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Sustainable sourcing of raw materials for the built environment

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ABSTRACT

Although the ongoing discussion on cement and concrete sustainability is mostly focused on CO_2 emissions, the management of raw materials used for construction also deserves the attention of the scientific community and industry. Each year, the construction and building sector incorporates about 40% of the over 90 billion tonnes of raw materials extracted from the Earth's spheres. Raw materials supply chains can be exposed to risks of critical shortages and price volatility, and their transport over long distances strongly contributes to the overall anthropogenic CO_2 emissions. Therefore, deploying strategies aimed at mitigating the impact of raw materials supply, in line with what envisaged by Sustainable Development Goal 12 will be crucial to the achievement of a sustainable construction industry.

1. Introduction

The huge impact of human activities on Planet Earth and its ecosystem has led a group of researchers to propose the definition of a new unit within the geologic timescale, named *Anthropocene* [1] (i.e. "the human epoch", from ancient Greek). The Anthropocene Working Group gathered evidence suggesting that the driving force of human activities on the earth's dynamics has become comparable to that of geological forces [2]. Despite the still ongoing fierce debate on whether the formal recognition as a geologic epoch is acceptable, "Anthropocene" has been acknowledged as a descriptive term, within both the academic and non-academic debate, of the anthropogenic environmental impact [3].

Within the cement and concrete science community, the current debate around the anthropogenic impact associated with cement and concrete production is mostly focused on the huge amount of emitted CO_2, its role on climate change, and possible mitigation strategies. Here, I will focus on a strictly related topic, which is the role of raw materials supply, and its impact in terms of resource depletion, landscape modifications, and associated socio-economic consequences.

Some examples of the use of alternative, local raw materials for construction are provided, inspired by the challenges outlined in the United Nations 2030 Agenda for Sustainable Development (Sustainable Development Goals- SDG) [4], with specific focus on SDG12 ("Ensure sustainable consumption and production patterns") and SDG11 – Target 11.c ("Support least developed countries, including through financial and technical assistance, in building sustainable and resilient buildings utilizing local materials"). Calcined clays and carbonates are considered in this contribution, since they are the most promising for use in alternative, low-CO_2 binders. Reviews are available for less widely used material, which can be locally available in developing countries, such as biomass and agricultural ashes [5,6].

2. Anthropogenic metabolism and the construction industry

The latest "Circularity Gap Report" estimates that, currently, about 100 billion tonnes (Gt) of raw materials are extracted each year, more than 90% of which being virgin resources, and only less than 10% obtained by recycling [7]. Projected data, based on a business-as-usual scenario, provide an estimated amount of over 170 Gt raw materials extracted by 2050. The report suggests that within the gross stock of extracted raw materials, "gravel, sand and crushed stone" represents the most extracted category, with a yearly mass of about 30 Gt, mostly incorporated into the building and construction sector, which accounts for the utilization of nearly 40 Gt of the whole raw material stream (Figure 1). These data show that, other than accounting for a significant share of the global anthropogenic CO_2 emissions, cement and concrete production has an enormous footprint in terms of raw materials consumption.

3. The impact of raw materials sourcing

Raw material extraction and flows can exert different forms of environmental and socio-economic impacts, and the emerging economies may be particularly exposed to such impacts. In the developing countries, price volatility associated with disruption of supply chains

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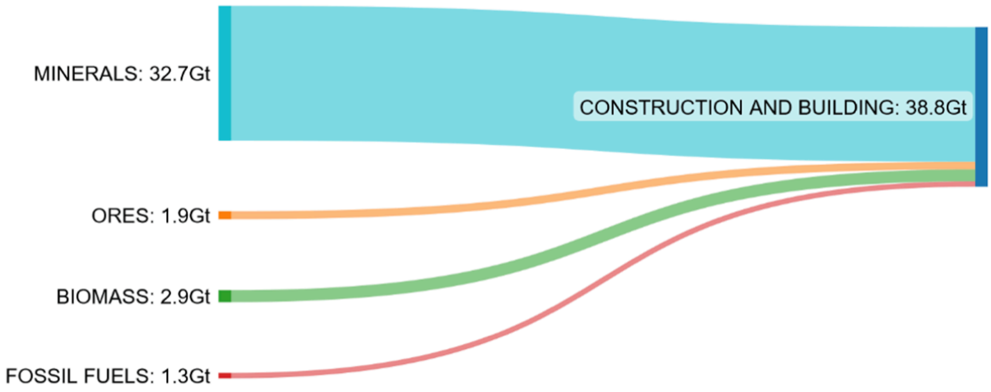

Fig. 1. Sankey plot (modified from [5]) displaying the global material flows associated with the construction and building sector.

Fig. 2. Area affected by illegal gold mining (*galamsey*) in Ghana. Photo courtesy of Federico Monica.

may affect food security [8] and also lead to fluctuations in the cost of building materials [9]. Moreover, extractive activities, especially when performed illegally, may have a direct environmental impact in terms of landform modification, which can then affect local communities. One example is *galamsey*, which refers to small-scale illegal gold extraction in Ghana. Illegal gold mining has a direct impact on the environment, because of loss of forest cover and biodiversity, water pollution and destruction of farming activities (Figure 2) and also negatively impacts on local communities, for example because of health risks associated with exposure to mercury [10].

Likewise, illegal raw material sourcing activities, associated with the building industry, can equally impact on the environment and local communities. One example is the extraction of sand, which has become one of the most critical resources [11]. High demand and increasing prices of river sand have prompted illegal extraction activities [12], which can affect the local communities, induce shoreline erosion, and increase the risk of flooding. Moreover, limestone quarrying for cement production can have an impact on the quality of soil, air and water [13].

4. Local approaches to the production of construction materials

The issues summarized in the previous sections demonstrate that the construction and building industry needs to address the need for sustainable sourcing of raw materials. More specifically, the points that need to be addressed are the following: a) the share of secondary raw materials sourced by recycling must be increased, this is especially true for aggregates, whose supply is becoming increasingly critical; b) "local" sourcing of raw materials for construction can potentially decrease CO_2 emissions associated with freight transport, mitigate price fluctuations associated with the disruption of supply chains, favoring the creation of local jobs. However, governance and regulation of localized raw material sourcing are fundamental aspects, to avoid incurring illegal activities.

4.1. Local sourcing of clays

The use of clay soils as raw materials for the production of sustainable cement has been receiving much attention from both academia and industry. Large overall availability, extensive geographical distribution, and low cost, make calcined clays the perfect candidates as a source of Al and Si to form hydration products in alternative cements with reduced clinker fraction. Use of low-grade clays in blended (binary or ternary) cements allow demand and costs to remain relatively low, because they are commonly discarded by competing industrial sectors (such as the ceramic and paper industries) [14]. Also, in alkali-activated materials the use of low-grade clays minimizes the demand of alkaline activator and its cost and environmental impact [15].

Lateritic soils, which are ubiquitous at tropical latitudes, are enriched in kaolinite and have a long history of usage in vernacular architecture. However, the red tint associated with the presence of significant amount of iron oxides and hydroxides currently limits their use, because: 1) in developing countries, the red coloring of earthen houses is associated with "poor" building materials, hence the lack of social acceptance; 2) most producers keep a conservative approach and consider "gray" color as a fundamental property of cement. However, these stereotypes have recently been questioned, for example in African countries, where construction methods that envisage the integration of modern technology and design, materials with low environmental footprint, and traditional architecture, are being suggested as a means of preserving the local cultural identity without compromising performance [16].

From the technological point of view, alternative (blended, alkali-activated, acid-activated) cements based on the use of calcined laterites in both blended cements and non-Portland cements are shown to be competitive in terms of mechanical performance [17–20]. In such alternative cements, the role of iron, which can be present in significant amounts in laterite soils (up to greater than 40% Fe_2O_3), has not been clarified yet. It has been suggested that the presence of iron may induce local lattice distortions, enhancing the loss of crystallinity and formation of amorphous phases during calcination [21]. In laterite-based non-Portland cements, Fe may contribute to the formation of reaction products [18].

Added environmental and economic value can derive from the utilization of excavated clay from mining of either high-grade kaolin or other ores and industrial minerals, which are commonly disposed of in open-air storage facilities. Depending on the nature of the mined resource, such waste clays can contain moderate to large amounts of clay minerals, and can be suitable for the production of blended cements [22], alkali-activated materials [23], and aggregates [24].

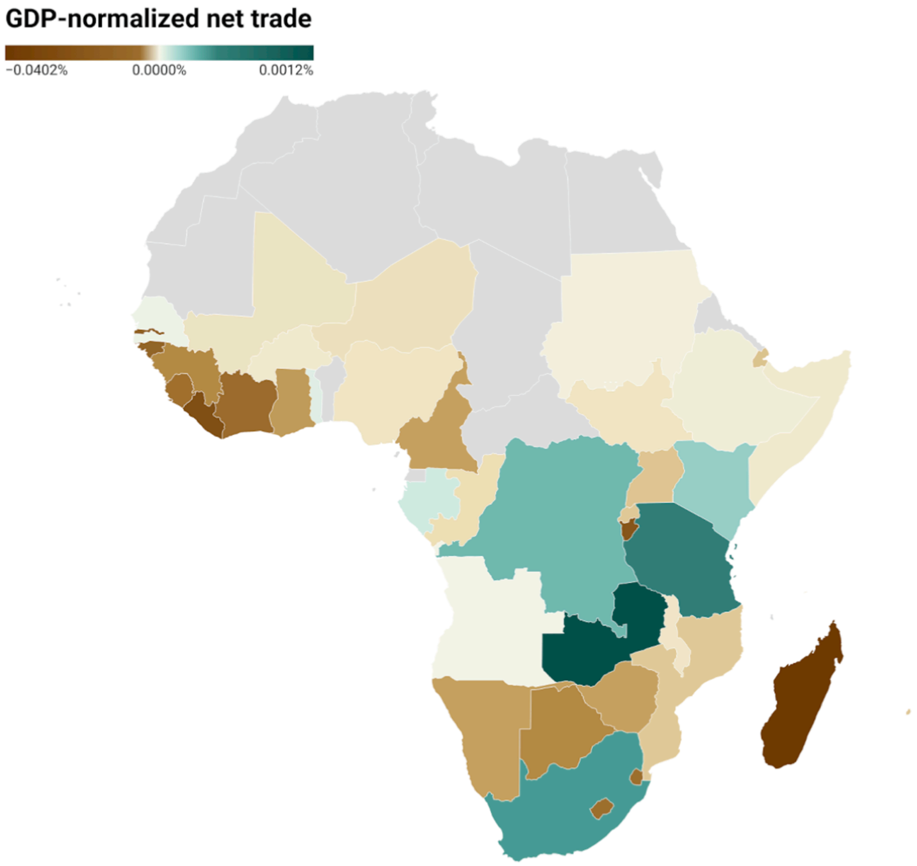

Fig. 3. Map displaying the value of net trade (export minus import, in USD) as percentage of national real GDP, for the trade category "limestone materials for manufacture of lime and cement", in Sub-Saharan African countries. Countries in brown hues are net limestone importers, countries in blue-green hues are net limestone exporters, countries in grey are either not considered part of Sub-Saharan Africa or have no data available. Personal processing of data from The Observatory of Economic Complexity and The World Bank. An interactive map with possibility of downloading the data is available at: https://www.datawrapper.de/_/LNp4d/. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

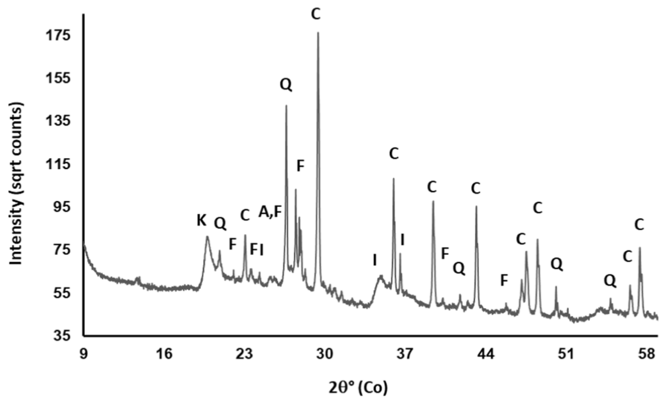

Fig. 4. XRD pattern of sample of caliche fines from quarrying activity in Kenya. Mineralogical phase labels: K = kaolinite; Q = quartz; F = feldspars; C = calcite; I = illite; A = anatase.

4.2. *Local sourcing of carbonates*

Other than representing the main raw material for the production of Portland cement, limestone is also commonly used in blended cement as a source of calcium carbonate, acting both as a filler and inducing the formation of carbo-aluminate phases. However, reserves of high-grade limestones may be somewhat limited in some developing countries, particularly in large parts of Sub-Sahar Africa. This has a strong impact on the local cement industry, which has to rely on massive import (Figure 3), with dramatic consequences in terms of price. In countries such as Ghana, alternative sources of calcium carbonate, such as clam shells, have been used e.g. for the production of lime and are classified as industrial minerals [25]. Different kinds of shells, commonly enriched in aragonite, have been used as a source of calcium carbonate in blended cements or as aggregates [26].

Dolomitic limestone can also be used as an alternative to high-purity limestone in sustainable cement production. While dolomite is not viable for clinker production, its addition in blended formulations, e.g. in ternary cements containing OPC and calcined clays, may represent an alternative where high-purity limestone is not locally available. Reaction pathways and strength development in such blends containing dolomite were reported to be comparable with those of LC3 cement [26]. One further alternative to high-purity limestone may be represented by sedimentary deposits known as caliche. Caliche (also known as calcrete, or with other local names such as kankar or kunkur) consists of hardened deposits formed by sedimentary or soil particles bound by a calcium carbonate matrix precipitated from saturated waters [27]. Caliche deposits with high $CaCO_3$ content can be used in clinker production, and quarry fines can potentially be used in blended cements. An example XRD pattern of caliche fines sampled in Kenya is reported if Figure 4, showing a mineralogical composition consisting of calcite and phases that may commonly occur in soil such as clay minerals, quartz, feldspars and anatase.

Finally, alkaline carbonates of geological origin can be used for the production of alkali-activated binders, with a milder, less impacting and cheaper activator compared to sodium or potassium silicate and hydroxides. For example, several million tonnes of reserves of sodium carbonates are estimated to be available in countries such as Botswana, Kenya, Ethiopia and Tanzania [28]. Sodium carbonate activators are especially effective with high-Ca alkali-activated materials such as those based on ground granulated blastfurnace slag and class C fly ashes [29,30]. Where such materials may not be available, activation of calcined clays with a combination of sodium carbonate and $Ca(OH)_2$ can be a viable option [31].

5. Outlook and conclusions

Portland cement is the most widely used type of cement in the world, holding a dominant market position in the construction industry. Despite its popularity, the production of Portland cement emits huge amounts of carbon dioxide, thus contributing to the global greenhouse effect. To address this issue, the design of alternative cements must take into consideration the specific needs and conditions of each application, as well as local availability of raw materials, moving away from the current "one-size-fits-all" approach. This requires a paradigm shift and a combined effort from all involved stakeholders, including academia, industry, and standard authorities, for such sustainable cements to have a positive impact on the environment and local communities.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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