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Environmental Impacts of Geomaterials Exploitation in the Republic of Congo

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Abstract: Geomaterials are extracted everywhere in Congo, generally without environmental and social impact studies. The objective of this study was to assess their exploitation and the associated environmental consequences. Data were collected through interviews and field surveys. A total of 163 quarry sites (17% industrial and 83% artisanal) were studied, with an annual production of nearly 52 million tons. The activity is carried out either in the open air or in water. Three types of materials are exploited: soft (65%), hard (35%) and smooth (0.1%). The activity is mainly centered around urban agglomerations, and sand and gravel are the most prized geomaterials, regardless of the type of exploitation. The geomaterials exploited come either from primary rocks (granite and quartzite) or from the products of their dismantling (accumulations of gravel, sandstone, recent sands or laterites). The various mining processes use, from extraction to finishing, incoming flows in the form of consumable materials (oils, greases, tires, etc.), in the form of energy (fuel, electricity, etc.), and in the form of water, in the form of energy (hydrocarbons, engines or explosives), water and outflows in the form of solid (abandoned gravel heaps), atmospheric (dust, gas, vapors) and liquid (lubricants, fuels, water for washing materials) discharges that induce various pollutions that affect all the compartments of the environment (physical environment, biodiversity, health and human well-being). The impacts of artisanal mining are mostly medium and minor, with only 18% of major impacts, in contrast to industrial mining, which generates 55% of major impacts and appears to be the most degrading for the environment. Despite of the legislative and regulatory texts, the exploitation sites are abandoned without any rehabilitation, which impacts the environment for a long time. To impulse a sustainable management of the activity, proposals have been made.

Keywords: Mining, Geomaterials, Impacts, Environment, Congo

1. Introduction

The main reason for the exploitation of geomaterials is the need for materials for the construction of buildings and structures, including physical communication infrastructures. These materials, elaborated in large quantities in the form of rock fragments called aggregates, represent the largest volumes of all mineral substances extracted from the subsoil. Worldwide, over 14 billion tons are extracted annually [1]. These materials are mined in the form of sand, gravel, clay, laterite, limestone, granite, ... [2], and used directly or broken up into aggregates, allowing the erection of buildings essential for the functioning of modern societies. However, the removal of natural resources and their preparation for use is damaging to the environment [3-9].

Studies on the impacts of geomaterial exploitations, throughout the world, show that the activity is generating environmental degradation [10]. It is for this reason that Dadi et al. already stated that the environmental impact assessment (EIA) is one of the instruments that must allow the respect of the spirit of the concept of "Sustainable Development" [11]. Indeed, studies on the impact of the exploitation of quarries of massive rocks have highlighted the health risks, the impact on the sites and the ecological potential [3]. The creation of a quarry introduces a disturbance that is expressed both ecologically (disruption of environments and species), environmentally (local change in water flows, modification of energy transfers) and in landscapes (sudden break in lines, clearing, etc.) [12]. This study conducted in France led to the institution of the environmental and social management plan (PGES) as a tool accompanying the exploitation, but also the French national strategy for the sustainable management of terrestrial and marine aggregates, quarry materials and substances [13].

In developing countries, mining and dredging regulations are often established without scientific understanding of the consequences, and projects are conducted without environmental impact assessments [14, 15]. As a result, global mining affects the provision, protection, and regulation of ecosystem services [16].

In Africa, as elsewhere, geomaterial quarries are an important source of income, the corollaries of which are the destabilization of the natural and economic balance of nearby rural areas, and the disappearance of agricultural land and a general degradation of the environment [17, 18, 6, 7]. Despite these adverse environmental consequences, impact studies of quarries are not widely available [16, 17, 19]. These studies have shown that unlike in Europe where operations are subject to strict regulations, no consistent obligations for environmental preservation are made in Africa.

Located in Central Africa, the Republic of Congo, has large deposits of geomaterials unevenly distributed in its subsoil [20]. In recent years, the Congo has been marked by environmental changes, impact of government works carried out in all departments, without any environmental consideration. However, works dedicated to geomaterial mining activities are scarce, even though Maouéné et al. showed that these activities were the cause of some diseases [21]. Furthermore, due to the lack of available knowledge on the location of deposits around each project, construction materials have been transported over very long distances. This makes their cost prohibitive and undoubtedly leads to unknown impacts along their itinerary. Thus, the Congo has a concomitant lack of data on the distribution of geomaterials in its territory, and the effects induced by the extraction and preparation of these materials. Considering the variability of the extraction methods and the important volume of the production of materials, all these activities would raise enormous problems on the environment. With the aim of contributing to the sustainable development of the extraction of construction materials, this work reviews the issue of geomaterials and its environmental and social impact in the Congo, to make suggestions that will help preserve the environment.

2. Material and Methods

2.1. The Study Setting

The study covered the entire national territory, which is characterized by different geological contexts and a dense hydrographic network on which geomaterial exploitation is developed.

The Congolese geological context is composed of Precambrian rocks that cover two-fifths of the territory, the rest being occupied by secondary, tertiary and quaternary formations [22]. Several geological units can be distinguished which present particularities in terms of geomaterial potentialities:

1) the Chaillu Massif is a huge granite batholith of about 300 km by 150 km, heavily eroded. It is the result of several phases of granitization, the last of which dates back about 2500 million years. This granitization has spared some metamorphic sectors to which are associated peaks of ultrabasic rocks and indications of valuable minerals (gold alluvium, columbite-tantalite, nickel, cobalt, chromium, diamond, corundum) and iron deposits (Zanaga, Mayoko). Granite is particularly interesting because it is mined around localities such as Mossendjo and Yaya.
2) the Ivindo and Sembé-Ouesso complex occupies the northern part and covers an area of 300 km by 200 km. It includes:
   a) the Ivindo complex, which is made up of crystalline and crystallophyllous rocks, is the equivalent of the Chaillu massif.
   b) the Sembé-Ouesso series, composed of quartzite sandstones at the base surmounted in discordance by sandstones, shales, and sandstone limestones with dolerite intrusions.
3) the Mayombe is a section of the West-Congolian (Pan-African) orogenic branch, it is the result of several orogenies (2000-600 MA) and includes three sets:
   a) a set of quartz and feldspathic micaschists constituting the Bikossi-Loemé series with intrusions of granitoids, green rocks and porphyroids.
   b) a set of sericite schists, graphite schists and grauwakes with intrusions of granodiorites and dolerites.
   c) a set of carbonaceous shales, quartzites, feldspathic sandstones and jasper forming the Mvouti-Mossouva series.
4) the synclinorium of western Congo includes the Niari depressions of the Nyanga and the schisto-calcareous and schisto-sandstone plateaus. It encompasses all formations above the lower tillite (the Louila, upper Tillite, Schisto-limestone and Schisto-sandstone). This synclinorium completes the history of the Precambrian formations of the Congo and encompasses two zones which are the Nyanga zone, a vast asymmetrical syncline, oriented NW-SE and the Niari zone, oriented NE-SW from Kissenda to the southwest of Kindamba.
5) The coastal sedimentary basin is nearly 150 km long

and 60 km wide. It has formations that represent three episodes of sedimentation:

a) The ante-saliferous dominated by a tectonic with horst and grabens, oriented NW-SE and a lacustrine to palustrine sedimentation constituted from bottom to top by polygenic conglomerates with a sandy clay matrix, coarse feldspathic and quartz sandstones of the Vandji-Lucula formation, Sialivakou marls, the Djéno formation formed essentially by very fine micaceous sandstones, fine micaceous silty-sandy clays, and greenish clays. The Pointe-Noire formation characterized by dark grey to black marls, the Toca carbonates, the green clays of Pointe Indienne, the Tchibota sandstone formation and the Chéla formation consisting of polygenic conglomerate, coarse to fine sandstone and bituminous clay.
b) the saliferous constituting the Loémé series and composed of several cycles where potassium and sodium salts alternate.
c) the post-saliferous, characterized by sandstones and limestones where numerous levels of phosphates are reported.

6) The Batéké Plateaux correspond to an immense plateau of 700m altitude, which extends into the DRC, subdivided into several small plateaus (Mbé, Ngo-Nsah, Djambala and Koukouya) by deep rivers (Léfini, Nkéni, Alima, Mpama...). The geological formations that make up the Batéké Plateaux belong to the Stanley-Pool series (conglomerates, silty mudstones, white feldspathic and silty sandstones) and to the Batéké Plateaux series (polymorphous sandstones and ochre sands).
7) The interior basin of the Cuvette Congolaise occupies one third of the national territory and forms a vast depression that includes formations of secondary age (sandstones, variegated mudstones, variegated and bituminous shales) surrounded by the Carnot sandstones that outcrop on the western and northern edges, and covered by quaternary formations that mask these formations in the vast marshy areas.

The Congo's hydrographic network is very dense and resembles a veritable spider's web. It is organized around two main basins to which should be added the small coastal basins.

1) The Congo River basin groups the main tributaries of the right bank, draining the northern and central parts of the country. The main collector is the Congo River, which borders the country for more than 600 km and passes through Brazzaville, where a large sand and sandstone mining sector is being developed. The tributaries that also host mining operations are the Oubangui and the Sangha.
2) The Kouilou-Niari basin, a little more than 55,340 km^2, covers practically the entire southwest of the country. The main collector is the Kouilou River, also called Niari in its middle course and Ndouo in its upper course. This river and its main tributaries drain the main towns in the south-central part of the country, from which they obtain most of their construction materials.
3) The coastal basins are made up of all the small rivers that cut into the coastal plain. The most important are the Nyanga, of which the Congolese territory controls only a part (5,800 km^2). However, the Loemé River with an area of 1,700 km^2 [23] controls the major geomaterial production basin in the Makola-Mboubissi area.

2.2. Methodology

The methods used for this study were a literature review, field investigations and laboratory works. The literature review allowed (i) the development of the methodology for identifying and assessing the environmental impacts of the various geomaterial exploitation sites throughout the national territory [3, 8]; (ii) the collection of information on certain sites in Congo [20, 24, 25]; (iii) to take stock of the situation of the impacts of geomaterials. The field investigations involved three main activities: (i) in situ surveys; (ii) site mapping and description; and (iii) identification of impacts in the sites and on the associated environment.

The surveys were based on a questionnaire submitted to the operators and/or artisanal miners on the sites. Information on the exploitation of the sites, notably the history, the geomaterial elaboration processes, the production capacity and the surface area of the exploitations were thus collected.

Mapping based on GPS coordinates allowed the elaboration of location maps of the construction material exploitation sites. The description of the sites is made with the help of a grid and focused on the geomorphological and geological aspects, while associating the nature of the exploited materials.

The approach followed to identify the impacts of the exploitation on the environment is based on the implementation of a checklist at the level of all sites, while their evaluation used the Fecto grid [26, 27].

Laboratory work focused on measuring turbidity in water collected from a few sites. Data processing used Excel (statistical processing), Sphinx (survey data tabulation), and ArcGis (map development) software.

3. Results

3.1. Location and Description of Geomaterial Exploitation Sites

The geomaterial exploitation sites appear to be scattered throughout the Congolese territory. A total of 168 mining sites have been counted, of which 29 are industrial and 139 are artisanal. Exploitation sites are mainly developed around urban areas.

The situation of geomaterials exploitation at the level of the administrative departments of the country is highly varied (Figure 1). The geomaterials exploitation sites are located either on primary rocks (granite and quartzite) or on products of dismantling of these (accumulations of gravels, sandstones, recent sands, or laterites). Artisanal exploitation is mainly concerned by secondary formations, while industrial exploitation affects both types of deposits.

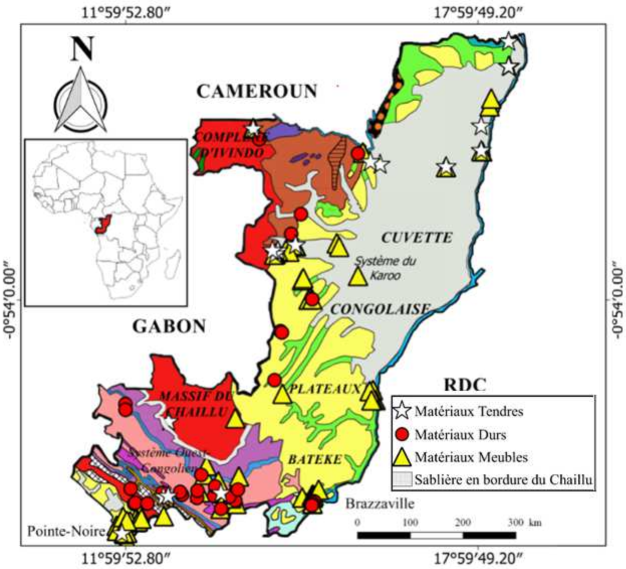

Figure 1. *Location of geomaterial exploitation sites on a geological map of Congo [22].*

3.2. Typology of Geomaterial Exploitation in Congo

Two main types of geomaterial exploitation are encountered in Congo: artisanal and industrial exploitation (Figures 2 and 3). Industrial exploitation is practiced by companies while artisanal exploitation is conducted by isolated individuals or small groups of artisans who work to build up piles of materials for sale. With 83% of the sites surveyed, artisanal mining predominates over industrial mining, which accounts for 17% of the sites (Table 1).

Figure 2. *View of an artisanal sandstone quarry in Brazzaville.*

Figure 3. *View of an industrial sandstone quarry in Brazzaville.*

Table 1. *Synoptic situation of geomaterial exploitation sites in Congo.*

Department	Mined materials	Artisanal sites	Industrial sites	Total
Pointe-Noire and Kouilou	Granite, sand, gravel, yellow/red soil	29	9	38
Niari	Sand, granite, quartzite, limestone, marble, laterite, silt, marl and clay	12	3	15
Lekoumou	Sand, quartzite, sandstone	3	2	5
Bouenza	Sand, gravel, dolomite, limestone, clay	21	2	23
Brazzaville and Pool	Sand, sandstone, yellow earth	16	9	25
Plateaux	Sand	6	0	6
Cuvette	Quartzite, laterite, clay	15	3	18
Cuvette- West	Sand, sandstone, laterite	6	0	6
Sangha	Quartzite, laterite, clay	8	1	9
Likouala	Sand, clay	23	0	23
Total		139	29	168
Pourcentage (%)		82,7	17,3	100

The frequency of industrial sites is highest in the departments near the country's two largest cities (Brazzaville and Pointe-Noire) where 62% of sites were identified (Figure 4). The lowest rates are found in the departments of Bouenza (6.9%), Lékoumou (6.9%) and Sangha (3.5%). As for artisanal sites, the highest frequencies are observed around the city of Pointe-Noire (20.9%), in Likouala (16.5%), in Bouenza (15.1%), around Brazzaville (11.5%) and in Cuvette (11.5%); the other departments have rates that vary between 2.2 and 8.6%.

Geomaterial extraction sites occupy different morphological positions in the landscape. They can be found either in large, low, flat areas (plains), or in flat, perched areas (plateaus) that have to be cut into for the extraction of the material, or at the level of the banks along rivers (U- or V-shaped valleys) that are dug or excavated, or at the level of small elevations of land (hills) that have to be cut into. The exploitation is mostly done by opening a quarry, but sometimes by taking the sand directly from the bottom of a river channel by dredging or shoveling techniques. The majority of sites (39%) are located in valleys, followed by sites in plains and hills (24%), and finally the fewest (12%)

are sites on plateaus (Figure 5). Furthermore, in terms of environment, taking into account the vegetation, the majority of sites (75%) are located in savannah, compared to 25% in forest (Figure 6).

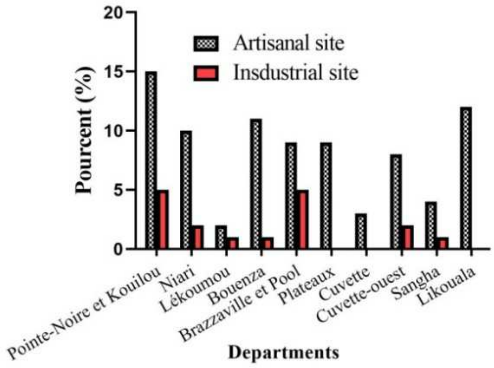

Figure 4. *Frequency of exploitation types by department.*

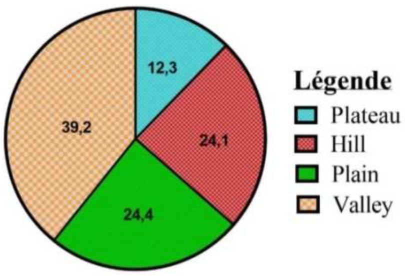

Figure 5. *Frequency of exploitation by landscape type.*

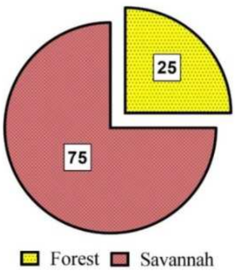

Figure 6. *Frequency of exploitation by vegetation type.*

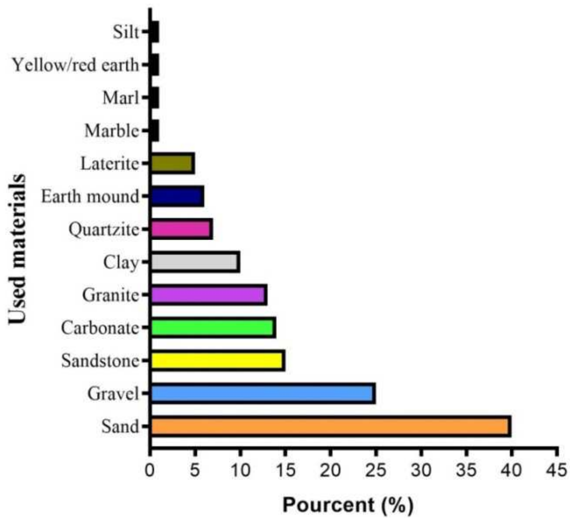

Figure 7. *Frequency of the main types of geomaterials exploited in Congo.*

3.3. Typology of Materials Exploited in Quarries

The diversity of materials mined in Congo by department (Table 1) and the frequency of geomaterials show that sand and gravel are the most favored, with 27 to 35% of sites (Figure 7). Other materials such as sandstone, carbonate, granite, clay, quartzite, mound soil and laterite are less exploited with a frequency of 3 to 10% of sites. Finally, marble, marl, yellow/red earth, and silts make up less than 1% of the sites exploited.

3.4. Geomaterials Production

The results of the survey carried out have made it possible to estimate the average annual production of geomaterials in Congo at 52 million tons [28]. The distribution of said materials is as follows: 34 million (65%) tons of soft materials (sand, gravel); 18 million (35%) tons the hard materials (limestone, dolomite, granite, marble...); and 48,000 tons (0.1%) of soft materials (clays) (Figure 8).

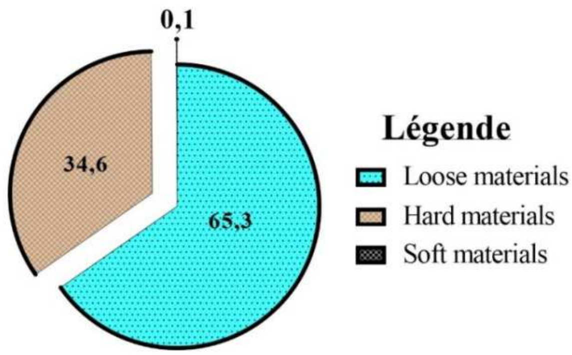

Figure 8. *Frequency of production by type of material exploited.*

3.5. The Mining Methods

The mining technics of geomaterials depend on the type of exploitation, the exploited materials and the level of technicity of the equipment. There are two types of exploitation: quarrying, which can be industrial or artisanal, and exploitation in the form of direct removal of materials, particularly sands and gravels, in areas of sediment deposition or in the channels of watercourses (Figures 9 and 10; Table 2).

3.5.1. Industrial Quarrying

Industrial quarries mainly produce aggregates. Production requires a certain number of operations, the most important of which are the extraction of the rock by blasting and handling or transport, and its treatment by crushing (Djoué and Louvoulou quarries) or by washing and screening (Bilala, Louémé and Cote Matève quarries). These quarries are the main suppliers of materials used in formal sector projects. The tools are motorized, and all the sites use an identical operating protocol. Mechanized activities start with blasting and end with loading into tipper trucks prior to dumping at the site of use. Processing stations are often simple with hoppers, crushers, screens and conveyors (Figure 9). However, in the quarries, handling is done discontinuously, i.e., in stages. There are no conveyor belts from the extraction area to the processing area. The processed products are stored on the ground in individual piles before being delivered to customers. No operator carries out site development or rehabilitation and all excavations are abandoned like this after the operation.

3.5.2. Artisanal Carrying

The main activity of artisans is the manual production of building materials (Figure 10). This category erects quarries for their own use or works on the edge of industrial quarries. The tools are rudimentary and consist mainly of crowbars, used tires to be burnt, drills, pins, hammers, and 5-10 kg sledgehammers. Loading is done with a hand shovel and transport with a wheelbarrow before using dump trucks to deposit the material on the construction sites. The tools and techniques used only allow for a small production that cannot cover the needs of the users, who are obliged to resort to industrial companies in the sector for large projects. To reduce the arduousness of the extraction phase, artisans grouped in cooperatives often join to carry out the blasting before continuing the activity by manual means. The sites are abandoned as they are after exploitation and no rehabilitation action is applied.

Artisans also use dredging and diving methods in localities bordering large rivers. The alluvial sand taken from the middle of the river is placed in dugouts and deposited in piles on the bank ready for sale. This process is typical of localities such as Impfondo and Mossendjo. Alluvial sand is also exploited by excavating the river banks. This practice often modifies the banks and widens the original channel, or even the hydrodynamics of the river. The sand collected can be clean and directly destined for use, or mixed with clay, in which case settling in running water is necessary to remove the clay fraction.

Figure 9. *Industrial processing scene: crushing of aggregates (Kombé, Brazzaville).*

Figure 10. *Artisanal processing scene: manual crushing of aggregates (Kombé, Brazzaville).*

Table 2. *Techniques and tools used for geomaterials exploitation.*

Types of operations	Production steps	Materials used	
		Artisanal activities	**Industrial activities**
Extraction	Extraction Stripping of barren level (0.5m-15m)	Machete, hoe, shovel, pickaxe.	Chainsaw, Excavator, Loaders.
	Drilling, Felling (hard materials)	Fire blasting, explosives, drill, sledgehammer, goggles, gloves	Explosives
	Direct removal (soft materials)	Shovel, wheelbarrow, buckets, waders, dugout Shovel	Excavator, Loader, dumper.
Loading, Transport	Handling and transfer of materials	Wheelbarrows, buckets, dugout canoes, dump trucks	Dumper and/or dump truck.
Processing	Crushing	Mass, hammer	Hopper, Crusher, Belt conveyor
	Screening, Washing	Sieves, buckets	Screening, De-sludging system

3.6. Environmental Impacts Related to the Exploitation of Geomaterials

The state of the environment of geomaterial exploitation sites was established throughout the national territory and concerned all sites in operation or already abandoned, whose access roads still exist. The identification of impacts is based on the interaction matrix between the activities carried out on the site and the valued elements of the environment: the biophysical environment (landscape, soil, water, air, fauna, flora) and the human environment (health, safety) (Table 3). The mechanization of some operations, for example, involves the use of inputs such as hydrocarbons and lubricants, but also the possibility of accidental losses and discharges into the air and water, in addition to the associated noise. Finally, a physical check in the field was used to identify visible impacts based on a checklist.

Table 3. *Matrix of interaction of exploitation methods with the environment.*

Type of quarries	Activities carried out	Impacted environment								
		Biophysical setting						Human setting		
		Landscape	Wildlife	Vegetation	Water	Soil	Air	Health	Safety	Jobs/Income
Industrial quarries	Discovered (15 m)	X	X	X	X	X	X	X	X	X
	Drilling of blast holes	X	X	X	X	X	X	X	X	X
	Blasting of blocks	X	X	X	X	X	X	X	X	X
	Direct loading of materials with mechanical shovel	X	X	X	X	X	X	X	X	X
	Transport of material to processing area	X	X	X	X	X	X	X	X	X
	Crushing	X	X	X	X	X	X	X	X	X
	Screening	X	X	X	X	X	X	X	X	X
	Washing	X	X		X	X	X	X	X	X
	Storage of materials and tailings in piles on the ground	X			X	X			X	X
	External transport to consumption areas	X	X	X	X	X	X	X	X	X
Artisanal quarries	Discovered (0.5-3 m)	X	X	X	X	X	X	X	X	X
	Block removal by sledgehammer (5-10 Kg)	X	X	X	X	X	X	X	X	X
	Blasting and burning of tyres	X	X	X	X	X	X	X	X	X
	Crushing	X	X	X	X	X	X	X	X	X
	Screening	X	X	X	X	X	X	X	X	X
	Washing	X	X		X	X	X	X	X	X
	Direct loading of materials by shovel	X	X	X	X	X	X	X	X	X
	Storage of materials and waste rock in piles on the ground	X			X	X		X	X	X
	External transport to consumption areas	X	X	X		X	X	X	X	X

3.6.1. Impact Identification

The observations made reveal at least 13 types of impacts identified on geomaterial sites (Figures 11-19). The environmental impacts of quarries vary according to the sites, the types of materials mined, and the methods and materials used. The impacts identified can be grouped into several families (Table 4). Thus, we distinguish:

a) Impacts on the soil and landscape: deforestation during overburden removal, stripping of the soil constituting the sterile level, presence of excavations and gaping holes of more than 100,000 m^3 per site, and generation of erosions, water bodies (abandoned lakes), abandonment of piles of materials, miscellaneous waste and machinery on site, pollution related to the accidental spillage of oils and fuels.

b) Impacts on air quality: degradation of ambient air quality by emissions of fine and inhalable suspended dust ($\Phi<10$ µm); emissions of toxic gases (CO_2, CO, NOX...) and greenhouse gases (GHGs) during blasting, operation of machinery and transport of processed materials, while the noise environment is affected by emissions of noise and vibrations.

c) Impacts on water quality: very high-water turbidity and suspended solids (SS), accidental spills of fuel, lubricants, and wastewater and/or soiled water, variation in water pH depending on the materials used, modification of riverbanks.

d) Impacts on the biological environment: loss of plant cover and biodiversity, destruction of ecological habitats, removal of wildlife in forest and savannah environments.

e) Impacts on the socio-economic environment: creation of temporary jobs and stimulation of other lucrative activities. But risks of accidents linked to explosives, crushing and transport of materials, disruption of road traffic.

f) The impacts on health: the health of operators and local populations is at risk because they are subject to stress and increased deafness, linked to the work rhythm, noise pollution and accidents. There are also cases of dust-related lung diseases or silicosis, dermatological and ophthalmological diseases, sexually transmitted diseases (STIs, HIV), and, more particularly among artisans, an increase in vibration-related muscular diseases [21].

Figure 11 below shows the ranking of observed impacts by frequency of occurrence at the sites in relation to the overall impacts. Abandoned excavations appear as the most frequent impact, followed by deforestation and soil stripping.

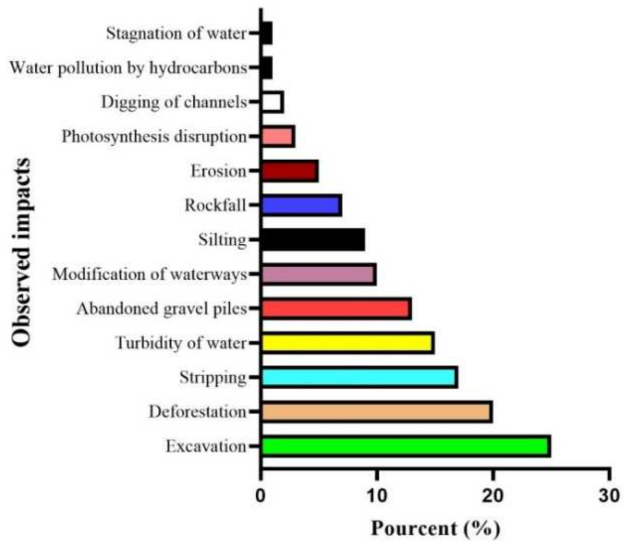

Figure 11. *Frequency of impacts observed on geomaterial exploitations sites in Congo.*

3.6.2. Impact Evaluation

The evaluation of the impacts caused by the exploitation of geomaterials, considers three main criteria: the intensity, the extent and the duration of the impacts (Fecteau's Matrix). Thus, this activity presents 95% of negative impacts and 5% of positive impacts and their importance varies according to the methods and also the techniques used (Table 4). These observed impacts are 59% of major importance in industrial quarries and 6% in artisanal quarries. 41% of the impacts in industrial quarries are of medium importance while in artisanal quarries this type of impact is estimated at 71%. Minor impacts are only observed in artisanal quarries with a frequency of 23% (Tables 4-6).

Table 4. *Impact evaluation of industrial quarries in Congo.*

Impacted environment	Valued elements of the environment	Impacts identified	Parameters of characterization							Evaluation
			Value	Nature	Intensity	Extent	Duration	Value of the affected component	Reversibility/ Irreversibility	Absolute significance
Biophysical environment	Landscape	Excavation	−	D	F	l	L	M	Irr	Major
		Landscape Modification	−	D	F	l	L	M	Irr	Major
	Wildlife	Removal of wildlife species	−	D	F	l	M	G	Rev	Major
	Vegetation	Loss of vegetation cove	−	D	F	l	L	G	Rev	Major
		Disruption of photosynthesis	−	D	M	l	L	G	Rev	Major
	Water	Increased turbidity	−	D	F	l	M	G	Rev	Major
		Destruction of waterways	−	D	F	P	L	G	Irr	Medium
	Soil	Erosion	−	D	F	l	L	G	Irr	Major
		Silting	−	D	M	P	L	G	Irr	Medium
		Bank/plantation flooding	−	D	M	l	M	G	Rev	Medium
		Slumping/subsidence	−	D	F	P	L	G	Irr	Medium
		Soil quality degradation by accidental oil spills	−	D	M	P	L	G	Irr	Medium
		Creation of water pools	−	D	F	P	L	G	Irr	Medium
	Air	Degradation of air quality	−	D	F	l	C	G	Rev	Medium
Human Environment	Health	Risk of contamination of diseases	−	D	F	l	L	G	Rev	Major
	Safety	Risk of accidents	−	D	F	l	M	G	Rev	Major
	Jobs/Income	Temporary job creation and increased income	+	D	F	l	M	G	Rev	Major

Legend: (-): Negative, (+): positive; D/I: direct/indirect; l: local; M: medium; L: long; F: strong; C: short; f: weak; G: large; Irr: irreversible; Rev: reversible.

Table 5. *Impact evaluation of the artisanal quarries in Congo.*

Impacted environment	Valued environmental components	Identified impacts	Parameters of characterization							Evaluation
			Value	Nature	Intensity	Extent	Duration	Value of the affected component	Reversibility/ Irreversibility	Absolute significance
Biophysical environment	Landscape	Excavation	−	D	F	P	L	M	Irr	Medium
		Landscape Modification	−	D	M	P	L	M	Irr	Medium
	Wildlife	Removal of wildlife species	−	D	F	P	L	G	Rév	Medium
	Vegetation	Loss of vegetation cove	−	D	F	P	L	G	Rév	Medium
		Disruption of photosynthesis	−	D	M	l	C	G	Rév	Medium
	Water	Increased turbidity	−	D	F	P	C	G	Rév	Minor
		Destruction of waterways	−	D	f	P	M	G	Irr	Minor
	Soil	Erosion	−	D	F	P	M	G	Irr	Medium
		Silting	−	D	M	P	M	G	Irr	Medium
		Bank/plantation flooding	−	D	F	P	C	G	Rév	Minor
		Slumping/subsidence	−	D	F	P	M	G	Irr	Medium
		Soil quality degradation by accidental oil spills	−	D	F	P	M	G	Irr	Medium
		Creation of water pools	−	D	F	P	C	G	Irr	Minor
	Air	Degradation of air quality	−	D	M	l	C	G	Rév	Medium
Human Environment	Health	Risk of contamination of diseases	−	D	F	l	M	G	Rév	Major
	Safety	Risk of accidents	−	D	F	l	C	G	Rév	Medium
	Jobs/Income	Temporary job creation and increased income	+	D	F	l	C	G	Rév	Medium

Legend: (-): Negative, (+): positive; D/I: direct/indirect; l: local; M: medium; L: long; F: strong; C: short; f: weak; G: large; Irr: irreversible; Rev: reversible.

Table 6. *Main characteristics of impacts related to the exploitation of geomaterials in Congo.*

Character of impacts	Artisanal operation	Industrial operation
Positive Impacts	5%	5%
Negative Impacts	95%	95%
Major impacts	6%	59%
Medium impacts	71%	41%
Minor impacts	23%	-

4. Discussion

4.1. Exploited Materials

The quantity of materials exploited as geomaterials in Congo is estimated at nearly 52 million tons per year. With a population of 4.415 million estimated by the CNSEE [29], this production corresponds to an average consumption of 11.78 t/inhab/year. The production of soft materials is 65.3% while that of hard materials is 34.6%, soft materials are represented at only 0.1% (Figure 3). This production presents a trend opposite to that observed in Belgium where, during the same period, on a production 59 million tons of aggregates, we have 27% soft materials and 73% hard materials [12]. This difference would be explained on the one hand by the fact that the geology of the densely populated areas in Congo is dominated by detrital sedimentary rocks or by the products of hard rock dismantling (Figure 1), or simply by the current construction techniques that use more concrete and are recognized as consuming by excellence sand throughout the world [16]. Moreover, this consumption of 11.78 t/inhab/yr is significantly higher than that of Belgium during the period which was 7 t/inhab/yr [13] but also than that of France which is 6 t/inhab/yr [31]. This high demand for geomaterials in Congo is certainly explained by the dynamic construction policy that was induced by the government's so-called "accelerated municipalization" program executed during the past decade. It places the Congo among the largest consumers of aggregates in the world, since it exceeds by its consumption, Singapore recognized for the same period as by far the largest importer of sand in the world [32, 33] and the largest consumer of sand per capita in the world with 5.4 t/inhab/yr.

4.2. Typology of Geomaterial Deposits in Congo

The characterization of exploited materials in relation to their geological occurrence allows the elaboration of a typology of geomaterials deposits in Congo. We can thus distinguish sand deposits or sandpits, deposits of alluvial aggregates (gravel, sand), deposits of earth used in the shaping of bricks, deposits of hard rocks (granite, limestone, sandstone and silstone...).

Sand deposits are characterized by their location in the landscape or geomorphological context and by their geological origin. According to the geomorphological context, we distinguish in Congo the alluvial sand which is exploited in the lively beds of the rivers and the sand of the exondated zones.

The alluvial sand is made up of sediment transported or deposited by the rivers following the erosion of the watershed. Two methods of exploitation are used for this sand: the direct taking in the minor bed of the watercourse in full water and loading on dugout canoes (sand of the Oubangui in Impfondo), the direct taking in the dried alluvial zone and loading in dump trucks (sand of the Congo river after the bridge of Djoué), the dredging of the sand constituting benches hindering the navigation and rejection in edge for formation of heaps to be valorized This sand is comparable to that obtained by the exploitation of the Niger River and used for urbanization in Bamako [33, 4]. The direct removal of sand from riverbeds is destructive to the environment. Indeed, this type of removal is a cause of the modification of riverbanks that can go as far as the incision of the channel, and thus disruption of hydrological regimes, it is also attributed to the destruction of forest areas and the disappearance of many animal and plant species [4, 6]. This kind of extraction has already been decried in Europe and is considered a threat to the global environment [16].

The sand exploited from the exondated areas comes from podzols which are soils resulting from the leaching of sandy soils by organic complexation phenomena [34]. This one acquires an excellent purity for an optimal use in construction. They are often found around settlements that develop on sandy soils in the departments of Brazzaville, Pointe-Noire and Cuvette. In the Brazzaville area, this highly prized sand is taken from the depression areas still called Lousséké [35]. But in Congo, white sand is also exploited in sandpits that can be integrated in an area constituting an arc around the Massif du Chaillu. It is almost outcropping between the limit of the Chaillu and Bouenzien formations and occurs in the form of sandpits without any relation to water courses in many localities bordering the Chaillu, such as Divénié, Titi, Bihoua (Figure 1). The extension can be established as a wide band of a few hundred meters to 1 km and the lithostratigraphy shows 1 to 2 m of sand overlying a layer of gravel that can reach 50 cm in some places. This would be a sand resulting from the dismantling of the Chaillu granite.

The deposits of alluvial aggregate are encountered in several localities and particularly in flats bordering important rivers. It is a mixture of gravel and sand that can be separated by sieving and purified by washing and screening, which is found all around the city of Pointe-Noire, from Cote-Matève to the localities of Loémé and Mboubissi.

The earth deposits represented by the mounds of earth and giant termite mounds found in the basin and Likouala (Figure 18). Clay soil is also found in several localities developed in marshy or non-marshy areas and is dug for brick making. The materials are collected without any technology either in a plot of land or at the level of the lowlands.

Figure 12. *Bihoua sand pit (Sibiti).*

Figure 13. *Kenké gravel pit downstream (Kingoma).*

Figure 14. *Kombé sandstone deposit (Brazzaville).*

Figure 15. *Séké Pembé dolomitic limestone deposit (Mabombo).*

Figure 16. *Clay deposit of Kenké amont (Kingoma).*

Figure 17. *Deposit of yellow/red earth of Côte Matève (Pointe-Noire).*

Figure 18. *Deposit of earth bank (Impfondo).*

Figure 19. *Séké Pembé silstone deposit (Mabombo).*

The hard rock deposits concern consolidated rocks that are either sedimentary rocks (sandstone, limestone, silstone) in the Niari Valley, or magmatic and metamorphic rocks (gneiss, granite, quartzite) in the Mayombe, Chaillu, West Cuvette and Sangha.). This kind of deposit has already been described in Maine et Loire in France [13], but here it is important to emphasize the diversity of materials mined, which reflects the diversity of the country's geological contexts.

4.3. The Methods of Extraction

The extraction of geomaterials, whether it is artisanal or industrial, is done according to identical principles, but with a variable degree of mechanization. The craft industry uses archaic tools with sometimes a partial replacement of certain stations by mechanized tools. This is the case for the only felling station, which rarely uses explosives, as observed at the Kombé site in Brazzaville. In this respect, it is comparable in Congo to that observed in certain regions of France. In particular, the low level of production linked to artisanal activity and its methodology can be noted. Indeed, this weakness in production has already been observed in the old artisanal pink sandstone quarries in Brittany [27]. These artisans developed a non-mechanized production and produced manually rubble and paving stones for the construction of private buildings, yet they used quite frequently blasting for the hard levels and a crusher to achieve a production of crushed gravel.

In Congo, this exploitation of sand and gravel appears by its methodology very destructive for the environment and hydrosystems as already noted by UNEP for the rest of the world [16]. The exploitation of hard rock and especially the production of aggregate with these materials has already revealed serious impacts on the health of artisans, with the appearance of vibratory diseases that quickly become irreversible [21].

4.4. Impacts of the Activity

At least thirteen types of impacts have been identified on the geomaterials sites (Figures 20 to 31). These direct impacts generally generate other less visible impacts. For example, excavations profoundly modify the landscape and predispose the site to erosion and lake formation. Deforestation contributes to the depletion of the forest in noble species since the operators do not obey any norm. The stripping of the soil makes it unsuitable for agriculture because of the departure of the surface layer known as arable. This king of impact has already been observed for gold panning sites in certain localities such as Siguiri in Guinea [36] where soil degradation characterized by the loss of the surface layer and nutrients that are soil organic matter and fertility has been observed, but also for sand and quarry exploitation sites [5, 7].

4.5. Sources of Impacts

The sources of environmental impacts in geomaterials quarries are numerous and depend on the phases and tools used. They include deforestation; stripping or overburden removal; excavation; backfilling; depositing waste rock, gravel piles and oil cans on the ground; incineration of tires; maintenance of heavy machinery and vehicles; fuel storage; blasting, crushing and screening of materials; transportation and loading of materials.

The digging of channels modifies the banks and creates risks of erosion and flooding. The impacts associated with this practice, often used by artisans, are similar to those already observed by a previous study conducted in Brazzaville [24]. Among these sources of impact are the rusticity, unsuitability of tools, and lack of protective equipment (PPE) that impact the health of artisans [21].

Figure 20. *Dust emission from drilling of mine holes (Kombé).*

Figure 21. *Dust emission from crushing of aggregates (Kombé).*

Figure 22. *Wastewater discharge into the Congo River.*

Figure 23. *Exposure of the groundwater table by excavation (Côte Matève).*

Figure 24. *High turbidity in the Montelé River (Boko Songo).*

Figure 25. *Exposure of the groundwater table by excavation at Mamboukou (Brazzaville).*

Figure 26. *Stripping of the sterile level (Kombé).*

Figure 27. *Destruction of vegetation cover (Kombé).*

Figure 28. *Excavation of the sand extraction area (Bilolo, Brazzaville).*

Figure 29. *Abandonment of the discovery soil (Nkounkou fils, Brazzaville).*

Figure 30. *Abandonment of waste oil cans (Djéno, Pointe-Noire).*

Figure 31. *Remaining incinerated tires (Motopompe, Nkayi).*

5. Conclusion and Suggestions

Geomaterials are mined in Congo with an annual production of more than 52 million tons. 163 geomaterial exploitation sites have been mapped throughout the country, mainly in the form of quarries. These quarries operate either in the open air or underwater and their exploitation techniques are predominantly artisanal (83% of sites against 17% of industrial quarries). Three types of materials are exploited in Congo, namely soft (65%), hard (35%) and soft (0.1%) materials. The various processes that take place within such an exploitation, from extraction to finishing, require input flows in the form of consumable materials (oils, greases, tires, etc.), in the form of energy (hydrocarbons, engine or explosives), water and output flows in the form of solid (abandoned gravel piles), atmospheric (dust, gas, vapors) and liquid (engine oil, hydrocarbons, water from washing materials) discharges.

Of course, the exploitation of these quarry materials is the basis of an economic stake for the municipalities in which they are located, on the one hand by creating jobs at the sites, on the other hand by the financial contribution to the revenues of these municipalities and to the development of the country from an infrastructure point of view. However, the processes and flows of materials and energy identified above lead to impacts on the biophysical and human environment (loss of vegetation cover, dust and exhaust gases, excavation, noise, vibrations, water pollution, erosion, landslides, mosquito proliferation, risk of accidents and contamination of sexually transmitted diseases, etc.). Artisanal mining is clearly distinguished by a dominance of medium and minor impacts with only 6% of major impacts, in contrast to industrial mining which has 59% of major impacts and appears to be the most degrading to the environment.

To eliminate, reduce or compensate for these impacts, which are considered severe or critical for the environment, it is necessary to propose some suggestions as a guide to good conduct for the protection of the environment, to be integrated into the EIA reports that are to be made mandatory.

Thus, any site, and particularly industrial sites, should ensure:

1) the progressive rehabilitation of sites, the backfilling of abandoned excavations, the waste management plan, the reforestation of affected areas.
2) the use of personal protective equipment and regular maintenance of the equipment.
3) the watering of dust sources and the improvement of operating techniques.
4) Stabilization of affected slopes and embankments through revegetation.

For its part, the state would benefit from putting in place appropriate legislation and creating a public health staff to raise awareness of diseases related to the activity and awareness and screening campaigns for STI/HIV in the geomaterials production basins.

After characterizing the impacts of quarrying, this work should continue with the determination of the physico-chemical parameters of the environment, which would make it possible to decide on possible contamination or pollution of the ecosystems where these facilities are located.

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