

Geomaterials: Latest Advances in Materials for Construction and Engineering Applications

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1. Introduction

The use of geomaterials spans long back into human history and relicts of man's endeavours remain as evidence of practical use of rocks and minerals for the benefit of evolving societies. As a discipline, the formal study and practice of geomaterials has evolved to be a distinct topic since the mid twentieth century. The practice of geotechnical and civil engineering gave rise to a sub-discipline, focused on the engineering properties of materials won from the earth (but largely excluding ores). Ore geology and production metallurgy have become subjects in their own right, focused on the recovery and processing of metals. Geomaterials, however, owe their early evolution to geotechnical activities which were concerned largely with the physical, rather than chemical, properties of consolidated and unconsolidated materials from the earth. Fookes [1] gives a substantial review of the topic as he saw it in 1991. Since then, this field of activity has expanded considerably, to include many new materials such as tyre crumb, ceramic wastes, combustion products and many other anthropogenic materials, which are not primary products of the extractive industries, but represent resource-efficient use of industrial by-products in much the same way as, for example, natural aggregates. The field currently occupies a space between four older disciplines and has become firmly established in its own right (Figure 1).

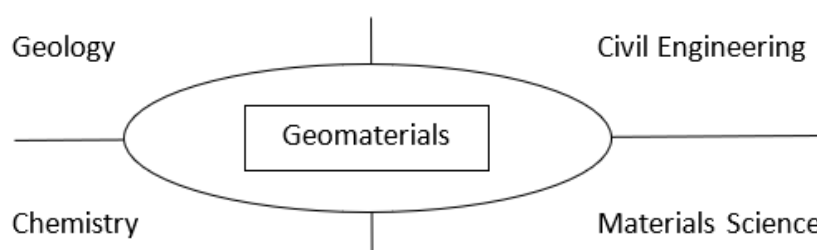


Figure 1. The discipline of geomaterials relates closely to other subjects.

In recent decades, our understanding of the importance of chemistry and microstructure in governing many engineering properties has grown, such that these aspects are firmly embedded in the study and practice of geomaterials. Before looking at geomaterials in any detail, it is appropriate to examine the use of the word over recent decades. Although the etymology of the word ‘Geomaterials’ is obvious, its first written use remains elusive; however, it seems to have appeared regularly in the literature since the 1960s and 1970s. One of the earliest uses of the term (1964) appears in a report [2] by the Highway Research Board of the Division of Engineering and Industrial Research, National Academy of Sciences, National Research Council (USA) which discusses the mechanical behaviour and properties of various materials found in geotechnical engineering, referring to them collectively as “geomaterials.” Analysis of word use in publications over the twentieth



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century allows an n-gram plot to be produced (Figure 2). This demonstrates the wide adoption of the term ‘Geomaterials’ in the 1980s and establishment of a burgeoning field of activity by the 21st century.

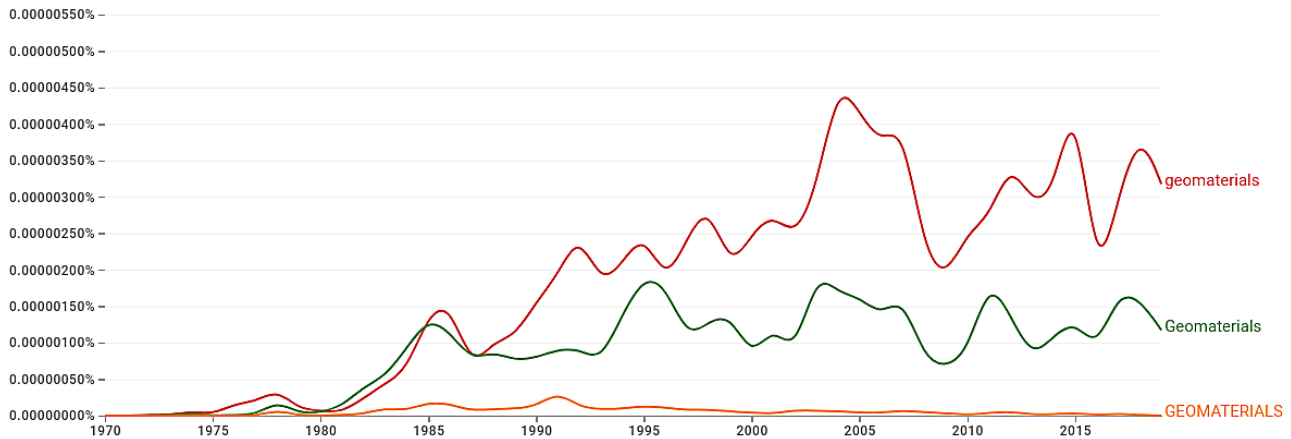


Figure 2. Use of the word ‘Geomaterials’ in English language books. Vertical axis is the fraction of the books examined by the Google™ n-gram generator (21 July 2023. <https://books.google.com/ngrams/>) per month, plotted against time.

Whilst the field of study is relatively recent, the practice dates back to the dawn of civilization. Both brick and stone have been in widespread use for at least 12,000 years, when bricks were initially hand moulded, often reinforced with plant fibres (commonly straw) and baked hard in the sun (Figure 3). Early fired bricks have been found in Banpo village [3], near Xi’an, China and these are 5500 years old. Brick making (both fired and unfired) was widespread by the Bronze Age and in the great empires of antiquity (Babylon, Assyria, Egypt, Persia, Phoenicia, etc.) whose people were skilled in both brick and stone masonry. Of similar antiquity is the calcining of limestone to make quick lime (CaO) and at a lower temperature, gypsum to make plaster. Both technologies were established in neolithic times and have a history of use spanning 10,000 years. By classical times (Greece, Rome), stone masonry was a major activity and many excellent examples of architectural and decorative stone work survive today.

The history of cement spans two periods of development. Lime mortar in construction was used since the Bronze Age and still survives to this day. Lime hardens by aerial carbonation to form a calcium carbonate–hydroxide binder which although robust, is moderately soluble. This left structures more susceptible to rain weathering than are their modern counterparts, hydraulic cements. A step change was seen in the Greek and Roman use of natural pozzolans (especially volcanic ash from Pozzuoli, Italy) that reacted with the alkaline pore solution to precipitate calcium silicate hydrate (CSH) gel which is much less soluble than lime mortar. The history and development of cement and concrete has been reviewed regularly and two contributions provide comprehensive summaries of this topic. Blezard [4] discusses the major developments in cement technology referring to the Lepinski Vir settlement in Serbia (7600 years ago) which he felt was the domain of the archaeologist, rather than scientist, but nonetheless contains the remnants of a ‘concrete’ floor. He also includes a photograph of an Egyptian mural from a site in Thebes, which shows workmen filling earthenware jars with water that is then mixed with lime and used as a mortar for stone masonry. Trout [5] gives an authoritative account of the development of cements from antiquity to the present and both publications report important milestones in the evolution of cement technology.



Figure 3. Çatalhöyük, Anatolia, Turkey. This neolithic settlement shows extensive use of mud brick construction from around 9000 years ago and is one of the best preserved neolithic/chalcolithic sites in the world. Image by Murat Özsoy (1958) Wikimedia Commons.

In the 1700s, John Smeaton, Bridley Higgins, Louis Viscat and Joseph Parker each made significant advances in producing hydraulic cements and in 1824 Joseph Aspdin was granted a patent on ‘Patent Portland cement’. This was made by calcining limestone with clay to produce cement clinker that could be ground and mixed with water to produce a waterproof (‘hydraulic’) cement. Although Aspdin did not reach high enough temperatures to advance the clinkering reactions to near completion, this paved the way to modern cement production. Work by Le Chatelier in the 1880s into the chemistry of cements firmly established the foundations of our understanding of cement production and use. Developments throughout the late 19th and early 20th centuries saw industrialisation of cement production on a global scale, such that by the mid-twentieth century, cement and concrete were the preferred materials for construction in many projects.

Developments in processing technology greatly influenced the production and use of geomaterials. The mechanical crushing, screening and washing of quarried stone drove the expansion of aggregate production far beyond the use of naturally produced sand and gravel, although mechanised recovery of natural aggregates also resulted in considerable expansion of these industries. Similarly, mechanised cutting and dressing of stone for construction and of slates for roofing developed throughout the industrial revolution, driven by demand from new building in the late 18th and 19th centuries. At this time, demand for roadstone expanded alongside the need for building, requiring both dressed stone for road cobbles and compacted stone for their base layers. The introduction of tarmacadam (late 19th century; J.L. McAdam, improved and patented by E.P. Hooley; 1902) led to a rapid increase in road construction and asphalt-bound roadstone provided the wearing surface layer of roads from the mid-twentieth century.

The current practice of geomaterials concerns the influence of material properties on their engineering properties in service. This spans the geotechnical concerns of slope stability and earthen construction to the processing and durability of rocks and minerals in the myriad of applications for which they are used. Mechanical and thermal property studies, on which the discipline was built, have been supplemented by a much increased understanding of how chemistry and microstructure control durability and service life. Poole [6] and Ingham [7] published comprehensive works considering the chemical, mineralogical and microstructural properties of geomaterials and show how a detailed understanding

of these aspects has led to greater confidence in explaining durability of the materials in service.

Figure 4 considers the major groups of geomaterials in terms of both their degree of consolidation and degree of processing. At the simplest level, unprocessed materials constitute the greatest proportion of geomaterials in use. Earth works, highway construction and excavation consume vast quantities of unconsolidated soil, aggregates and rock-fill, emplaced and compacted with long service lives in mind. An understanding of the mineralogy of such massive engineering projects ensures the risk of, for example, ground heave as a result of oxidation of pyrite in rocks may be minimised. Mineralogical instability is turned to advantage, however, in highway construction, where minerals in the igneous rocks used as road stone weather at different rates, ensuring the wear from vehicle tyres exposes fresh surfaces and maintain a high coefficient of friction between the tyre and the road. This gives rise to the concept of ‘Polished Stone Value’ (PSV) addressed in current standards for aggregates (e.g., BS EN 932 1997) [8].

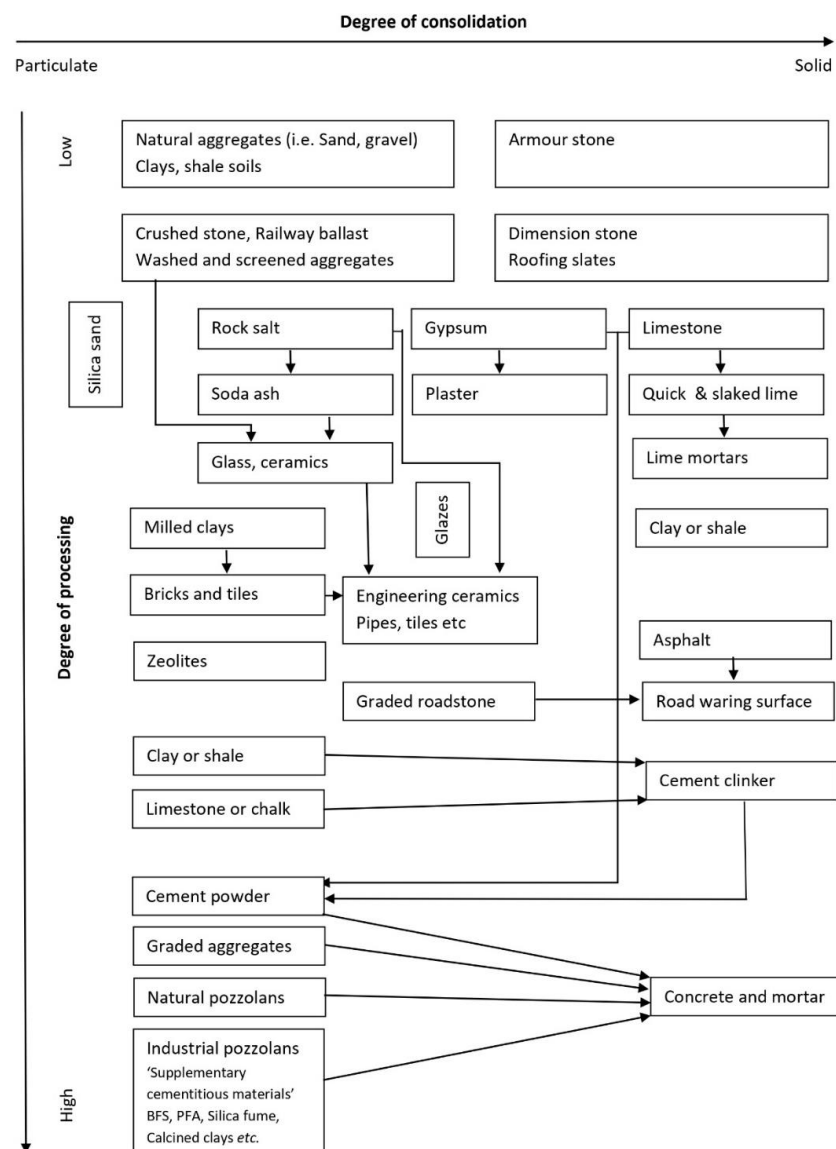


Figure 4. Major groups of geomaterials in terms of both their degree of consolidation and degree of processing.

Geomaterials are processed to varying degrees. Rocksalt (NaCl) is used directly in highway de-icing but is largely processed to form soda ash (Na_2CO_3), a major precursor for

the chemical industries. In terms of geomaterials it is used in glass manufacture (it lowers the temperature of the silicate melt) which is used with other geomaterials as a glaze on many fired clay products such as pipes and tiles. These fired clay products, along with modern brick production, globally account for over 3,000,000,000 tonnes of clay per year. Gypsum is calcined to produce plaster products and is an essential component in cement manufacture. Blended with ground cement powder, it controls the hydration kinetics of the aluminates in the clinker, preventing ‘flash set’. Limestone is an important geomaterial, both as a building stone and as a source of calcium in cement production and through simple calcining is the precursor for lime products (CaO and Ca(OH)_2). Zeolites should be considered amongst modern geomaterials, reflecting their use as ion exchange media in permeable reactive barriers (PRBs). This rather niche application is part of a much wider field of subsurface barrier construction to control the flow and quality of groundwater and, particularly, to constrain pollutant migration. Permeable reactive barriers allow the passage of ground water through chemically active media. Zeolites can sorb specific ions from a solution, whereas zero valent iron controls the redox potential of mobile solutions. Crushed limestone in PRB applications is used to raise the pH of moderately acid ground waters which may then precipitate metal ions from solution. An example of a non-permeable sub surface barrier is curtain wall construction. A trench is excavated into which a mineral mixture is poured. One example is a Portland cement—blast furnace slag and clay mixture—which never truly hardens. It remains compliant, setting to form a very low permeability semi-solid, which restricts the flow of groundwater through it.

Recent decades have seen the concept of resource efficiency become important to society and the economy. The re-use of industrial wastes and by-products is of mounting importance, driven in part by corporate social responsibility and in part by the rising taxation on waste disposal. This has led to the inclusion of many new materials in the geomaterials field. To this can be added spent foundry sands, ceramic wastes from many sources, waste sea shells, crushed brick and concrete wastes, highway ‘blacktop’ planings and a wide range of solid combustion products, all of which are reused in construction. Demolition waste has been used as bulk fill and highway sub-base layers for many years. The inclusion of supplementary cementitious materials has been driven by the desire of the cement industry to reduce the embedded carbon of cement, following a report by the World Business Council for Sustainable Development in 2002. This highlighted the CO_2 emissions released by the cement industry and the need for change. The solutions were considered by Gartner [9] who described low energy cement clinkers:

- (A) Pozzolan-based cements.
- (B) Calcium (sulfo)aluminate-based cements (made from low-grade alumina sources).
- (C) Calcium sulfate-based cements.

Gartner compares the pros and cons of each approach and concludes that “*Based on the present analysis, the most promising low- CO_2 alternative cementing systems appear to be those that make use of large amounts of either natural or artificial pozzolans or those that effectively stabilise hydrated calcium sulfates (e.g., as ettringite)*”. The United Nations Environment Programme commissioned a study (Scrivener et al. 2016) [10] which also considers a range of options. Most promising of these is the use of calcined, kaolinitic clays blended with (and importantly, replacing) much of the Portland cement clinker. The technology, known as LC^3 , includes limestone flour in the mixture and is proving to be a step-change in CO_2 reduction from cements, as the raw materials are widely available and need simple processing. Lehna and Preston [11] similarly considered options for CO_2 reduction focusing on “*the potential to blend clinker with alternative materials, and on the use of ‘novel cements’—two levers that can reduce the need for clinker itself by lowering the proportion of clinker required in particular cement mixtures*”. These reports all agree that reduction in the amount of cement clinker used (the ‘clinker factor’) is the key to reducing embedding carbon dioxide in cement production.

A wide range of industrial pozzolans have been considered but relatively few have been adopted commercially. Some (for example ground granulated blast furnace slag from the iron industry and pulverised fuel ash from coal fired power generation) have been

in wide use for a century or so. They work by providing a source of silica (commonly aluminosilicate) which dissolves in the highly alkaline cement pore solution. The consequence is that more hydration products are formed but by using less cement clinker. Many other materials have a more modest place in the market. Silica fume, wood ash, rice husk ash and ‘metakaolin’ (calcined kaolin clays) are all in widespread use but limited, often local availability, or high price prevent their wider adoption. The specialist in geomaterials needs an ever-growing knowledge of the materials used to make blended cements.

To conclude, it is appropriate to consider new materials entering the spectrum of geomaterials. Waste tyres, for example, are both a waste and a resource. When disaggregated into tyre crumb, they can be used as a permeable (but not high load-bearing) medium and is commonly used in playground and footpath construction. Glass cullet is used to some extent as an aggregate but rarely in structural concrete, owing to the risk of alkali–silica reaction. However, when finely ground [12] (<40 µm), this material has considerable potential as a constituent in blended cements.

Ingenuity and the constant need to recycle materials at the end of their service lives will ensure new geomaterials enter the field continuously.

2. About This Special Issue

Geomaterials account for the majority of all goods consumed by mankind due to their massive application in the construction of buildings, the execution of civil and geotechnical works, as well as in environmental engineering projects. These kinds of materials may retain their primary characteristics (ornamental rocks, stone aggregates, clay barriers, compacted soils, etc.) or can be artificially manufactured either from natural raw materials or from wastes (cement, concrete, ceramics, expanded lightweight aggregates, geopolymers, mineral wool, etc.).

The growing increase in population and demand for natural resources means that these geomaterials, so widely used, need to be studied in depth in order to adapt to current needs, while contributing certain technological, environmental and economic benefits. Therefore, geomaterials *have been, are and will be* strategic assets with an enormous socio-economic and environmental impact.

In this regard, this Special Issue includes a series of articles focused on recent advances in geomaterials’ research, with special emphasis on their potential application in the aforementioned sectors. The findings presented not only shed light on the knowledge we have had about geomaterials to date, but also pave the way for future research in order to delve deeper into their improvement, development and sustainability for future generations.

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