Effect of the Cement-to-Water Ratio and Fractal Granular Model on the Prediction of Concretes Compressive Strength

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Abstract
The main objective of this work was to highlight the contribution of cement-to-water C/W ratio and the fractal dimension FD model to the prediction of the compressive strength of concrete. In particular, the fractal dimension FD concept relative to the size distribution of the granular mixtures provided an insight into the fineness and compactness of the granular mixtures. The unconventional fractal granular model FGMg also effectively contributed to highlight the correlation between cement-to-water ratio and compressive strength RC28 of concretes. Initially, 99 granular mixtures of concretes composition available in literature were investigated and for which the granular distributions by means of the fractal dimension FD model and the granular range D/d were we determined. Then, 36 concrete mixtures endowed with different granular mixtures were elaborated and analysed. These enabled to validate and evaluate the reliability of the basic granular fractal model FGMg and the influence of cement–water C/W ratio of concretes mixtures when predicting the concretes compressive strength RC28. The analytical model provided a close correlation with the experimental values of the compressive strength RC28 of all the concretes. The correlation highlighted the relevance of including fractal granular model FGMg that denoted the skeleton of the concretes and the cement–water C/W ratio that referred to the binders into concretes mixtures when predicting RC28. The theoretical approach whose effectiveness was highlighted using a “limited” number of real case studies may pave the way for further studies, when selecting the two key-factors for the prediction of concretes compressive strength RC28.

Keywords: concrete, compressive strength, granularity, fractal dimension, unconventional parameter

1 Introduction
Compressive strength is one of the most important properties of concrete in the hardened state. As well as compressive strength, other very important properties worth mentioning are compactness, workability, durability, cement class AFNOR NF EN 197–1 (2012), gravel/sand G/S ratio, granular range D/d and grain size of granular concrete mixtures. All these properties were related to common criteria that are regarded in the design of concrete. Of these criteria, it is worth pointing out the cement/water C/W ratio whose impact on a number of all the above properties and concretes compressive strength was demonstrated and well referenced in the literature, since the early research works on concretes by Abrams (1918), American Concrete Institute ACI 211.1–91 (1991); and Bolomey (1936).

Although a large number of previous experimental studies showed that the cement/water ratio C/W Yves Petit et al. (2011) was one of the fundamental variables to be accounted for in concretes design, other factors were also relevant and may greatly influence the formulation of the concretes. Many researchers, such as Lecomte and Thomas (1992); Chouicha (2006); Sebsadj and Chouicha...
The aim of the research work was to consider the fractal dimension $FD$ of the granular concrete mixtures in the hardened state in order to determine and identify the basic granular mixtures $FD_g$ or the granular mixtures with concrete fines $FD_C$. The study was based on the concept of the compactness of granular mixtures, which were identified by means of the so-called fractal dimension $FD$. The granular mixtures involved binders consisting of cement alone and cement with mineral admixtures. The effects of the two binders contributed to the prediction of the 28-day compressive strength $RC_{28}$ of the concretes and the results served as a database for the validation and evaluation of the reliability of the proposed analytical approach.

The experimental work was carried out in two separate stages. In the initial stage, we applied the fractal analysis approach to the data provided in a number of previous works available in literature in order to give the intended results a credible basis. Regarding these experimental investigations, 99 granular mixtures of concretes composition available in the literature were investigated and for which the granular distributions by means of the fractal dimension $FD$ model and the granular range $D/d$ were determined. Therefore, an appropriate selection of some of the data was required to apply the granular fractal model. The data were referred to some results of the granular analysis and dosages of the constituents together with the densities and the measured or empirical values of the concretes compressive strength $RC_{28}$. Also, several explanations options were provided—on the basis of a graphical analysis—to investigate the contribution of the conventional and non-conventional variables that may have a direct impact on the compressive strength $RC_{28}$ of concretes. In the next stage, 36 concrete mixtures including different granular mixtures were elaborated and analysed. The achieved results were considered to improve the accuracy and the reliability of the proposed analytical approach. A relatively brief description of the results was then included. Subsequently, an alternative method was suggested to study the concretes using the granular fractal model $FGM_g$ and the cement/water $C/W$ ratio for the prediction of the compressive strength $RC_{28}$ of concretes.

### 2 Data Collection and Fractal Dimension

Fig. 1 illustrates the design automation diagram for the model, based on collected data to determine the effectiveness of the conventional and non-conventional variables on the prediction of the compressive strength $RC_{28}$ of concretes. As the objective of the experimental work was to identify some granular mixtures using the granular fractal model $FGM_g$ and enable the model to determine the size distribution of the granular concrete mixtures using the fractal dimension $FD$, this consisted in collecting a number of empirical data from available literature studies related to the formulation of different types of concretes. Of course, valuable insight was gained from previously available studies where a series of 99 concrete mixes was collected from the chronologically ordered works on different types of concrete mixtures using European methods. These included the works of Al-Saadani (2000), Mennaai (2008), Boukli et al. (2009), Gemrachi et al. (2009), Boutilba et al. (2014), Boukli et al. (2014), Derabla and Bennalek (2014), Mehramdia and Benois (2018), Benouis and Grini (2011), Benouis and Mehramdia (2018). It should also be specified that most of these studies were prepared on different types of concrete mixtures using European standards. To achieve the second goal of the study, we elaborated two types of concretes to determine the most appropriate implementation approaches and the best formulation methods. Two groups of granular concrete mixtures were used with a different granular range $D/d$ together with two types of sand, that is, fine dune sand DS and coarse quarry sand QS.

#### 2.1 Materials

Two types of concretes were used to investigate the contribution of the concretes grain size distribution and cement-to-water $C/W$ ratio on the prediction of the compressive strength $RC_{28}$ of concretes. These included concretes based on the same CEM II 42.5 cement, and Superplasticizer SP admixture (MEDAFLOW 30). Silica fume FS was added to the concretes at the rates of 8.58 and 9.42% by mass of cement. The specific gravity of CEM II 42.5 cement, and silica fume was 3.10 and 2.30.

The chemical composition of the Portland CEM II 42.5 cement, silica fume and admixture is reported in Table 1 and the physical and mechanical properties of the aggregates used are well detailed in Table 2. The tests on aggregates properties were carried out at the Laboratory of Sustainable Development and Computer Science (LDDI: Laboratoire de Développement Durable et d’Informatique) of the University Ahmed Draia, of Adrar (Algeria). The XRD analysis of the aggregates was carried out in accordance with standard NF EN 15305.

The granular skeletons of the two concretes were noted $D_{15}$ and $D_{25}$. In addition, two types of sand were used in these concretes, namely a graded fine dune sand DS and a graded quarry sand QS, as shown in Fig. 2. In fact, the concretes consisted of aggregates with a maximum size of 15 and 25 mm, respectively.
2.2 Concretes Formulations

To improve the workability of the concretes—while keeping the same cement-to-water C/W ratio—we added a high water-reducing ether poly-carboxylate super-plasticiser with a rate of 1.25% by mass of cement. Like other admixtures, the ether poly-carboxylate super-plasticiser increased the workability of concretes and reduced the amount of mixing water, which may make the concrete easier to instal. As a result, the compactness of the concretes increased and the associated compressive strength $R_{C28}$ improved. The concretes were consequently elaborated to achieve three levels of workability, which were firm, soft or plastic and very soft or very plastic. This enabled to show that the impact of the unconventional factor—fractal dimension FD—on the compressive strength $R_{C28}$ of concretes, for a specified C/W ratio.
The cement-to-water \( C/W \) ratio of the various concretes mixtures were varied, as shown in Tables 3 and 4. The fractal dimension values of \( D_{15} \) and \( D_{25} \) of the concretes granular mixtures ranged from 2.67 to 2.73 with a correlation coefficient \( R^2 = 0.96 \) and between 2.61 and 2.68 with a correlation factor equal to at least \( R^2 = 0.97 \), respectively. The composition of the reference concrete granular mixtures of Tables 3 and 4 are free of any adjuvant or mineral addition.

### 3 Fractal Model and Granular Mixture

Fractal analysis, which was applied to determine the granular distribution of concrete mixtures using fractal dimension \( FD \) and granular range \( D/d \) was discussed in detail by many researchers in previous experimental works. These mainly included studies by Chouicha (2006) and Lecomte and Thomas (1992). The use of the fractal dimension \( FD \) in concretes was also adopted in the chronological order by other researchers such as Turcotte et al. (1997), Sebsadji and Chouicha (2012), Abdeldjalil and Yousfi (2020), Rezaie et al. (2020), Dan et al. (2020), Xuang and Mingzhi (2021) and Rouibi and Chouicha (2021). It should be recognised that this approach was very efficient in providing the value of the fractal dimension \( FD \) while converting the granular analysis curves into fractal lines. Hence, the linear matching of the number of grains cumulated in the granular mixtures was based on the dimensions of the aggregates, while the correlation coefficient was taken in due account.

#### 3.1 Fractal Character and High-Performance Concretes

During the modular engineering analysis for the determination of high-performance concrete HPC granular mixtures, Lecomte and Thomas (1992) employed the number of grains by modifying Caquot’s law (1937), which was defined with a negative slope (− 2.8) of the fractal line as illustrated in Eq. (1). According to Lecomte and Thomas

### Table 1 Chemical compositions of Portland CEM II 42.5, silica fume and admixture.

| Chemical composition       | Cement (%) | Silica-fume (%) | Characteristics | Superplasticizer |
|----------------------------|------------|-----------------|-----------------|-----------------|
| Silicon dioxide, SiO₂      | 21         | 95              | Density         | 1.07            |
| Calcium oxide, CaO         | 63         | 0.50            | Extrait sec     | 30%             |
| Iron oxide, Fe₂O₃          | 3.2        | 1               | Aspect          | Liquide         |
| Aluminium oxide, Al₂O₃     | 4.5        | 0.50            | Couleur         | Brun clair      |
| Magnesium oxide, MgO       | 1.3        | 1               | PH              | 6–6,5           |
| Potassium oxide, K₂O       | 0.4        | /               | Teneur en chlore| 0.1 g/l         |
| Sulphur trioxide, SO₃      | 2          | 0.5             | Dosage          | 0,5 à 2,0% C    |
| Sodium oxide, Na₂O         | 0.05       | /               |                 |                 |
| Cl⁻                        | 0.008      | 0.01            |                 |                 |
| CaO L                      | 0.9        | /               |                 |                 |

### Table 2 Characteristics of aggregates—results of XRD analysis.

| Characterisation | Fine and coarse aggregate | XRD results | Aggregate | Dune sand |
|------------------|---------------------------|-------------|-----------|-----------|
|                  | DS | QS | 3/8 | 8/15 | 15/25 | SiO₂ (%) | Al₂O₃ (%) | Fe₂O₃ (%) | CaO (%) | MgO (%) | SO₃ (%) | DS |
| Densité absolue (g/cm³) | 2.64 | 2.59 | 2.64 | 2.63 | 2.65 | 33.34 | 5.38 | 6.37 | 24.17 | 19.66 | 0.17 | 44.06 |
| Équivalent de sable | 84.4 | 69.65 | 84.4 | 69.65 | 84.4 | 84.4 | 84.4 | 84.4 | 84.4 | 84.4 | 84.4 | 84.4 |
| Module de finesse | 2.35 | 2.93 | 2.35 | 2.93 | 2.35 | 2.35 | 2.35 | 2.35 | 2.35 | 2.35 | 2.35 | 2.35 |
| Absorption d'eau (%) | 0.5 | 1.71 | 2.15 | 1.92 | 0.79 | 0.5 | 0.5 | 0.5 | 0.5 | 0.5 | 0.5 | 0.5 |
| Micro-Deval | 32.4 | 24 | 32.4 | 24 | 32.4 | 32.4 | 32.4 | 32.4 | 32.4 | 32.4 | 32.4 | 32.4 |
| Los Angeles | 19.66 | 18.28 | 19.66 | 18.28 | 19.66 | 19.66 | 19.66 | 19.66 | 19.66 | 19.66 | 19.66 | 19.66 |

![Fig. 2 Granular classes used (DS, QS, Gravels 3/8, 8/15 and 15/25).](image-url)
### Table 3  Mixture proportions of concrete D_{15}

| Mix (kg/m³) | CEM II | SF | Fine aggregate | Coarse aggregate | SP | W/C ratio |
|-------------|--------|----|----------------|-----------------|----|-----------|
|             |        |    | QS             | DS              |    |           |
| B10 QS F-D_{15} | 350.00 |    | 817            | 253             | 707 | 1.68      |
| B11 QS F-D_{15} | 350.00 |    | 817            | 253             | 707 | 4.38      | 1.82      |
| B12 QS F-D_{15} | 350.00 | 34.32 | 817           | 253             | 707 | 4.38      | 1.55      |
| B13 QS P-D_{15} | 350.00 |    | 781            | 253             | 743 | 1.68      |
| B14 QS P-D_{15} | 350.00 |    | 781            | 253             | 743 | 4.38      | 1.55      |
| B15 QS P-D_{15} | 350.00 | 34.32 | 781            | 253             | 743 | 4.38      | 1.82      |
| B16 QS TP-D_{15} | 350.00 |    | 746            | 217             | 814 | 1.82      |
| B17 QS TP-D_{15} | 350.00 |    | 746            | 217             | 814 | 4.38      | 1.55      |
| B18 QS TP-D_{15} | 350.00 | 34.32 | 746            | 217             | 814 | 4.38      | 1.68      |
| B01 DS F-D_{15} | 350.00 |    | 576            | 298             | 912 | 1.55      |
| B02 DS F-D_{15} | 350.00 |    | 576            | 298             | 912 | 4.38      | 1.82      |
| B03 DS F-D_{15} | 350.00 | 34.32 | 576            | 298             | 912 | 4.38      | 1.68      |
| B04 DS P-D_{15} | 350.00 |    | 525            | 280             | 984 | 1.68      |
| B05 DS P-D_{15} | 350.00 |    | 525            | 280             | 984 | 4.38      | 1.82      |
| B06 DS P-D_{15} | 350.00 | 34.32 | 525            | 280             | 984 | 4.38      | 1.55      |
| B07 DS TP-D_{15} | 350.00 |    | 517            | 252             | 1020 | 1.55 |
| B08 DS TP-D_{15} | 350.00 |    | 517            | 252             | 1020 | 4.38      | 1.68      |
| B09 DS TP-D_{15} | 350.00 | 34.32 | 517            | 252             | 1020 | 4.38      | 1.82      |

### Table 4  Mixture proportions of concrete D_{25}

| Mix (kg/m³) | CEM II | SF | Fine aggregate | Coarse aggregate | SP | W/C ratio |
|-------------|--------|----|----------------|-----------------|----|-----------|
|             |        |    | QS             | DS              |    |           |
| B10 QS F-D_{25} | 400.00 |    | 791            | 225             | 440 | 383       | 1.78      |
| B11 QS F-D_{25} | 400.00 |    | 791            | 225             | 440 | 383       | 5.00      | 1.66      |
| B12 QS F-D_{25} | 400.00 | 33.00 | 791           | 225             | 440 | 383       | 5.00      | 1.88      |
| B13 QS P-D_{25} | 400.00 |    | 763            | 222             | 434 | 397       | 1.78      |
| B14 QS P-D_{25} | 400.00 |    | 763            | 222             | 434 | 397       | 5.00      | 1.88      |
| B15 QS P-D_{25} | 400.00 | 33.00 | 763           | 222             | 434 | 397       | 5.00      | 1.66      |
| B16 QS TP-D_{25} | 400.00 |    | 727            | 222             | 471 | 397       | 1.66      |
| B17 QS TP-D_{25} | 400.00 |    | 727            | 222             | 471 | 397       | 5.00      | 1.88      |
| B18 QS TP-D_{25} | 400.00 | 33.00 | 727           | 222             | 471 | 397       | 5.00      | 1.78      |
| B01 DS F-D_{25} | 400.00 |    | 561            | 289             | 490 | 507       | 1.66      |
| B02 DS F-D_{25} | 400.00 |    | 561            | 289             | 490 | 507       | 5.00      | 1.88      |
| B03 DS F-D_{25} | 400.00 | 33.00 | 561            | 289             | 490 | 507       | 5.00      | 1.78      |
| B04 DS P-D_{25} | 400.00 |    | 537            | 267             | 522 | 501       | 1.88      |
| B05 DS P-D_{25} | 400.00 |    | 537            | 267             | 522 | 501       | 5.00      | 1.78      |
| B06 DS P-D_{25} | 400.00 | 33.00 | 537            | 267             | 522 | 501       | 5.00      | 1.66      |
| B07 DS TP-D_{25} | 400.00 |    | 520            | 248             | 522 | 539       | 1.66      |
| B08 DS TP-D_{25} | 400.00 |    | 520            | 248             | 522 | 539       | 5.00      | 1.88      |
| B09 DS TP-D_{25} | 400.00 | 33.00 | 520            | 248             | 522 | 539       | 5.00      | 1.78      |
(1992), this represented the upper limit of the fractal dimension. According to Lecomte and Thomas (1992), this was an upper limit of the fractal dimension:

\[ V = V_0 \sqrt[5]{d/D}, \]

where \( V \) was the size of the voids in the optimised granular mixture; \( V_0 \) was a constant equal to 0.47 for infinite mixtures, and 0.35 for finite mixtures; \( d \) was the diameter of the thinnest grains and \( D \) the diameter of the largest ones.

### 3.2 Fractal Aspect and Porosity

Chouicha (2006) derived an equation with which it was possible to determine the porosity of the experimentally elaborated concretes. The analytical model was based on the concept of fractal dimension \( FD \). The fractal dimension denoted the slope of the fractal line resulting from the conversion of the particle sizes curves of a given granular mixture. Figs. 3 and 4 demonstrate the transformation of several particle size curves into fractal lines of several granular mixtures that were investigated in this work. This conversion allowed to determine the values of the fractal dimension \( FD \) corresponding to the studied granular mixtures.

Each of the two classes of granular mixtures \( D_{15} \) and \( D_{25} \) used in concretes comprised 6 different mixtures, namely 3 mixtures were formulated with crushed quarry sand QS and 3 others with natural dune sand DS. Therefore, each type of mixture was used to produce three concretes with different workability types, i.e. firm concrete FC, plastic concrete PC and very plastic concrete VPC.

### 3.4 Granular Mixtures of Concretes Collected

For the granular mixtures of the concretes, investigations were carried out using previously collected data. The data gathered indicated that the concretes produced from different granular mixtures exhibited an almost perfect fractal distribution of the grains. This was again confirmed on the different types of concretes that were designed and examined during the years between 2000 and 2016. Fig. 5 provides an example showing the conversion of granular distributions into concrete fractal distributions for some selected concretes. Therefore, it was possible to state that granular mixtures may be clearly identified using the fractal dimension \( FD \) and the granular extent \( D/d \).

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**Fig. 3** Identifications of \( D_{15} \) concrete granular curves using the fractal dimension \( FD_g \). a Granulometric curves, b fractal straight lines.
Once the granular curves of the basic granular mixtures of the examined concretes were converted into fractal lines, we found that the values of the fractal dimension varied between 2.49 and 2.97. However, the granular distribution of all the concretes granular mixtures—including those elaborated with cement and mineral additives—revealed fractal size values ranged from 2.47 to 2.79. Besides, the correlation coefficients $R^2$ ranged between 0.90 and 0.99 and proved the quasi-fractal distribution indeed.

These findings enabled to determine the fractal granular model for granular base FGMC of a basic granular mixture without cement and no mineral additives [see Eq. (3)] as well as the fractal granular model for concrete mixtures FGMC, as follows:
where $FD_g$ and $FD_C$ were the fractal dimensions of basic granular mixtures and concretes; $D/d_g$ was the granular range of the basic granular mixtures and $D/d_C$ was the granular range of the granular mixtures of concretes.

Fig. 5 shows the variance of the fractal dimension FD values of the basic granular mixtures. Table 5 provides a summary of the data used to identify the basic granular mixtures (aggregates only) of the concretes as well as the granular concrete mixtures (aggregates + cement + mineral additives) for the fractal granular model of all data collected and sorted by the

$$FGM_g = FD_g \cdot \log \left( \frac{D}{d_g} \right),$$

$$FGM_C = FD_C \cdot \log \left( \frac{D}{d_C} \right),$$

where $FD_g$ and $FD_C$ were the fractal dimensions of basic granular mixtures and concretes; $D/d_g$ was the granular range of the basic granular mixtures and $D/d_C$ was the granular range of the granular mixtures of concretes.

**Table 5** Concrete with the same $FGM_g$ value of the base granular mixture.

| Authors                  | Number of concretes | Fractal granular model | Fractal dimension and correlation | D/d_g (mm) |
|--------------------------|---------------------|------------------------|----------------------------------|------------|
|                          | TN                  | N/FD_g | FGM_g | FGM_C | FD_g | $R^2$ | FD_C | $R^2$ |
| Benouis and Grini (2011) | 7                   | 2      | 6.93  | 14.96 | 2.67  | 0.90  | 2.72  | 0.98  | 31.5/0.08 |
|                          | 1                   | 7.29  | 14.90 | 2.81  | 0.90  | 2.71  | 0.98  |
|                          | 1                   | 7.71  | 15.07 | 2.97  | 0.90  | 2.74  | 0.98  |
|                          | 1                   | 6.93  | 15.12 | 2.67  | 0.90  | 2.75  | 0.98  |
|                          | 1                   | 6.90  | 15.18 | 2.66  | 0.90  | 2.76  | 0.98  |
|                          | 1                   | 6.98  | 15.34 | 2.69  | 0.90  | 2.79  | 0.98  |
| Boukli et al. (2009)     | 34                  | 17     | 6.90  | 14.52 | 2.66  | 0.98  | 2.64  | 0.99  | 31.5/0.063 |
|                          |                     |        | 14.68 |       | 2.67  | 0.99  |       |
|                          |                     |        | 14.79 |       | 2.69  | 0.99  |       |
| Boukli et al. (2009)     | 17                  | 6.93  | 14.52 | 2.67  | 0.98  | 2.64  | 0.99  |
|                          |                     |        | 14.68 |       | 2.67  | 0.99  |       |
|                          |                     |        | 14.79 |       | 2.69  | 0.99  |       |
| Boutiba et al. (2014)    | 2                   | 2      | 6.33  | 12.64 | 2.64  | 0.99  | 2.69  | 0.99  | 20/0.08 |
| Derabla and Benmalek (2014) | 8               | 8      | 6.71  | 12.75 | 2.80  | 0.97  | 2.55  | 0.99  | 20/0.08 |
| Guemmadi et al. (2009)   | 26                  | 9      | 6.49  | 14.21 | 2.60  | 0.99  | 2.68  | 0.99  | 25/0.08 |
|                          | 7                   | 6.49  | 14.37 | 2.60  | 0.99  | 2.71  | 0.99  |
|                          | 3                   | 6.49  | 14.26 | 2.60  | 0.99  | 2.66  | 0.99  |
|                          | 1                   | 6.49  | 14.10 | 2.60  | 0.99  | 2.66  | 0.99  |
|                          | 1                   | 6.49  | 14.05 | 2.60  | 0.99  | 2.65  | 0.99  |
|                          | 1                   | 6.36  | 14.21 | 2.55  | 0.99  | 2.68  | 0.99  |
|                          | 1                   | 6.56  | 13.99 | 2.63  | 0.99  | 2.64  | 0.99  |
|                          | 1                   | 6.51  | 14.10 | 2.61  | 0.99  | 2.66  | 0.99  |
|                          | 1                   | 6.31  | 14.31 | 2.53  | 0.99  | 2.70  | 0.99  |
|                          | 1                   | 6.44  | 14.42 | 2.58  | 0.99  | 2.72  | 0.99  |
| Mehamdia and Benouis (2018) | 06                 | 06     | 6.76  | 14.74 | 2.71  | 0.91  | 2.73  | 0.98  | 25/0.05 |
| Mennaai (2008)           | 01                  | 01     | 5.97  | 12.69 | 2.49  | 0.97  | 2.70  | 0.97  | 20/0.08 |
| Saadani (2000)           | 15                  | 1      | 6.23  | 12.55 | 2.49  | 0.98  | 2.67  | 0.99  | 25/0.063 |
|                          | 1                   | 6.33  | 12.85 | 2.53  | 0.99  | 2.68  | 0.99  |
|                          | 1                   | 6.63  | 12.90 | 2.55  | 0.98  | 2.69  | 0.99  |
|                          | 2                   | 6.70  | 12.95 | 2.58  | 0.96  | 2.70  | 0.99  |
|                          | 1                   | 6.73  | 13.00 | 2.59  | 0.98  | 2.71  | 0.99  |
|                          | 1                   | 6.76  | 13.04 | 2.60  | 0.98  | 2.72  | 0.99  |
|                          | 1                   | 6.78  | 13.09 | 2.61  | 0.97  | 2.73  | 0.99  |
|                          | 1                   | 6.83  | 12.85 | 2.63  | 0.95  | 2.68  | 0.99  |
|                          | 4                   | 6.86  | 12.90 | 2.64  | 0.95  | 2.69  | 0.99  |
|                          | 1                   | 6.91  | 12.95 | 2.66  | 0.95  | 2.70  | 0.99  |

$TN$ total number of concretes by author, $N/FD_g$ number of concretes by author of same $FD_g$. 
authors’ works. These authors were Mennaai (2008), Boukli et al. (2009), Guemmadi et al. (2009), Boukli et al. (2014), Boutiba et al. (2014), Benouis and Grini (2011), Derabla and Benmalek (2014), Mehamdia and Benouis (2018), Benouis and Mehamdia (2018) and Saadani (2000).

4 Relevant Parameters of Concretes

The quality of concretes was identified by means of some of the parameters outlined above. These parameters affected directly the prediction of the concretes compressive strength $R_{C28}$. However, there are only a few conventional standards such as the cement-to-water $C/W$ ratio, granular mixture densities $d_{mg}$ and gravel-to-sand $G/S$ ratio as well as some less conventional ones like the quantities $D/d_g$, $D/d_C$, $F_{DC}$, $F_{DG}$, $Por(D/d)$ that may basically be incorporated into the analysis in order to achieve the intended objectives.

4.1 Effects of Conventional Parameters

Effects of the gravel-to-sand $G/S$ ratio and density $d_{mg}$ of previous works on simultaneously assessed concretes were investigated herein. As the results available in the literature revealed that most works did not deal with the compressive strength $R_{C28}$ of aggregates, we considered the available findings to assess the classification of aggregates. Considering the classical parameter used to classify the different aggregates, that is the density $d_{mg}$ of the granular mixtures, one may observe in Fig. 6a that several values of the concrete strength $R_{C28}$ corresponded to the same $d_{mg}$ value of the data collected. The findings suggested that the observations were not in themselves sufficient to convey an idea of the strength properties of the aggregates. Besides, Fig. 6b clearly reveals that several values of $R_{C28}$ correlated with the same value of the $G/S$ ratio obtained from the collected data.

This suggested that this parameter alone was not sufficient to define the aggregates. As the results in Fig. 6b explicitly illustrate, the $G/S$ ratio alone cannot be regarded as a relevant parameter to comprehensively explain or understand the behaviour of concretes in terms of compressive strength $R_{C28}$.

In the case of the cement-to-water $C/W$ ratio of previous combined concretes, several researchers worked on different grades and classes of cement and arrived at rather scattered results. Fig. 7 shows that all the concretes designed by Saadani (2000), Boukli et al. (2009), Derabla and Benmalek (2014) and Benouis and Mehamdia (2018) reported different values of the compressive strength $R_{C28}$ at 28 days, whereas the cement-to-water $C/W$ ratio remained constant. Again, the $C/W$ ratio may not be considered as a decisive factor. However, the results relating to the compressive strength $R_{C28}$ of concretes, obtained by other authors, notably Boukli et al. (2009), Guemmadi et al. (2009) and Mehamdia and Benouis (2018), appeared to be fairly well balanced on either side of a straight line for a varying $C/W$ ratio. In these three works, the authors used concretes with the same basic granular mixtures. It
is once again no longer sufficient to consider the cement-to-water $C/W$ ratio as the only crucial factor for several granular mixtures at the same time, as evidently demonstrated in Table 5.

In the case of the cement-to-water $C/W$ ratio of previous concretes, separately included, the results displayed in Fig. 8 indicate that the authors used the same basic granular mixture, namely the same value of $F_{GMG}$ in the concretes compositions. A linear relationship was also observed between the $C/W$ ratio and the concretes compressive strength $R_{C28}$. This was evidenced by the variances of the $F_{GMG}$ and $F_{GMG}$ models. The types of concretes studied supported the relevant contribution of the $C/W$ ratio when assessing the concretes compressive strength for substantially similar basic granular mixtures.

4.2 Effects of Unconventional Parameters

This section was devoted to highlighting the relevance of some non-conventional parameters. In particular, this section aimed to determine the contribution of the parameters to the formulation of concretes and to highlight the associated impact on the concretes compressive strength $R_{C28}$. To do this, we first looked specifically at the porosity relationship of basic granular mixtures in terms of fractal dimension $F_{DG}$, using Eq. (2). Then, the expression $Por(d/D)$ was used to determine the compactness of the granular mixtures. The parameters $F_{DG}, \log(D/d_g)$ and $F_{DC}, \log(D/d_C)$ were also used.

Regarding the porosity of granular mixtures, Fig. 9a clearly demonstrates that for the same porosity values, the basic granular mixtures (aggregates only) changed the values of the concretes compressive strength $R_{C28}$, as already pointed out by several previous studies. Hence, the need to classify the concretes with the same porosity into a single category. Fig. 9b highlights the porosity of dry granular concrete mixtures vs. the fractal dimension (FD), using Eq. (2).

For the fractal parameters $F_{GMG}$ and $F_{GMG}$, Fig. 10a and b plots the evolution of the compressive strength $R_{C28}$ of concretes vs. the fractal dimension $F_{DG}$ of the granular mixtures and the fractal dimension $F_{DC}$ of the dry concrete mixtures. Fig. 10a and b indicates that some concrete types that belong to the same research work were of the same $F_{DG}$ basic granular mixtures values, whereas the corresponding values for the fractal dimension $F_{DC}$ for the granular concrete mixtures were found to be different.

In turn, Fig. 10c and d plots the evolution of the compressive strength $R_{C28}$ of concretes vs. the fractal granular model $F_{GMG}$ of the basic granular mixtures and the fractal granular model $F_{GMG}$ of the dry concrete mixtures. They reveal that concretes may have the same fractal granular model $F_{GMG}$ values for the basic granular mixtures and different corresponding values for the fractal model granular model $F_{GMG}$ for concretes dry mixtures.

Such findings emphasised once again the above statements in that the fractal dimension $FD$ alone was not able enough to define the concretes. Hence, the reason for investigating the combination of the fractal granular model $F_{GMG}$ with the cement-to-water $C/W$ ratio to see how these two factors may affect the compressive strength $R_{C28}$ of the concretes.

5 Results and Discussion

To establish a proper relationship that allowed determining the concretes compressive strength $R_{C28}$ by means of the fractal granular model $F_{GMG}$ and the cement-to-water $C/W$ ratio, we decided to perform a graphical analysis of the concretes behaviour in terms of the compressive strength $R_{C28}$ from the collected data already shown in Figs. 8 and 9. In this case, the same basic granular mixtures or granular mixtures with the same $F_{DG}$ values were used; see Fig. 10. The results were largely satisfactory and the relationship between
Fig. 8  (See legend on previous page.)
the fractal granular model $\text{FGM}_g$ and the cement-to-water $C/W$ ratio to determine the compressive strength $R_{C28}$ of concrete was very straightforward.

5.1 Fractal Granular Model

For the sake of comparisons, Figs. 11–15 display the evolution of the compressive strength $R_{C28}$ of concretes, as formulated by several authors. The results of the concretes compressive strength $R_{C28}$ were determined using the fractal granular model $\text{FGM}_g$ and the cement-to-water $C/W$ ratio for the same data collected. The use of the $\text{FD}_g, \log (d/D)$ parameter enabled to demonstrate the significance of the porosity/compactness of the fractal granular model $\text{FGM}_g$ of the basic granular mixtures on the properties of the concretes. The results reported above (see “Fractal aspect and porosity” section) showed the relationship between the cement-to-water $C/W$ ratio and the compressive strength $R_{C28}$ of the concrete mixtures, for the given value that was found when using the fractal granular model $\text{FGM}_g$. In the following, the experimental work was extended to cases in which two or three specific concrete classes having the same fractal granular model $\text{FGM}_g$ value.

De Larrard (2000), Chidiac et al. (2013) and Moutassem and Chidiac (2016) were among the several previous researchers who studied the effect of mineral additions on the compressive strength $R_{C28}$ of concretes. However, these studies did not explicitly include this parameter in their respective models, as the analyses required a larger number of concretes to be elaborated and because of the complex calculations involved. In addition, Figs. 12 and 13 show the results reported in the work of Boukli (2009) on the evolution of the compressive strength $R_{C28}$ vs. the cement-to-water the ratio $C/W$ for the same value of the fractal granular model $\text{FGM}_g$ for the basic granular mixtures of the concretes.

As stated above and well detailed in Fig. 14 reported by Guemmadi et al. (2009), the experimental studies on concretes with mineral additions available in the technical literature with mineral admixtures did not provide sufficient precision to understand the effect of admixtures on the evolution of the concretes compressive strength $R_{C28}$ vs. the cement-to-water $C/W$ ratio. For this reason, we decided not to consider the concretes with similar characteristics to those reported by the fractal granular model $\text{FGM}_g$. Fig. 11 already demonstrates the evolution of the compressive strength $R_{C28}$ vs. the cement-to-water $C/W$ ratio and the results of which were validated herein.

Fig. 15 shows the evolution of the compressive strength $R_{C28}$ vs. the cement-to-water $C/W$. Based on the work of Derabla and Benmalek (2014), only concretes with the same values of the fractal granular model $\text{FGM}_g$ of the basic granular mixtures were regarded and for which a representation of the granular mixtures of concretes using the associated fractal granular model $\text{FGMC}$ was also provided.

On the other hand, Fig. 16a and b gives a very simple reading of the curves, which show the evolution of the compressive strength $R_{C28}$ vs. the ratio $C/W$ in the basic granular mixture of the concrete. The experimental
results of the work of Boutiba et al. (2014) and Mehamdia and Benouis (2018) were also presented. All the above illustrations showed the influence of the value given by the fractal granular model \( \text{FGM}_g \) of the basic granular mixture and the fractal granular model \( \text{FGM}_c \) of the granular concrete mixtures.

### 5.2 Compressive Strength of Concrete

Figs. 11–15 show the results that are already reported in Table 5. The results were collected from previous works and constituted a fundamental database. They enabled to identify both the basic granular mixtures and the granular mixtures of the concretes studied herein. Also, the analytical results obtained from the curves shown in Figs. 10–16 show satisfactory correlations between the compressive strength \( R_{C28} \) of the concretes, the cement-to-water \( C/W \) ratio and the effect of the fractal granular model \( \text{FGM}_g \). However, the analytical model developed here needs to be further validated by additional experimental work. The influence of the fractal granular model \( \text{FGM}_g \)—as an unconventional parameter—was studied by means of the classical parameters outlined above. However, further work is needed to include other parameters, such as those related to the theory of paste optimisation, also called the excess paste theory. It is worth noting that the study was based on the two-phase model.
of concrete according to the analytical model proposed in this work.

In the light of the experimental results found in the actual experimental research work, one may notice that the basic granular mixtures, which were identified using the fractal granular model FGM with a granular range $D/d_{gr}$, corresponded well to a given porosity of the granular mixture. One may also notice that the binder volume used in these mixtures may change depending on the two $FGM$ and $D/d_{gr}$ parameters.

We therefore decided to use the French standard NF EN 206-1 (2016) to determine the real class of cement to be applied. According to the specifications contained therein, the same standardised granular base mixture.

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**Fig. 11** Effect of the fractal dimension on the evolution of strength $R_{C28}$ is according to the $C/W$ ratio. a Result of the effect of $FD_g$, $FD_c$, b linear and exponential fit correlations $R^2$.

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**Fig. 12** Evolution of $R_{C28}$ as a function of the ratio $C/W$ the aggregate DA Boukli et al. (2009). a Results of all concretes $FD_g$ and $FGM_c$, b results given by the models $FGM_g$ and $FGM_c$. 
must always be used with standardised sand. Nevertheless, as future perspectives, we are intending to apply the model proposed to a larger number of concrete compositions for a better validation. Besides, further experimental investigations may further be developed on other types of concretes in order to develop a more general model for the prediction of the compressive strength $R_{C28}$. To this end, other parameters affecting this feature as well as the relationship widely used by Feret (1892) may also be included. In particular, we are thinking to complete this work with an experimental analysis in order to know the impact of the fractal
dimension $FD$ of the granular mixtures distribution in order to validate the results obtained.

Beyond the above perspectives, the experimental work described here enabled us to derive three consecutive main results. The initial outcomes concerned the fractal granular fractal model of the granular mixtures, which was based on the results of the particle size analysis. The followings findings concerned the $C/W$ ratio, which was fixed when the concretes were formulated. The last results were related to the compressive strength $RC_{28}$ of the concretes, as well illustrated in Fig. 17 for some selected concretes. Tables 6
and 7 summarise the results obtained for the concretes granular mixtures concretes $D_{15}$ and $D_{25}$, respectively. These results were used for the verification of the new unconventional model proposed in this work.

6 Experimental Verification

Starting from the processing of the empirical data collected in the literature, we were prompted to undertake an experimental analysis in order to validate the model. In the experimental phase, several granular mixtures, endowed with different granular distributions and featuring the fractal dimension $FD$ were used. As explained earlier, two categories of concrete with two granular ranges, namely $D_{15}$ and $D_{25}$, were investigated. A similar gravel was used for all the granular mixtures, but with two different types of sands, namely quarry sand $QS$ and dune sand $DS$. This was accomplished in order to obtain several granular mixtures with different particle size distributions. As a result, 18 granular concrete mixtures were selected in each group, as earlier detailed in Tables 3 and 4. In addition, several $C/W$ ratios were adopted depending on the workability of the intended concretes and the associated impact on the evolution of the concretes compressive strength $R_{C28}$. The main objective of this experimental analysis was to evaluate the reliability of the analytical approach by means of the fractal granular model results for the basic granular mixtures of concretes. With this analysis, we may ascertain both the results reached from the available literature and the results achieved in the case of the concretes elaborated in this experimental work.

The results in the literature differed with respect to the materials used, the type of concrete studied and the means of concrete formulation employed. Despite these differences, we managed to define the geometric model trajectory of the graphical results after applying the granular fractal model mixture $FGM_g$ of the basic granular mixtures. The experimental results found in this experimental work provided further evidence of the analytical results shown earlier in Fig. 11. The graphical results for all the laboratory elaborated concretes, shown in Fig. 18, were quite similar.

Based on the graphical analysis derived from Fig. 19, we were interested in determining the path of the fractal granular model in order to understand the evolution of the compressive strength $R_{C28}$ as a consequence of the

| Mixture/concrete | $C/W$ ratio | $R_{C28}$(MPa) | Fractal granular model |
|------------------|-------------|----------------|-----------------------|
|                  |             |                | $FD_g$     | $R^2$ | $FGM_g$ | $FGM_C$ |
| C10 QS F-D_{15}  | 1.68        | 42.08          | 2.76       | 0.97  | 6.63    | 15.24   |
| C11 QS F-D_{15}  | 1.82        | 63.70          | 2.76       | 0.97  | 6.63    | 15.24   |
| C12 QS F-D_{15}  | 1.55        | 63.15          | 2.76       | 0.97  | 6.63    | 15.24   |
| C13 QS F-D_{15}  | 1.68        | 57.84          | 2.73       | 0.97  | 6.54    | 15.25   |
| C14 QS P-D_{15}  | 1.55        | 62.20          | 2.73       | 0.97  | 6.54    | 15.25   |
| C15 QS P-D_{15}  | 1.82        | 29.81          | 2.73       | 0.97  | 6.54    | 15.25   |
| C16 QS TP-D_{15} | 1.82        | 27.10          | 2.72       | 0.97  | 6.66    | 15.25   |
| C17 QS TP-D_{15} | 1.55        | 45.59          | 2.72       | 0.97  | 6.66    | 15.25   |
| C18 QS TP-D_{15} | 1.68        | 48.01          | 2.72       | 0.97  | 6.66    | 15.25   |
| C01 DS F-D_{15}  | 1.55        | 21.95          | 2.72       | 0.96  | 6.52    | 15.02   |
| C02 DS F-D_{15}  | 1.82        | 23.87          | 2.72       | 0.96  | 6.52    | 15.02   |
| C03 DS F-D_{15}  | 1.68        | 21.28          | 2.72       | 0.96  | 6.52    | 15.02   |
| C04 DS F-D_{15}  | 1.68        | 46.30          | 2.71       | 0.96  | 6.49    | 15.10   |
| C05 DS P-D_{15}  | 1.82        | 27.30          | 2.71       | 0.96  | 6.49    | 15.10   |
| C06 DS P-D_{15}  | 1.55        | 48.94          | 2.71       | 0.96  | 6.49    | 15.10   |
| C07 DS P-D_{15}  | 1.55        | 49.32          | 2.68       | 0.96  | 6.41    | 15.12   |
| C08 DS TP-D_{15} | 1.68        | 20.86          | 2.68       | 0.96  | 6.41    | 15.12   |
| C09 DS TP-D_{15} | 1.82        | 45.54          | 2.68       | 0.96  | 6.41    | 15.12   |

Fig. 17 Mechanical compressive strength tests $R_{C28}$. 

Table 6 Compressive strengths $R_{C28}$ for concrete $D_{15}$ and values of the granular fractal model.
cement-to-water \( C/W \) ratio and the effect of the fractal granular model \( FGM_g \). For this, we handled the obtained graphical results by linear and exponential fittings of the \( D_{15} \) and \( D_{25} \) concretes results but the exponential adjustment proved to be more feasible than the linear one. The values obtained for the correlation factor \( R^2 \), which corresponded to the linear fitting, were 0.66 and 0.84 for the \( D_{15} \) and \( D_{25} \) concretes, respectively. On the other hand, the value of the correlation factor, which corresponded to the exponential function fitting,
was equal to 0.99 for both $D_{15}$ and $D_{25}$ concretes; see Tables 6 and 7. Indeed, Eq. (5) implied that the analytical results provided a clearer insight into the evolution of the fractal granular fractal model $FGM_g$, under exponential fitting:

$$R_{C28} = Y_0 + A \times e^{(R_0 \times C/W)},$$

$$FGM_g = 6.66 - R^2 = 0.99, R_{C28} = 66.62 - 1.25 \times 10^6 \times \exp(-6.40 C/W)$$

All the above data may be used to elaborate a new model that should more effectively contribute to the prediction of concretes compressive strength $R_{C28}$, taking into account that the linear modulation approach can only help to define the granular distribution of granular mixtures and also to facilitate the determination of the fractal dimension $FD$ value. Within this same vein, the granular fractal model $FGM_g$ may be regarded as an important unconventional variable that should effectively contribute to the prediction of the concretes compressive strength $R_{C28}$ while taking into account the exponential fitting of Eq. (5). In addition, the granular fractal model $FGM_g$ readily defined the granular distribution of granular concrete mixtures with a known fractal dimension $FD$ value.

7 Conclusions

The experimental work was mainly concerned with the study of the compressive strength $R_{C28}$ of concretes by means of two key-factors, namely the fractal granular model $FGM_g$ of basic granular mixtures for concretes, as an unconventional factor and the cement-to-water $C/W$ ratio, as a conventional factor. The experimental work consisted of collecting data concerning the composition of several concretes available in the literature as well as concretes elaborated within the experimental programme. Processing with the empirical data collected enabled to establish analytical relationships. Experimental investigations on granular mixtures for concretes allowed to validate and evaluate the reliability of the proposed analytical approach. Based on the results obtained, the following conclusions may be drawn:

- The experimental results enabled to validate the analytical approach, thereby affirming the effectiveness of the two key-factors, i.e. the fractal granular model $FGM_g$ and the cement-to-water $C/W$ ratio, in affecting the prediction of the compressive strength $R_{C28}$ of the concretes.
- Unlike other studies that did not specifically address the grains size distribution in a direct manner, the grain distribution of granular mixtures in the experimental work herein was described using the value of the fractal dimension $FD$ value.
- Findings allowed to highlight the reliability of the fractal granular model $FGM_g$ in determining the type of granular distribution of the basic granular concrete mixtures.
Based on the above findings and the various concrete compositions (materials used, concrete types studied and means of concrete formulation employed), the compressive strength $R_{C28}$ of the concretes allowed validating the impact of the unconventional key-factor, namely the fractal granular model $\text{FGM}_g$ for the granular mixtures.

Use of similar basic granular mixtures with several levels of cement pastes contributed to demonstrate the impact of both the fractal granular model $\text{FGM}_g$ and cement–water $C/W$ ratio on the prediction of concretes compressive strength $R_{C28}$.

The authors still believe that to achieve the intended objective, more experimental work is needed to extend the range of concretes and to further demonstrate the effectiveness of the fractal granular model $\text{FGM}_g$ in predicting the concretes compressive strength $R_{C28}$, taking into account other unconventional factors such as the effect of excess paste volume and the two-phase concrete model.

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Author contributions
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Available data and materials
The database used and/or analysed in this study is available and can be provided to anyone upon reasonable request.

Declarations
Competing interests
The authors declare that there are no conflict of interests.

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