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Gravels Used in Goma (DR Congo): Influence on Concrete Properties

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Abstract: The quality of aggregates governs the behaviour of concrete in both the fresh and hardened states. In Goma, the gravels used in construction come from various sources and production methods, but their characteristics remain poorly documented. This study characterises four gravels commonly used in Goma, namely mechanically crushed gravel (GCM), manually crushed gravel (GCMa), rounded river gravel (GR) and all-in gravel (GTV), and analyses their influence on workability, hardened concrete density and 28-day compressive strength. The gravels were characterised by particle size analysis, particle density, water absorption, porosity and resistance to fragmentation (Los Angeles coefficient). Four concretes were designed using the Dreux-Gorisse method with 350 kg/m³ of CEM IV/B 42.5 cement and a constant effective water content of 193.4 L/m³ (effective w/c = 0.55). Slumps ranged from 5.0 to 6.0 cm. The 28-day compressive strengths reached 22.0, 20.5, 14.0 and 16.5 MPa for B-GCM, B-GCMa, B-GR and B-GTV, respectively. Over these four observations, the Los Angeles coefficient showed the strongest inverse relationship with strength (r = −0.995), whereas absorption and porosity were only weakly related to it. The case of GR, with a measured absorption of zero but the lowest strength, shows that no single indicator is sufficient to predict concrete performance. Compared with the literature, the GR and GTV gravels produce concretes weaker than recycled-aggregate concretes made in Goma. This study provides an experimental basis for the systematic characterisation of aggregates intended for concrete in Goma.

Keywords: *Concrete, Aggregates, Los Angeles Coefficient, Water Absorption, Compressive Strength.*

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I. INTRODUCTION

Aggregates form the mineral skeleton of concrete and occupy about 60% to 80% of its volume [1] [2]. Their particle size distribution, shape and surface texture influence the water demand and workability of cementitious mixtures [3]. This effect extends to the hardened state, since the packing of the skeleton and the bond between paste and particles contribute to the mechanical behaviour of the composite [4].

The moisture condition of aggregates must also be taken into account. Water absorption reduces the water immediately available to the paste and can modify the effective water/cement ratio, the slump and the strength of concrete [5]. Mix design must therefore be adapted to the

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actual characteristics of local materials; methods based on workability, dispersion and cohesion show the value of combining several parameters rather than relying on a single indicator [6].

In volcanic regions, this issue is particularly important, because the nature and condition of volcanic materials lead to highly variable physical and mechanical properties [7]. Studies on volcanic scoria from Cameroon show that aggregate density, moisture content and mix parameters all affect the mechanical response of concrete [8]. More generally, the petrographic and physico-mechanical characteristics of the rocks used as aggregates are directly related to the quality of the concrete produced [9].

Resistance to fragmentation, characterised by the Los Angeles coefficient, is a common indicator of aggregate quality [10]. Tunç and Alyamaç established a relationship between Los Angeles loss and concrete strength [11], while the dependence of this loss on rock texture shows that the mechanical behaviour of an aggregate depends on its structure and nature [12]. Aggregate type and specimen geometry also influence the measured compressive strength, hence the need for identical experimental conditions in a comparative study [13]. Finally, aggregate type can modify both the strength and the permeability of concrete [14]. Its influence nevertheless depends on the target strength level: Özturan and Çeçen obtained similar strengths with basalt and gravel in normal-strength concretes, but marked differences in high-strength concretes [15], and several studies relate coarse aggregate quality to the strength, modulus and ductility of concrete [16] [17]. These studies justify a combined reading of aggregate properties and concrete performance.

In Goma, the gravels used in construction come from different sources and production methods, and their properties are not systematically controlled. A previous study in Goma showed that concretes made with recycled demolition aggregates reached 17.25 to 21.5 MPa, compared with 25.8 MPa with crushed basalt gravel [18], but no study has yet compared the different natural gravels sold locally. The main objective of this study is to assess the influence of the quality of four local gravels on workability, hardened concrete density and 28-day compressive strength. The specific objectives are: 1) to characterise the four gravels (particle size distribution, particle density, water absorption, porosity and resistance to fragmentation); 2) to compare their effects in controlled mixes; and 3) to examine the relationships between gravel properties and the performance of the corresponding concretes.

II. MATERIALS AND METHODS

This section presents the origin of the constituents, followed by the characterisation methods for the aggregates and concretes. The characterisations were carried out in the laboratories of the Université Catholique la Sapientia de Goma and the Université Libre des Pays des Grands Lacs.

- *Study Area and Origin of the Constituents*

The study was carried out in the city of Goma, capital of North Kivu Province, in the eastern Democratic Republic of the Congo (Figure 1). North Kivu Province extends from 2°04' S to 0°58' N in latitude and from 27°12' E to 29°59' E in longitude. It is bordered to the north by Ituri Province, to the west by Tshopo and Maniema Provinces, to the south by South Kivu and to the east by Uganda and Rwanda. The city of Goma, whose centre lies at 1°39' S and 29°12' E, occupies the northern shore of Lake Kivu, between Nyiragongo Territory to the north and the Rwandan border to the east. Its territory lies approximately between 1°37' S and 1°42' S in latitude and between 29°08' E and 29°15' E in longitude (WGS 84 coordinate system). The local context is marked by materials of volcanic and alluvial origin and by a variety of crushing and placing practices.

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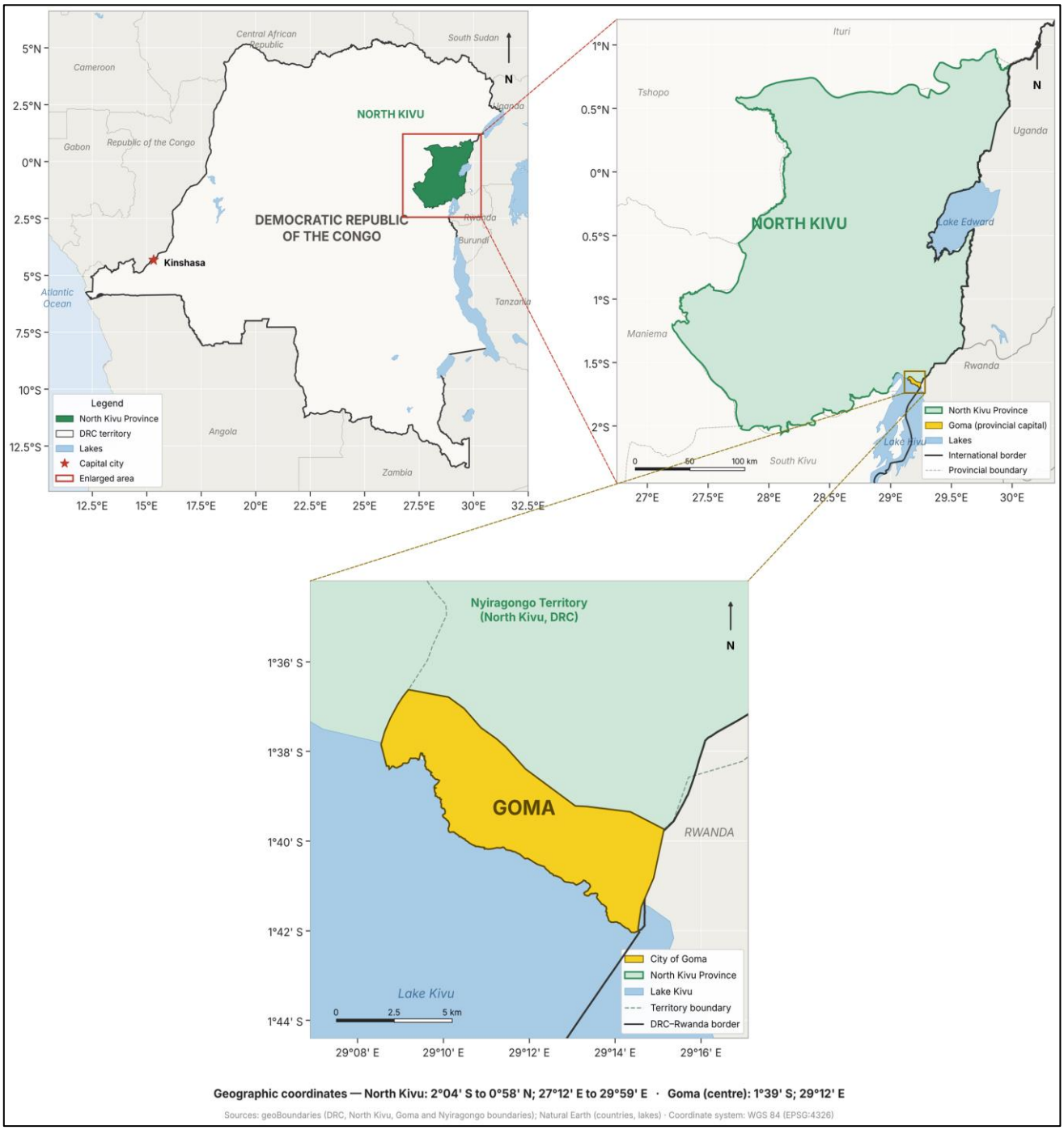


Fig 1 Location of the Study Area: Democratic Republic of the Congo (Top Left), North Kivu Province (Top Right) and City of Goma (Bottom). Sources of Administrative Boundaries: GeoBoundaries [19] and Natural Earth; WGS 84 Coordinate System

- *Gravels*

Four gravels representative of the Goma market, all with a maximum size D_{max} = 25 mm, were selected. The mechanically crushed gravel (GCM) comes from the CARRIGO industrial quarry in Goma; it is produced by crushing basalt and undergoes controlled screening and washing. The manually crushed gravel (GCMa), also of volcanic origin, comes from an artisanal quarry where the rock is broken with hammers. The rounded gravel (GR) was sampled from an alluvial deposit along a river in Sake; initially rounded and smooth, it was manually crushed in the laboratory before use to give it an angular shape comparable to that of the other gravels. The all-in gravel (GTV) is an unsorted raw mixture purchased from a common retail outlet. For each gravel, a primary sample of about 50 kg was collected and then reduced by quartering in accordance with NF EN 932-1.

- *Sand*

A single batch of 0/4 river sand, washed to remove clay fines and then oven-dried to constant mass, was used in all four concretes in order to focus the comparison on the coarse aggregate. Its characteristics are presented in Table 1.

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Table 1 Characteristics of the 0/4 Sand

Property	Method / Standard	Value
Fines content (< 0.063 mm)	NF EN 933-1	1.5%
Fineness modulus	NF EN 933-1	2.73
Sand equivalent	NF EN 933-8	82
Coefficient of uniformity, C_u	D_{60}/D_{10}	6
Coefficient of curvature, C_c	$D_{30}^2/(D_{10}\cdot D_{60})$	1.06
Particle density	NF EN 1097-6	2.62 t/m³

Table 1 shows that the sand is clean (1.5% fines; sand equivalent of 82). Its fineness modulus of 2.73 lies within the usual range for concrete sands, and the coefficients $C_u = 6$ and $C_c = 1.06$ indicate a well-graded distribution. Using this sand in all four concretes limits the influence of the fine aggregate on the comparison.

- *Cement*

The binder is a CEM IV/B 42.5 pozzolanic cement complying with NF EN 197-1 [20], produced in Rwanda by Cimerwa and commonly used in Goma. A single production batch was used for all mixes. Its physical characteristics are presented in Table 2.

Table 2 Physical Characteristics of the CEM IV/B 42.5 Cement

Property	Standard	Value
Particle density	NF P18-558	2995 kg/m³
Standard consistence	NF EN 196-3	28.5%
Initial setting time	NF EN 196-3	150 min
Final setting time	NF EN 196-3	270 min

Table 2 shows that the cement presents no anomaly. Its particle density of 2995 kg/m³ is typical of a composite cement with pozzolanic additions and is used to calculate the absolute volumes of the mix. Its standard consistence of 28.5% lies within the usual range. The initial setting time (150 min) comfortably meets the NF EN 197-1 requirement (≥ 60 min for class 42.5), and final setting occurs at 270 min, leaving sufficient working time. As the binder is identical in all four concretes, it introduces no variability into the comparison.

- *Water*

The mixing water is drinking water from the Goma city supply network, considered to comply with NF EN 1008. The same water was used for all concretes and all characterisations.

➢ *Characterisation Methods*

- *Characterisation of the Gravels*

The gravels were characterised for particle size distribution, determined by sieving (NF EN 933-1 [21]); for particle density, water absorption and water-accessible porosity, calculated from the oven-dry (M_s), saturated surface-dry (M_{sss}) and immersed (M_{imm}) masses after 24 h of immersion (NF EN 1097-6 [22]); and for resistance to fragmentation, expressed by the Los Angeles coefficient (NF EN 1097-2 [23]). The cumulative passing, particle density, absorption coefficient, porosity and Los Angeles coefficient are calculated using Equations (1) to (5):

$$P_j = (1 - \Sigma R_i/M) \times 100 \quad (1)$$

$$\rho_a = M_s/(M_s - M_{imm}) \quad (2)$$

$$WA_{24} = 100 \times (M_{sss} - M_s)/M_s \quad (3)$$

$$P = 100 \times (M_{sss} - M_s)/(M_{sss} - M_{imm}) \quad (4)$$

$$LA = 100 \times (5000 - m)/5000 \quad (5)$$

Where R_i is the cumulative mass retained on sieves of rank $i \leq j$, M the initial dry mass of the sample, and m the mass (in g) of material retained on the 1.6 mm sieve after rotation in the Los Angeles drum, for an initial sample of 5000 g.

- *Mix Design*

The concretes were designed using the Dreux-Gorisse method [24] for strength class C20/25 (NF EN 206/CN [25]) and consistence class S2 (target slump of 6 cm). The target mean strength is $f_{cm} = 1.15 \times 20 = 23$ MPa. The C/W ratio is obtained from Bolomey's formula (Equation (6)), with a true cement class $\sigma'_c = 35$ MPa and an aggregate coefficient $G' = 0.50$ (aggregates of ordinary quality, $D_{max} = 25$ mm):

$$C/W = f_{cm}/(G'\cdot\sigma'_c) + 0.5 = 23/(0.50 \times 35) + 0.5 = 1.81 \quad (6)$$

The cement content, read from the Dreux-Gorisse chart, is 350 kg/m³, giving an effective water content of 350/1.81 = 193.4 L/m³ (effective w/c = 0.55). With a packing density of 0.82, the absolute volume of aggregates is 0.703 m³, divided into 44% sand and 56% gravel. To keep the effective w/c ratio constant, the water absorbed by each gravel (WA_{24} × gravel mass) was added to the effective water. The mix compositions are given in Table 3.

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Table 3. Composition of the Four Concretes per 1 m³

Constituent	B-GCM	B-GCMa	B-GR	B-GTV
CEM IV/B 42.5 cement (kg)	350	350	350	350
0/4 sand (kg)	804	804	804	804
Gravel (kg)	1036	1036	972	984
Effective water (L)	193.4	193.4	193.4	193.4
Absorption water (L)	13.0	20.7	0.0	24.6
Total water added (L)	206.4	214.1	193.4	218.0
Theoretical density (kg/m³)	2396	2404	2319	2356

Table 3 shows that the cement and sand contents are constant. The gravel mass is proportional to its particle density, since the absolute volume of gravel is identical in all four concretes. The absorption water is 13.0 L/m³ for GCM (1.25% of 1036 kg), 20.7 L/m³ for GCMa (2.00% of 1036 kg), 0 for GR and 24.6 L/m³ for GTV (2.50% of 984 kg). The total water added thus ranges from 193.4 L/m³ (B-GR) to 218.0 L/m³ (B-GTV), and the theoretical density from 2319 to 2404 kg/m³.

- *Casting and Curing of Specimens*

After mixing, each concrete was cast in 16 × 32 cm cylindrical moulds. Nine specimens were made per mix, three for each of the ages of 3, 7 and 28 days. The specimens were demoulded after 24 h and then cured in water until testing. As the 3- and 7-day results could not be used, only the 28-day age is analysed in this paper.

- *Characterisation of Fresh and Hardened Concrete*

In the fresh state, workability was characterised by the Abrams cone slump (NF EN 12350-2). At 28 days, the density of hardened concrete was determined according to NF EN 12390-7, and the compressive strength was then measured according to NF EN 12390-3 [26] on a hydraulic press complying with NF EN 12390-4, at a loading rate of 0.5 ± 0.2 MPa/s. Each reported value is the mean of three specimens.

- *Data Analysis*

The results were first compared descriptively. Pearson correlation coefficients r (Equation (7)) were then calculated, on an exploratory basis, between the gravel properties and the 28-day strength:

$$r = \Sigma(x_i - \bar{x})(y_i - \bar{y}) / [\Sigma(x_i - \bar{x})^2 \cdot \Sigma(y_i - \bar{y})^2]^{1/2} \quad (7)$$

These coefficients are based on only four observations (n = 4); they are therefore used neither to establish statistical significance nor to infer a causal relationship.

III. RESULTS AND INTERPRETATION

➢ *Particle Size Distribution of the Gravels*

The cumulative passing of the sand and the four gravels is given in Table 4 and plotted in Figure 2.

Table 4 Cumulative Passing (%) of the Sand and the Four Gravels

Sieve (mm)	Sand 0/4	GCM	GCMa	GR	GTV
50	100.00	100.00	100.00	100.00	100.00
25	100.00	73.03	60.00	69.00	56.00
16	100.00	3.22	7.00	13.00	6.00
9.5	99.56	0.16	1.00	1.00	0.30
6.3	97.28	0.16	0.13	0.14	0.03
3.35	86.28	0.16	0.13	0.14	0.03
1.7	73.08	0.16	0.13	0.14	0.03
1	57.56	0.16	0.13	0.14	0.03
0.7	49.57	0.16	0.13	0.14	0.03
0.5	38.46	0.16	0.13	0.14	0.03
0.3	22.67	0.15	0.12	0.13	0.03
0.25	17.42	0.15	0.12	0.13	0.03
0.125	4.63	0.14	0.11	0.12	0.03
0.08	0.06	0.13	0.11	0.11	0.02

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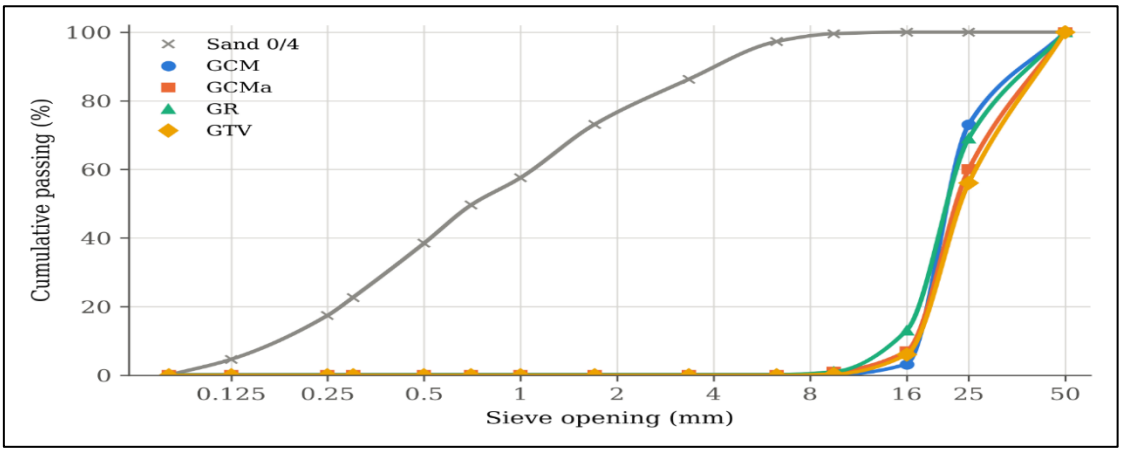


Fig 2 Grading Curves of the Sand and the Four Gravels

Table 4 and Figure 2 show that the four gravels have narrow gradings, lying essentially between 16 and 25 mm: less than 13% passing at 16 mm and practically no passing below 9.5 mm. They differ mainly in the proportion of particles larger than 25 mm. GCM is the finest and most uniform (73.03% passing at 25 mm, 3.22% at 16 mm), reflecting the screening of industrial production. GR (69% at 25 mm) contains the largest 9.5/16 fraction (13% passing at 16 mm). GCMa (60%) and especially GTV (56%) are the coarsest. Combined with the 0/4 sand, these gravels form a gap-graded skeleton with no 4/16 fraction, which affects the packing of the mix and its water demand [27].

➢ *Physical and Mechanical Properties of the Gravels*

Table 5 Physical and Mechanical Properties of the Four Gravels

Property	GCM	GCMa	GR	GTV
Particle density (t/m³)	2.633	2.633	2.471	2.501
Water absorption, WA_{24} (%)	1.25	2.00	0.00	2.50
Porosity (%)	1.36	2.20	0.00	2.94
Los Angeles coefficient (%)	13	18	57	46

Table 5 and Figure 3 show that the two crushed gravels, GCM and GCMa, have the highest particle density (2.633 t/m³). GCM combines it with an absorption of 1.25%, a porosity of 1.36% and the lowest Los Angeles loss (13%). GCMa has the same density, but higher absorption (2.00%), porosity (2.20%) and Los Angeles coefficient (18%). According to the categories of NF EN 12620 [28], these two gravels fall into categories LA_{15} and LA_{20}, which are suitable for structural concrete.

GR has a lower density (2.471 t/m³) and the highest Los Angeles coefficient (57%). Its measured absorption and porosity are 0.00%; this value should be understood as below the resolution of the weighing, not as a complete absence of water-accessible pores. GTV combines the highest absorption (2.50%) and the highest porosity (2.94%) with a Los Angeles loss of 46%. These two gravels fall into category LA_{50} (GTV) and above 50% (GR), respectively, well beyond the categories usually accepted for structural concrete [28]. The four materials are therefore not distinguished by a single criterion: geology, texture and internal structure act together on the measured resistance to fragmentation [29].

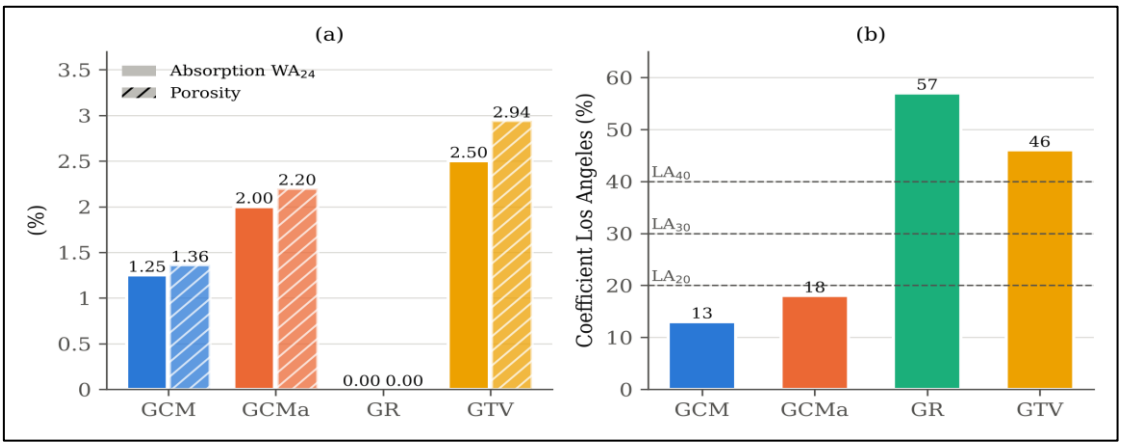


Fig 3 Properties of the Gravels: (a) Water Absorption and Porosity; (b) Los Angeles Coefficient and Thresholds of the NF EN 12620 LA Categories

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➢ *Workability of the Concretes*

Table 6 Slump of the Fresh Concretes

Concrete	Slump (cm)	Target Class (NF EN 206)
B-GCM	5.8	S2 (5–9 cm)
B-GCMa	5.3	S2 (5–9 cm)
B-GR	5.0	S2 (5–9 cm)
B-GTV	6.0	S2 (5–9 cm)

Table 6 and Figure 4 show that the four concretes fall within the target consistence class S2, with slumps ranging from 5.0 cm (B-GR) to 6.0 cm (B-GTV). The small spread indicates that the absorption water correction maintained comparable workability, consistent with the role of absorption on the water actually available [5]. The remaining differences are consistent with particle shape and grading [4]. B-GR and B-GCMa, whose gravels were crushed by hand and have irregular shapes, are the stiffest (5.0 and 5.3 cm). B-GTV, whose gravel is the coarsest (Table 4) and therefore has the lowest specific surface to wet, is the most fluid despite having the highest absorption.

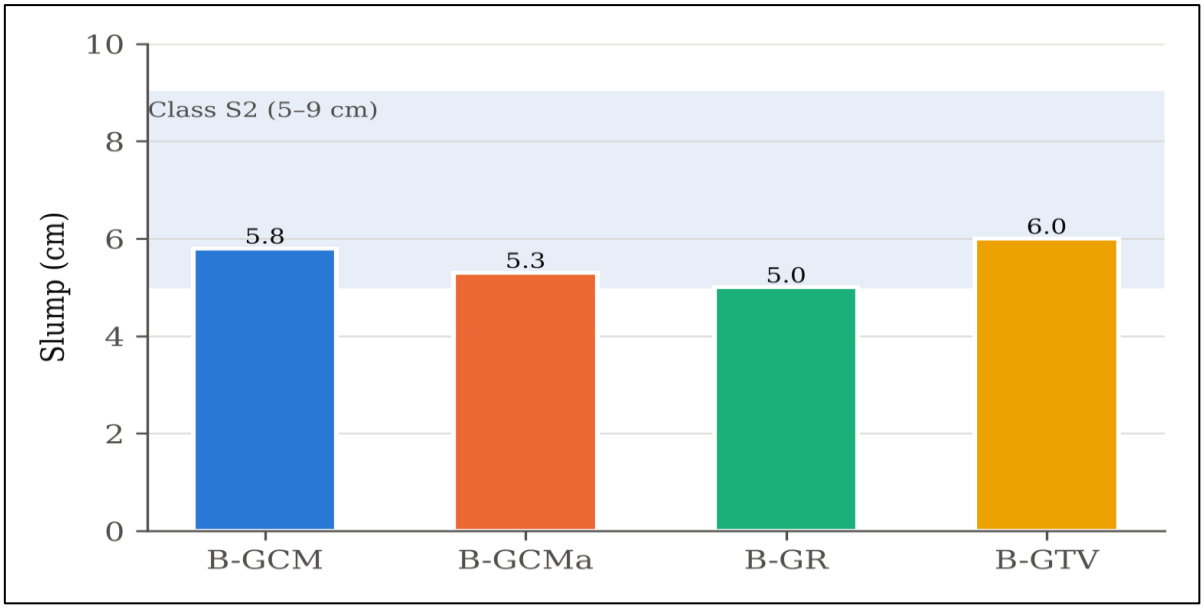


Fig 4 Abrams Cone Slump of the Concretes and Range of Consistence Class S2

➢ *Density and Compressive Strength of the Concretes*

Table 7 Density and Compressive Strength of the Concretes at 28 Days (Mean of Three Specimens)

Concrete	Density (kg/m³)	$f_{c,28}$ (MPa)
B-GCM	2390	22.0
B-GCMa	2355	20.5
B-GR	2305	14.0
B-GTV	2280	16.5

Table 7 and Figure 5 show that density and strength generally decrease together, except for the B-GR/B-GTV pair. B-GCM has the highest density (2390 kg/m³) and strength (22.0 MPa), followed by B-GCMa (2355 kg/m³; 20.5 MPa). B-GR reaches 2305 kg/m³ and 14.0 MPa, while B-GTV, the least dense (2280 kg/m³), develops an intermediate strength of 16.5 MPa. Figure 6 compares the measured densities with the theoretical values of Table 3: they are close for B-GCM and B-GR (difference below 1%), but 2% lower for B-GCMa and 3% lower for B-GTV. These two concretes were made with the most absorbent and coarsest gravels, which suggests less effective compaction or excess voids. The strength range is 8.0 MPa for a mean of 18.25 MPa, and the difference between the extreme values represents 57% of the minimum value. With an identical mix design, changing the coarse aggregate therefore leads to a large difference in mechanical behaviour.

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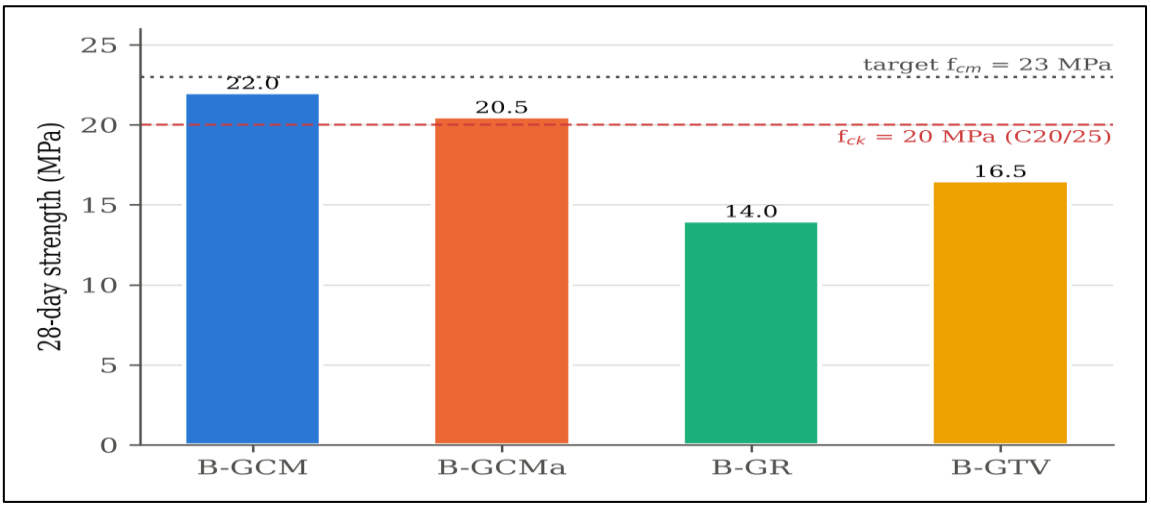


Fig 5 Compressive Strength of the Concretes at 28 Days, Compared with the Characteristic Strength of Class C20/25 and the Target Mean Strength

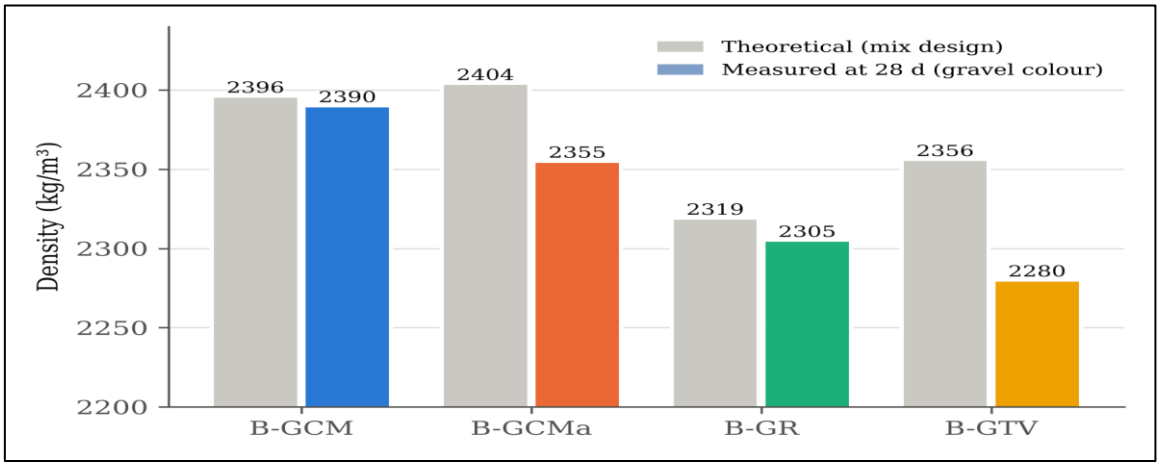


Fig 6 Theoretical (Mix Design) and Measured Densities of the Hardened Concretes at 28 Days

Figure 5 shows that no concrete reaches the target mean strength of the mix design (f_{cm} = 23 MPa). The strengths of B-GCM (22.0 MPa) and B-GCMa (20.5 MPa) remain close to the 20 MPa characteristic cylinder strength of class C20/25, whereas B-GR and B-GTV are clearly below it. This comparison is not proof of conformity: conformity requires production control and statistical acceptance criteria (NF EN 206), whereas a mean of three specimens does not provide a characteristic strength.

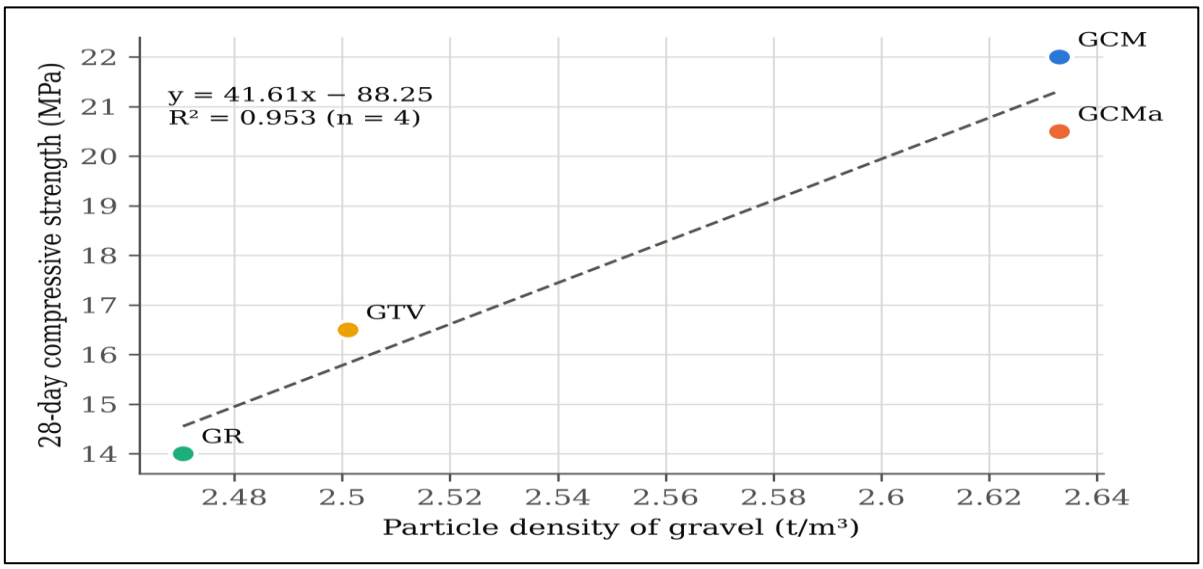


Fig 7 Exploratory Relationship between Gravel Particle Density and 28-Day Compressive Strength (n = 4)

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Figure 7 shows an increasing trend between gravel particle density and concrete strength (R^2 = 0.953). This relationship must be interpreted with caution, since density reflects neither the intrinsic strength of the particle nor its shape, texture or grading.

➢ *Comparative Summary*

Table 8 Summary of Gravel Properties and Concrete Performance

Indicator	B-GCM	B-GCMa	B-GR	B-GTV
Gravel absorption (%)	1.25	2.00	0.00	2.50
Gravel porosity (%)	1.36	2.20	0.00	2.94
Los Angeles (%)	13	18	57	46
Slump (cm)	5.8	5.3	5.0	6.0
Concrete density (kg/m³)	2390	2355	2305	2280
$f_{c,28}$ (MPa)	22.0	20.5	14.0	16.5

Table 8 brings together the gravel properties and the concrete performance. It shows that B-GCM combines the lowest Los Angeles loss, low absorption and porosity, and the highest density and strength. B-GCMa behaves similarly, with slightly less favourable values. GR is a special case: despite a measured absorption and porosity of zero, it has the lowest resistance to fragmentation, and its concrete reaches only 14.0 MPa. GTV, more absorbent and more porous but less friable (LA = 46%), gives 16.5 MPa. No single indicator can therefore predict concrete strength.

➢ *Relationships between Gravel Properties and Concrete Performance*

Table 9 Exploratory Correlations between the Measured Variables and 28-Day Strength (n = 4)

Variable	R	R^2	Interpretation
Los Angeles coefficient (%)	−0.995	0.989	Very strong inverse relationship
Gravel particle density	+0.976	0.953	Strong direct relationship
Concrete density	+0.875	0.765	Strong direct relationship
Water absorption (%)	+0.403	0.162	Weak relationship
Slump (cm)	+0.383	0.147	Weak relationship
Porosity (%)	+0.354	0.125	Weak relationship

Table 9 shows that the inverse correlation between the Los Angeles coefficient and strength is the strongest (r = −0.995; R^2 = 0.989; Figure 8): in this limited data set, the most friable gravels give the weakest concretes, in agreement with the results of Tunç and Alyamaç [11]. Gravel particle density also shows a strong direct relationship (r = +0.976), but a dense yet mechanically weak aggregate may behave differently.

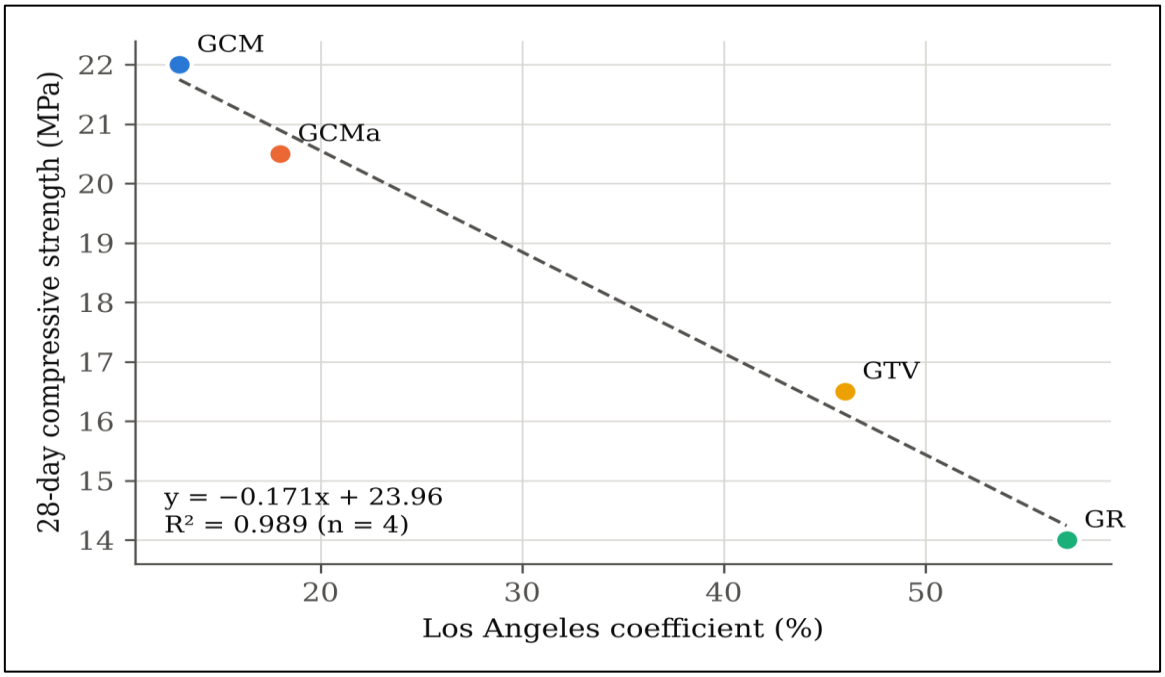


Fig 8 Exploratory Relationship between the Los Angeles Coefficient and 28-Day Compressive Strength (n = 4)

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The correlations with absorption (r = +0.403) and porosity (r = +0.354) are weak, and their counter-intuitive positive sign mainly shows that four observations cannot isolate the specific effect of these variables. GR, with zero absorption and porosity but the lowest strength, illustrates this. This finding is in line with studies recommending that petrography, texture, porosity and mechanical properties of aggregates be considered together [30]. Hardened concrete density is also strongly correlated with strength (r = +0.875; Figure 9), although B-GTV, less dense but stronger than B-GR, departs from the trend. This relationship is consistent with studies showing that aggregate type modifies the density, strength and failure mode of concrete [31]. Finally, slump is only weakly related to strength (r = +0.383): similar slumps do not guarantee similar strengths.

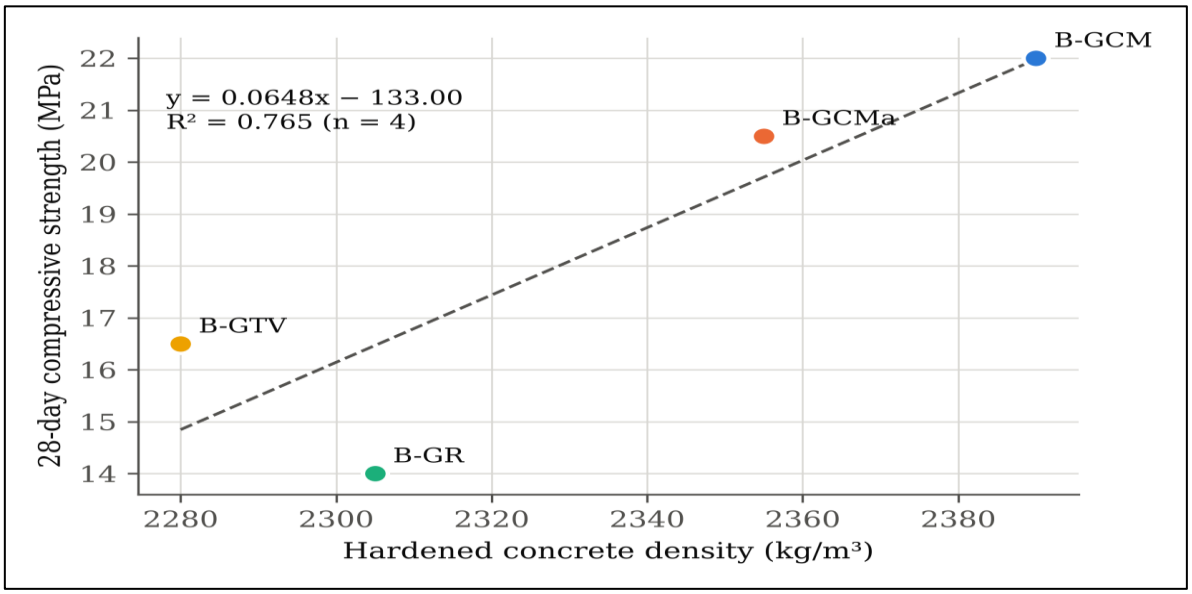


Fig 9 Exploratory Relationship between Hardened Concrete Density and 28-Day Compressive Strength (n = 4)

➢ *Discussion and Comparison with the Literature*

The results of each characterisation are compared here with published values. Table 10 lists, property by property, the values of the present study and those of the literature, and Figure 10 compares the 28-day compressive strengths.

Table 10 Comparison of the Measured Characteristics with Literature Values

Characteristic	Present Study	Literature	Ref.
Sand fineness modulus	2.73	2.5 (natural sand, Goma); 3.3 (recycled sand); target range 2.2–2.8	[18]
Sand equivalent	82	67.6 (natural sand, Goma); 78 (recycled sand)	[18]
Gravel grading	Narrow, ≈ 16/25 (≤ 13% passing at 16 mm)	Continuous 5/25 (90% passing at 16 mm; 31% at 10 mm)	[18]
Gravel particle density (t/m³)	2.47–2.63	2.78 (crushed basalt, Goma); 2.38 (recycled); 2.6–2.7 (most natural aggregates)	[1] [18]
Water absorption WA_{24} (%)	0–2.50	1.28–1.62 (limestone coarse aggregates)	[5]
Gravel porosity (%)	0–2.94	Concrete strength decreasing with aggregate porosity (R^2 = 0.83)	[9]
Los Angeles coefficient (%)	13–57	50% limit; only one quarry in three compliant; categories LA_{15} to LA_{50}	[28] [32]
Slump (cm)	5.0–6.0 (w/c 0.55)	5–9 (w/c ≈ 0.49)	[18]
Hardened concrete density (kg/m³)	2280–2390	≈ 2400 (normal-weight concrete)	[33]
$f_{c,28}$ (MPa)	14.0–22.0	25.8 (basalt) and 17.25–21.5 (recycled); 28–32; 25.88–27.58	[9] [18] [27]
LA – strength relationship	R^2 = 0.989 (n = 4)	R^2 ≈ 0.60	[13]

Table 10 shows that the differences from the literature are not limited to strength: the grading of the four gravels, as well as the density and Los Angeles coefficient of GR and GTV, also lie outside the values usually reported for concrete aggregates. The following subsections examine each characteristic.

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- *Sand and Gravel Grading*

The sand used is cleaner and better graded than the natural Lake Kivu sand studied by Grâce et al. [18]: its sand equivalent is 82 versus 67.6, and its fineness modulus of 2.73 remains within the recommended 2.2–2.8 range, whereas that of their recycled sand (3.3) exceeds it. The fine aggregate therefore cannot explain the performance differences observed. The main difference concerns the gravels: the 5/25 basalt gravel of Grâce et al. has a continuous grading (90% passing at 16 mm and 31% at 10 mm), whereas the four gravels of this study have a narrow grading, with at most 13% passing at 16 mm and practically none below 9.5 mm. Combined with the 0/4 sand, they form a gap-graded skeleton lacking a 4/16 fraction, whereas the Dreux-Gorisse method assumes a continuous grading curve [24]. This lack of intermediate particles reduces the packing of the mix [3] [27] and probably contributes to the fact that even B-GCM remains below the target mean strength.

- *Particle Density, Absorption and Porosity of the Gravels*

Most natural aggregates have a particle density between 2.6 and 2.7 t/m³ [1]. GCM and GCMa (2.633 t/m³) lie within this range, but remain below the crushed basalt from Goma studied by Grâce et al. (2.78 t/m³) [18]. GR (2.471 t/m³) and GTV (2.501 t/m³) are markedly lighter and approach the recycled aggregates of the same study (2.38 t/m³). This is consistent with Figure 7: the least dense gravels are also those that give the weakest concretes.

The absorption of GCM (1.25%) is of the same order as that of the limestone coarse aggregates studied by Alhozaimy (1.28% to 1.62%) [5], whereas GCMa (2.00%) and especially GTV (2.50%) are more absorbent. Petrounias et al. show that concrete strength decreases as aggregate porosity increases ($R^2 = 0.83$) [9]. In the present study, this trend does not appear ($r = +0.354$), because GR, whose measured porosity is zero, gives the weakest concrete. This disagreement supports the hypothesis that the absorption and porosity of GR were underestimated, already noted in Section 3.2, and shows that a low-porosity but friable aggregate escapes the usual porosity–strength relationship.

Alhozaimy also showed that dry aggregates absorb only about 75% of their absorption capacity during mixing, the remainder staying as free water, and that pre-wetted aggregates give concretes 8% to 12% stronger [5]. Applied here, this proportion would leave about 3.3 L/m³ of additional free water for B-GCM, 5.2 L/m³ for B-GCMa and 6.2 L/m³ for B-GTV, i.e. an effective w/c of 0.56 to 0.57 instead of 0.55. According to Bolomey's formula, the corresponding strength loss would be 2% to 4%, i.e. less than 1 MPa. It therefore cannot explain the 8 MPa difference between the concretes. The absorption of coarse aggregates does, however, influence the permeability, microstructure and durability of concrete [34], which were not characterised here.

- *Resistance to Fragmentation (Los Angeles Coefficient)*

The Los Angeles coefficients of GCM (13%) and GCMa (18%) correspond to categories LA_{15} and LA_{20} of NF EN 12620 [28], those of good-quality aggregates. Those of GTV (46%) and GR (57%) approach or exceed the 50% limit used by Pardo et al. in the Philippines, where only one quarry in three met this threshold [32]; GR even exceeds it. This heterogeneity of local sources is comparable to that observed in Goma, where the gravels on the market cover a range of 13% to 57%.

The relationship between the Los Angeles coefficient and strength ($R^2 = 0.989$) is stronger than that of Yehia et al. ($R^2 \approx 0.60$) [13], obtained on a more varied set of natural, lightweight and recycled aggregates. Tunç and Alyamaç show that Los Angeles loss must be combined with the w/c ratio and the aggregate/cement ratio to predict strength [11]; here, both ratios being fixed, the gravel is the only variable, which partly explains the strength of the correlation, beyond the small number of observations. Likewise, Petrounias et al. obtain strengths between only 28 and 32 MPa (a 14% spread) with igneous rocks of different qualities [9], compared with 14.0 to 22.0 MPa (57%) in this study, where the Los Angeles coefficient varies much more. Özturan and Çeçen also observe that, in normal concretes of about 30 MPa, basalt and gravel lead to similar strengths [15]: in this range, the effect of the aggregate generally remains moderate, except when it is very friable, as with GR and GTV.

The failure mode sheds light on this result. Zhou et al. observe that concretes with weak coarse aggregates fail through the particles, whereas those with strong aggregates fail at the paste–aggregate interface [31]. Kılıç et al. show that at three months the strength of concretes made with basalt, limestone or sandstone aggregates is of the same order as that of the parent rock [17], and Beshr et al. that the weakest aggregates give the weakest concretes [16]. The very low strength of B-GR is consistent with failure governed by particle fracture (LA = 57%), the gravel becoming the weak link of the composite. The influence of rock genesis and microstructure on engineering properties points in the same direction [35].

- *Workability*

The slumps obtained (5.0 to 6.0 cm) fall within the same class S2 as those of Grâce et al. (5 to 9 cm), who had to add water to the more absorbent recycled-aggregate concretes to maintain the same workability [18]. Here, the water correction applied limited the spread to 1.0 cm. Konitufe et al. characterised the workability and strength of concretes with angular and rounded aggregates [27], and particle shape mainly affects the rheology and water demand of the mix [36]: the hand-crushed gravels (GR and GCMa), more angular and irregular, give the stiffest concretes (5.0 and 5.3 cm).

- *Density and Strength of the Concretes*

A normal-weight concrete reaches about 2400 kg/m³ [33]. B-GCM (2390 kg/m³) is close to this value, whereas B-GTV (2280 kg/m³) is 5% lower. As Figure 6 shows, this deficit reflects more voids, consistent with the coarse and gap-graded grading of GTV.

For strength, the most direct comparison is with Grâce et al. [18], also carried out in Goma, using the Dreux-Gorisse

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method, with 350 kg/m³ of cement and on 16 × 32 cm cylinders. Their reference concrete with basalt gravel reaches 25.8 MPa, 17% more than B-GCM (22.0 MPa). This difference is explained by a lower w/c (about 0.49 versus 0.55), a denser gravel (2.78 versus 2.63 t/m³) and a continuous grading. More strikingly, B-GR (14.0 MPa) and B-GTV (16.5 MPa) remain below all their recycled-aggregate concretes (17.25 to 21.5 MPa): some natural gravels sold in Goma therefore give concretes weaker than recycled demolition aggregates. The igneous-rock concretes of Petrounias et al. reach 28 to 32 MPa despite a higher w/c (0.63) [9], and those of Konitufe et al. 25.88 to 27.58 MPa [27]. Finally, while the angular aggregates of Konitufe et al. gain 6.6% in strength over rounded aggregates, GR, although crushed in the laboratory to make it angular, gives a concrete 36% weaker than B-GCM: the gain in shape does not compensate for the friability of the rock.

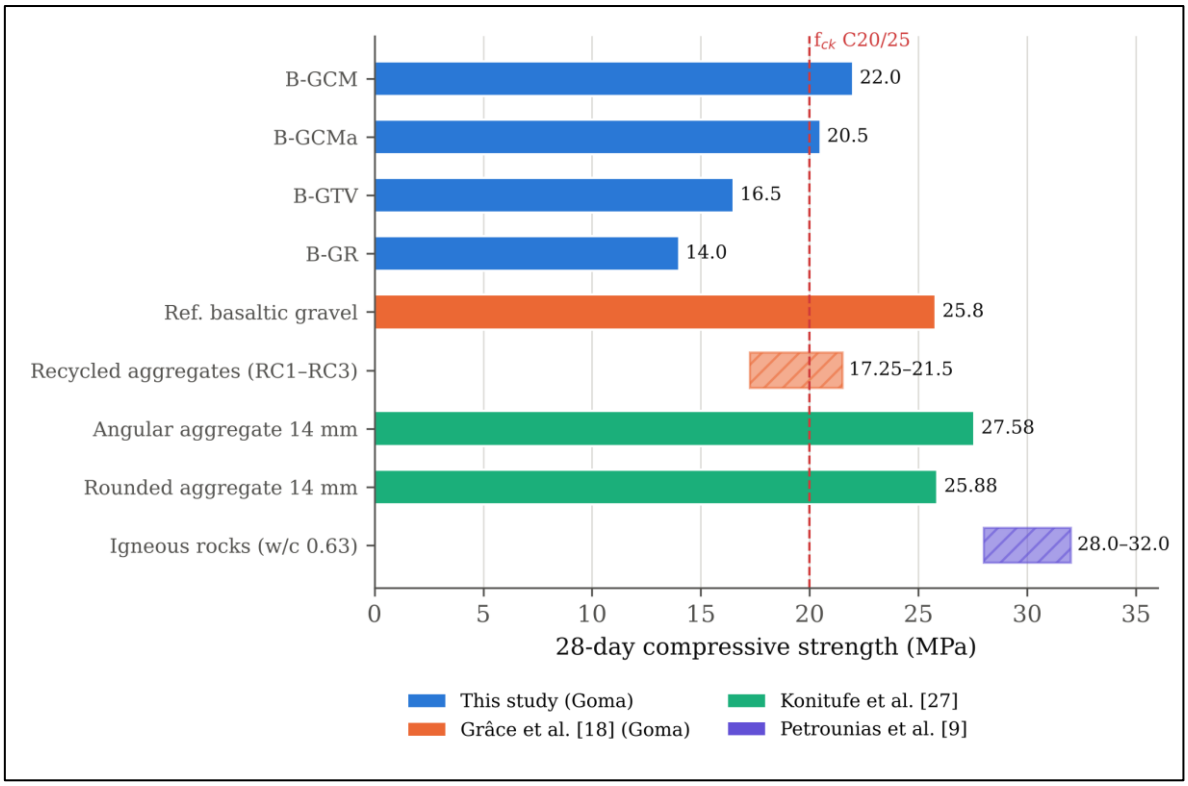


Fig 10 28-Day Compressive Strengths of the Present Study Compared with those of the Literature (Hatched Bars: Ranges of Values)

- *Summary*

All characterisations converge. GCM and GCMa have properties comparable to those of the good-quality aggregates described in the literature (particle density 2.63 t/m³, absorption 1.25% to 2.00%, LA ≤ 20%) and give concretes close to the target class. GR and GTV combine a low density, a Los Angeles coefficient outside the usual limits and, for GTV, a high absorption. Their concretes are the least dense and the weakest, even below recycled-aggregate concretes. The intrinsic quality of the rock therefore prevails over shape and absorption, and systematic control combining grading, particle density, absorption and Los Angeles coefficient should precede the use of any gravel in structural concrete in Goma. These conclusions are those of a local comparative characterisation, not a classification of all available aggregates.

➢ *Limitations and Perspectives*

The study covers four gravels and four mixes; the correlations presented are therefore exploratory and allow no statistical inference. As the 3- and 7-day results could not be used, the strength development over time could not be analysed. No direct durability measurements (permeability, chloride penetration, carbonation) were made, and the zero absorption and porosity of GR should be interpreted with caution.

Future work should cover a larger number of quarries and samples, a petrographic characterisation of the rocks and complementary characterisations (Micro-Deval, durability indicators), linking aggregate properties, microstructure and concrete performance [37]. Recent numerical approaches also make it possible to quantify the effect of particle shape and absorption on workability [38], and a better knowledge of the actual moisture condition of local aggregates would improve the accuracy of mix designs [34].

IV. CONCLUSION

This study compared four gravels commonly used in Goma and their influence on concretes designed under controlled conditions. The main results are as follows:

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- The gravels show a high variability in grading, particle density (2.47 to 2.63 t/m³), absorption (0% to 2.5%) and resistance to fragmentation (LA from 13% to 57%).
- Thanks to the absorption water correction, the four concretes show comparable slumps (5.0 to 6.0 cm, class S2).
- At 28 days, the strengths are 22.0 MPa (B-GCM), 20.5 MPa (B-GCMa), 16.5 MPa (B-GTV) and 14.0 MPa (B-GR); only the crushed-gravel concretes approach the strength of the target class C20/25.
- The Los Angeles coefficient is the property most strongly related to strength ($r = -0.995$, $n = 4$), whereas zero absorption, such as that of GR, does not guarantee a high strength when the aggregate is friable.
- Compared with the literature, the density of the GR and GTV gravels (2.47 to 2.50 t/m³) is lower than that of the crushed basalt of Goma (2.78 t/m³), their Los Angeles coefficient approaches or exceeds the usual 50% limit, and their concretes (14.0 and 16.5 MPa) remain below the recycled-aggregate concretes of the same city (17.25 to 21.5 MPa).

The quality of a gravel must therefore be assessed from a set of complementary characteristics. These results, limited to the materials and conditions studied, justify a systematic characterisation of local aggregates before their use in structural concrete in Goma, and provide an experimental basis for laboratories, contractors and engineers in the region.

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