TECHNO-ECONOMIC AND ENVIRONMENTAL ANALYSIS OF
ALKALI ACTIVATED MATERIALS CONTAINING
PHOSPHOGYPSUM AND BLAST FURNACE SLAG

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The construction sector as a whole contributed US$3.3 trillion to the global economy in 2008 [1]. In
the same year, worldwide production of cement was around 2.9 billion tonnes [2], making it one of
the highest-volume commodities produced worldwide [3]. Such an enormous volume of production
is also associated with a very significant environmental impact. Cement production contributes at
least 5-8% of global CO2 emissions [4] because the production requires the high-temperature
decomposition of limestone. Demand for cement is still growing rapidly, especially in the developing
world [5]. Due to limited reserves of limestone and increasing carbon taxes, the concrete industry
faces challenges to meet the growing demand of Portland cement (OPC) [1], meaning that there is an
urgent need for alternative binders without further compromising the Earth’s atmospheric CO2 levels
[3]. Alkali activated materials (AAMs) are among several alternative binders which are being
discussed today with a view towards obtaining environmental savings in the construction industry.
One of the advantages of AAMs over traditional OPC is the much lower CO2 emissions, mainly due to
the avoidance of a high-temperature calcination step in AAM synthesis [3].

The AAM technology also provides the opportunity for the utilisation of waste streams [3]. The
valorisation of industrial wastes into building materials has become an important feature in materials
development once reduce the need of wastes disposal and the decrease of scarce resources
utilisation [6]. AAMs are a class of amorphous alkali aluminosilicates, essentially consisting of a
repeating unit of sialate monomer (-Si-O-Al-O-). A variety of aluminosilicate materials such as
kaolinite, feldspar and industrial solid residues such as fly ash, metallurgical slag, mining wastes etc.
have been used as solid raw materials in AAM synthesis. These source materials should be highly
amorphous and possess sufficient reactive glassy content, low water demand and be able to release
aluminium easily [7]. This potential is also supported by the fact that there is abundant of industrial
wastes generated in various industries which are causing problems in terms of finding an ideal
solution for disposal purposes [8]. In current research, a blend of phosphogypsum and ground
granulated blast furnace slag (GGBFS) was chosen as solid raw materials. These industrial wastes were chosen based on capacity, homogeneity and urgency for Flanders with the aim to promote large volume recycling/reuse of these waste materials to prevent environmental and health risks, scarcity of land and other issues, and to create a closed-loop industrial system were everything has its use. In this scope, AAM synthesis offers the greatest potential in solving not only the waste management problems related to the aluminosilicate solid waste materials generated from various industries, but also the environmental degradation related to the use of OPC as primary binder material in the construction industry.

Phosphogypsum is a by-product of phosphate production from phosphate ore or fluoroapatite. Despite the suitability of this secondary mineral, its actual application in building materials has remained limited [9]. The worldwide use of phosphogypsum in building materials is probably well below 15% of output [10]. It is classified as hazardous waste because a relatively high level uranium series radionuclide material, which provokes a negative environmental impact and many restrictions on its use [11]. Overall, discharges into water, stacking and landfilling have remained the dominant fate of the mineral waste considered here [12]. The worldwide generation of phosphogypsum is estimated to be in the order of 100-280 million tons per year [13]. The total amount produced up to 2006 worldwide is estimated to have been about 6 billion tons. It is also estimated that, by 2006, a total of 2.6-3.7 billion tons has been accumulated in stacks worldwide, representing 44-62% of the total amount produced up to that time. World phosphate production is expected to increase incrementally, leading areas of growth are planned in Africa and the Middle East [14]. In Europe, there are over 30 phosphoric acid plants, annually producing more than 21 million tons phosphogypsum [15]. These plants mostly dump the phosphogypsum on their own land or in excavated areas, e.g. old lignite pits, sand mines or quarries. Especially in Germany, particularly in the Ruhr area, old mines and excavated areas are used. In France, phosphogypsum is used agriculturally as structure-improving agent for the soil, but quantities used are negligible. In some cases, it is discarded in tidal rivers, however disposal into smaller inland rivers is not allowed at all. Germany is the only European country which uses phosphogypsum to replace natural gypsum as a raw material for building materials, but still considerable quantities are simply dumped [16]. In Belgium, the phosphate industry has been an important industrial activity since about 1920, especially in the northern part (Flanders). Roughly 38 million tons of phosphogypsum were disposed of in dumps and landfills, which are situated in three distinct areas. One plant still produces 0.25 million tons per year [17]. Besides the presence of radionuclides, phosphogypsum contains a relatively high level of fluoride and some heavy metals (such as arsenic, barium, cadmium, chromium, lead, mercury, selenium and silver) [18], influenced by the phosphate ore composition and quality, the wet process
employed, plant operation efficiency, disposal method and the age, location and depth of the stack [19]. However, most of the phosphogypsum is stockpiled without any previous treatment [11]. Due to the presence of radionuclides such as radium, uranium and their decay products, phosphogypsum is considered radioactive and can contain as much as 60 times the levels normally found prior to processing [11]. The rate at which phosphogypsum is produced far exceeds the rate at which it is used and the need for the disposal of large amounts will remain. The management of these stacks requires care because of the large volumes and land areas involved, the potential for emissions of dust and radon and the potential for seepages. The management is the same as for engineered structures containing other types of naturally occurring radioactive materials (NORM) in bulk amounts, such as residues from the mining of radioactive ores [18]. In Flanders, the disposal of NORM waste costs €175 per ton [20]. These large production volumes, environmental and economic concerns provide a very compelling reason to identify and promote further ways of safely using phosphogypsum as a co-product of phosphoric acid production rather than having to manage it as waste [20].

GGBFS is the by-product from the blast-furnaces used to make iron, produced by water quenching of molten blast furnace slag [21]. It is estimated that annual world GGBFS output in 2015 was in the order of 300 to 360 million tons [22]. Compared with phosphogypsum, GGBFS has a considerably higher degree of utilisation [10]. More than 75% of GGBFS is used as supplementary cementitious material worldwide [21]. The storage of GGBFS not only occupies a large amount of land resources, but also causes environmental pollution to the soil, underground water and the atmosphere [23]. In 2009, GGBFS was sold at $50-$80 per ton [24]. Long-term demand for GGBFS likely will increase because its use in concrete yields a superior product in many applications and reduces the unit carbon dioxide emissions footprint of the concrete related to the OPC content [22]. In Europe, 30 million tons of GGBFS is produced yearly, of which approximately 80% (or 20 million tons per year) is used in cement or concrete [25]. In Flanders, Arcelor Mittal Gent is the only producer of GGBFS. In 2012, they produced 1.12 million tons and this production rate is fairly stable over the last years [26].

This limited application in building materials, especially for phosphogypsum, can thus in part be attributed to the presence of minor components having a negative impact on production economics and product quality [27, 28] and gives rise to issues from the perspective of production and indoor environment, but also for the wider environment [12]. This has also sparked criticism regarding the use of them in building materials in view of negative impacts on working conditions as well as on the indoor and wider environment, associated with the life cycle of building materials [12, 29, 30], which has reduced demand for their application [9]. In the development of recycling options, release of harmful components has to be examined and tackled indispensably. Nevertheless, the development
of economic valorisation options is crucial from the industrial point of view. Compared with GGBFS, phosphogypsum has a considerably lower degree of utilization; greater efforts of basic and applied research are therefore necessary in order to widen its field of application. Therefore, current research focusses on AAMs which are developed especially for the valorisation of the considered mineral wastes here.

The objective of this work is to identify the crucial variables for rendering the production of AAMs based on Flemish phosphogypsum and GGBFS mineral wastes profitable. Therefore, a preliminary techno-economic analysis has been carried out for a process design especially developed for their valorisation. After developing a process diagram for the production of AAMs, the net present value of the cash flows generated has been determined. The minimum selling price of the produced building materials has been determined, taking into account uncertainties by performing Monte Carlo sensitivity analysis. Finally, this preliminary techno-economic analysis is used to identify the key variables for the profitability of the production of AAMs from phosphogypsum and GGBFS. The environmental aspects of the process are expressed in global warming potential (GWP). The evaluation of GWP is based on a life cycle assessment.

REFERENCES


