heading there is an increase in those relating to ground improvement. It might be instructive to think about directions in which the three subject areas might develop in the future: this is therefore somewhat of a class-A prediction (Lambe, 1973).

Aggregates will always be needed as a construction material, whether used in isolation or mixed with binders. There have been considerable advances in the characterization of particle shape with new laser scanning apparatus. This allows a better understanding of potential particle interlocking and hence stiffness and strength properties. Durability is always an important consideration and particle shape can play a role in this respect, especially for angular aggregates prone to crushing where there may be significant consequent changes in their grading and hence stiffness and strength. Durability is also closely linked to the environment and the effect of its changing nature (e.g. chemistry) on the constituent materials. More advanced experimental

classification techniques allow the controlling factors to be identified and analysed. Historically, all soils have been modelled analytically as continua. This is particularly unrealistic for aggregates, becoming more so with increasing particle size. Advances in computing technology have allowed analyses of particulate assemblies to be performed using discrete element modelling (DEM). It is likely that these models will continue to develop with increasing sophistication, eventually allowing some practical boundary value problems to be analysed.

In the area of building stone, the international recognition of this material as global heritage, with more and more stone types being nominated for this international designation, is evidence that these resources, widely used over the centuries and now forming part of a common heritage, are to be studied in their own right, and as a direct means of preserving the stone buildings erected over the centuries. Evolving technological advances now permit detailed characterization, involving the use of more and more sophisticated methods – allowing also for the identification of replacement stones which are compatible with, but not necessarily identical to, stones which have not weathered well over long periods of time. This however does not mean that materials and methods for the treatment of the original, weathered stone are not continuing – future developments to be observed include inorganic treatments (and here oxalates and phosphates, but also calcium and barium hydroxides, are at the forefront), the increasing use of nanomaterials as consolidants and protective coatings, and the search for elusive salt control methods, in particular using salt crystallisation inhibitors. Another area where research, and practice, are increasing and developing is that of the role played by biological organisms not only in biodeterioration, but also as a means of bioremediation (including biomineralisation and biocleaning methods). In the aggregate field, the search for new resources continues – with waste materials and marine deposits being favoured; these are also in part due to environmental concerns, where also awareness has increased, and can be expected to increase even further.

Earthworks, like aggregates, will always be needed as part of civil engineering construction. Although the number of papers in QJEGH seems to be declining with respect to more historical works, this may be a result of the areas in which the understanding of earthworks is advancing. There have been major advances in the understanding of unsaturated soils (almost all soils excavated and replaced during construction activity are unsaturated) with constitutive models being developed which allow for more realistic analyses of real boundary value problems. Equally, in order to calibrate and validate such analyses, understanding the field response of these works is fundamental. The sophistication of field monitoring has developed enormously in

recent years, both in terms of the technology of what can be monitored and the frequency, storage and transmission of data. More papers on these subjects (a small number are received) would help maintain and develop this area within the journal.

Ground improvement, within the broad area of earthworks, is another developing area, as reflected in the number of papers being submitted. Often the ground improvement process involves a chemical element being added to the ground, and those conversant with geology are often able to assess this component better than those with an engineering background. This factor is important from the perspectives of durability and environmental impact of the process used.

For all of the geomaterials discussed in this paper, durability is a crucial factor, especially in terms of the longevity of the materials and hence of the structures within which they are used. Durability is directly linked to sustainability and the need to re-use as much as we can, so as not to deplete our resources unnecessarily and also to try to avoid treating the materials in a way such that they are difficult to work with effectively in the future.

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