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RESEARCH

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 FGM_g also effectively contributed to highlight the correlation between cement-to-water ratio and compressive strength R_{C28} 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 FGM_g and the influence of cement–water C/W ratio of concretes mixtures when predicting the concretes compressive strength R_{C28}. The analytical model provided a close correlation with the experimental values of the compressive strength R_{C28} of all the concretes. The correlation highlighted the relevance of including fractal granular model FGM_g that denoted the skeleton of the concretes and the cement–water C/W ratio that referred to the binders into concretes mixtures when predicting R_{C28}. 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 R_{C28}.

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); Sebsadji and Chouicha

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(2012); Qing et al. (2019); Peng et al. (2020); Di et al. 2020; Xu et al. (2021); Rouibi and Chouicha (2021) extensively studied the concept of fractal dimension, as an identification factor of granular mixtures.

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 R_{C28} 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 R_{C28}. 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 R_{C28} 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 R_{C28} 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 R_{C28} 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), Guemmadi et al. (2009), Boutiba et al. (2014), Boukli et al. (2014), Derabla and Benmalek (2014), Mehamdia and Benois (2018), Benouis and Grini (2011), Benouis and Mehamdia (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 R_{C28} 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.

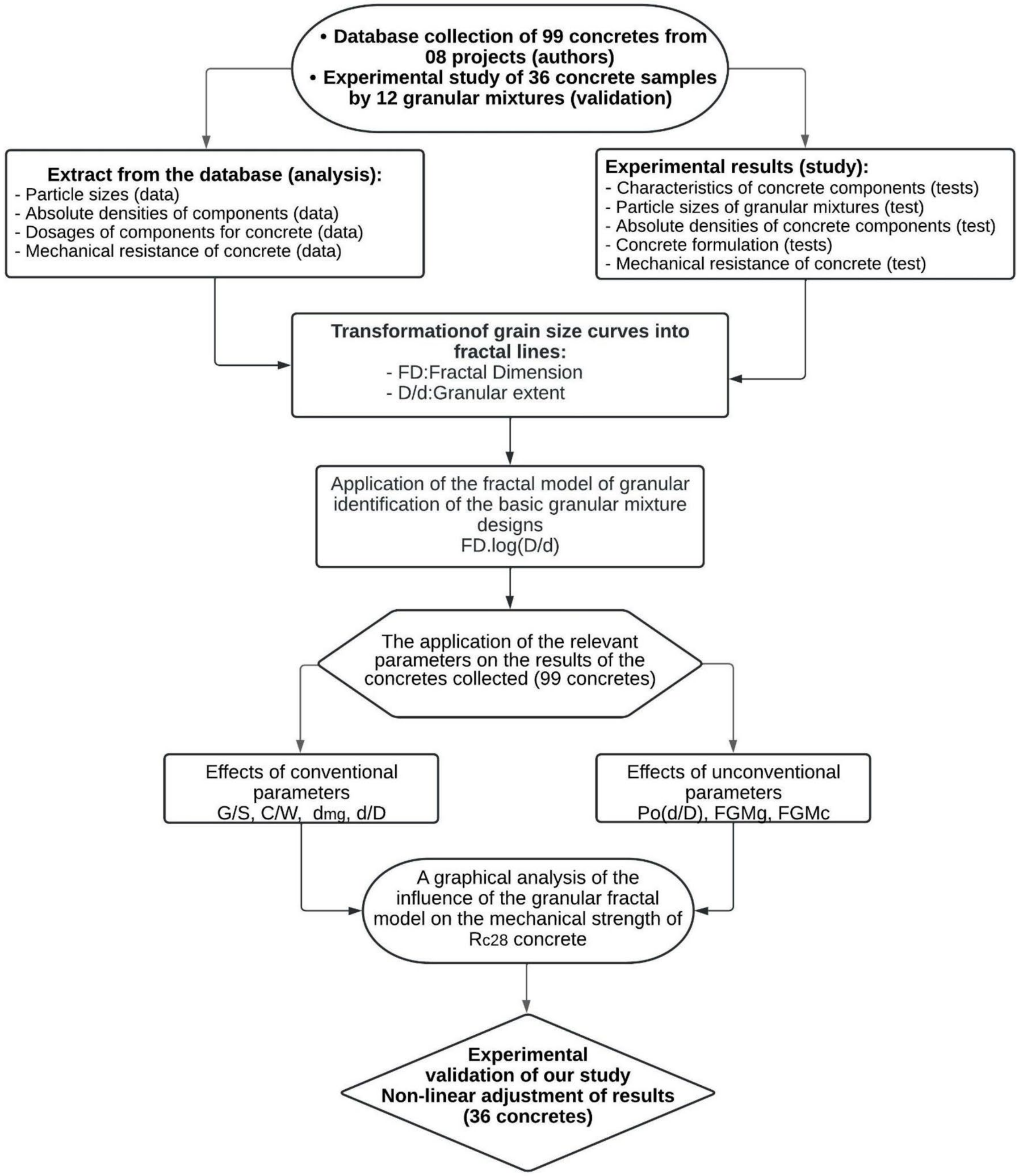

Fig. 1 Design automation diagram for the proposed approach, based on collected data.

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.

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

Chemical composition	Cement (%)	Silica-fume (%)	Characteristics	Superplasticizer
Silicon dioxide, SiO_2	21	95	Density	1.07
Calcium oxide, CaO	63	0.50	Extrait sec	30%
Iron oxide, Fe_2O_3	3.2	1	Aspect	Liquide
Aluminium oxide, Al_2O_3	4.5	0.50	Couleur	Brun clair
Magnesium oxide, MgO	1.3	1	PH	6–6,5
Potassium oxide, K_2O	0.4	/	Teneur en chlore	0.1 g/l
Sulphur trioxide, SO_3	2	0.5	Dosage	0,5 à 2,0% C
Sodium oxide, Na_2O	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		Fine and coarse	DS
Densité absolue (g/cm^3)	2.64	2.59	2.64	2.63	2.65	SiO_2 (%)	33.34	44.06
Équivalent de sable	84.4	69.65				Al_2O_3 (%)	5.58	1.33
Module de finesse	2.35	2.93				Fe_2O_3 (%)	6.37	0.04
Absorption d'eau (%)	0.5	1.71	2.15	1.92	0.79	CaO (%)	24.17	25.34
Micro-Deval			32.4	24	18.2	MgO (%)	4.07	1.00
Los Angeles			19.66	18.28	15.32	SO_3 (%)	0.17	2.65

Fig. 2 Granular classes used (DS, QS, Gravels 3/8, 8/15 and 15/25).

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 3 Mixture proportions of concrete D_{15}.

Mix (kg/m3)	CEM II	SF	Fine aggregate		Coarse aggregate		SP	W/C ratio
			QS	DS	3/8	8/15		
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	3/8	8/20	15/25		
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:

$$V = V_0 \sqrt[5]{d/D}, \quad (1)$$

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 dry granular mixtures of concretes using the porosity and melting as well as the fractal dimension:

$$\mathrm{Por}(d/D) = \mathrm{Por}(d) - A_I.e^{\frac{-(FD.\log(d/D)-(3.\log(d/D))^2}{2W^2}}. \quad (2)$$

In this equation, Por(d/D) was the granular mixtures porosity d/D; Por(d) was the porosity of elementary class d; log(d/D) was the optimal granular fractal modulus; FD.log(d/D) was the granular fractal modulus; W was the standard deviation that described the scattering around the optimal value FD_{Opt}.Log(d/D)andA_I was the tightening coefficient that described the tightening process effect.

3.3 Fractal Dimension and Granular Mixtures of Concretes

Regarding the granular mixtures 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}andD_{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.

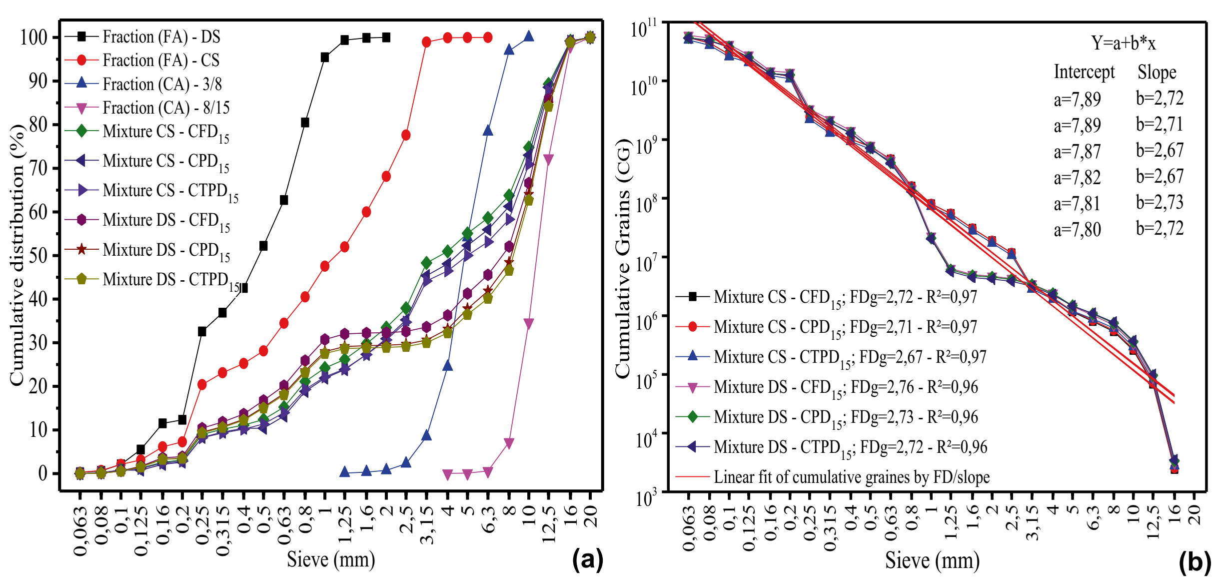

Fig. 3 Identifications of D_{15} concrete granular curves using the fractal dimension FD_g. **a** Granulometric curves, **b** fractal straight lines.

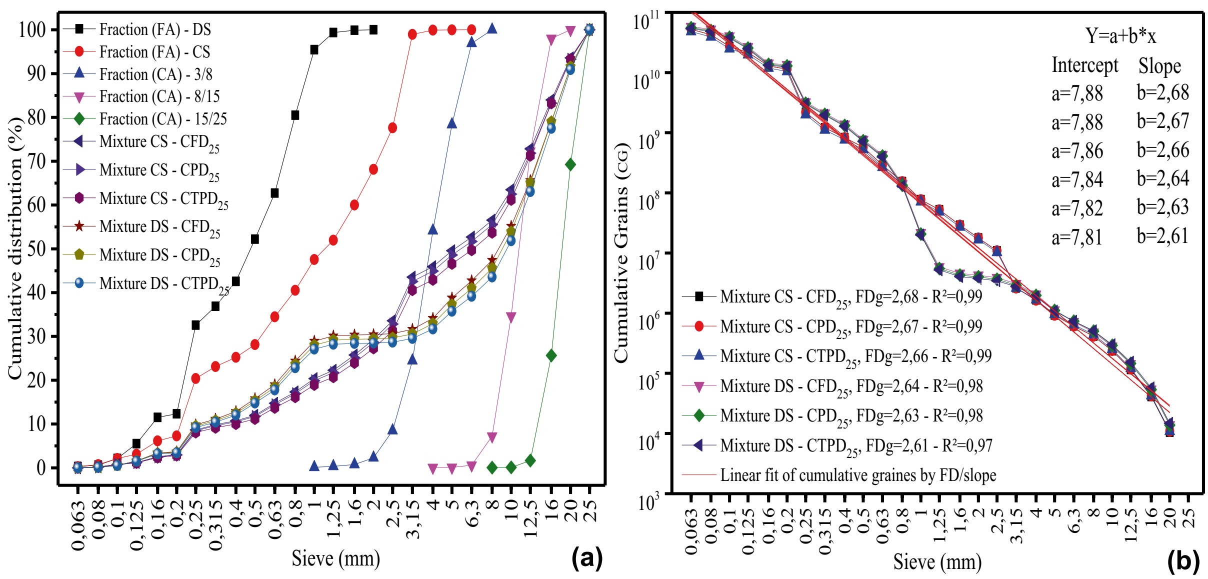

Fig. 4 Identifications of D_{25} concrete granular curves using the fractal dimension FD_g. **a** Granulometric curves, **b** fractal straight lines.

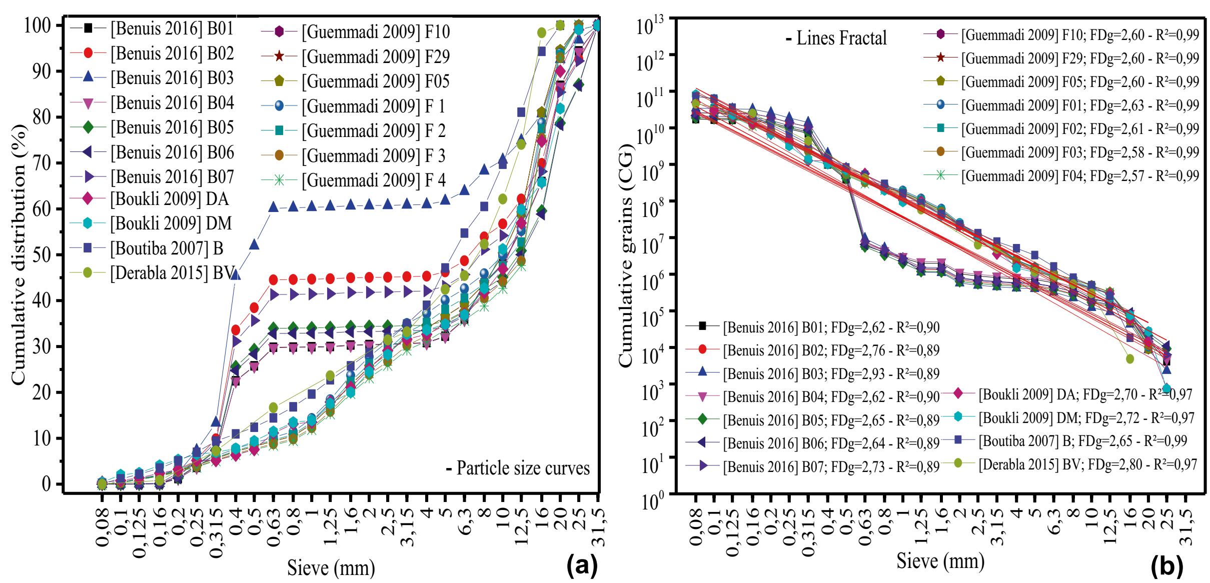

Fig. 5 Transformation of grain size curves into fractal lines (collected data). **a** Grain size curves, **b** fractal straight lines.

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 FGM_g of a basic granular mixture without cement and no mineral additives [see Eq. (3)] as well as the fractal granular model for concrete mixtures FGM_C, as follows:

$$FGM_g = FD_g.\log\left(\frac{D}{d_g}\right), \quad (3)$$

$$FGM_C = FD_C.\log\left(\frac{D}{d_C}\right), \quad (4)$$

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

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
	TN	N/FD_g	FMG_g	FMG_C	FD_g	R^2	FD_C	R^2	(mm)
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	0.98	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	
		2	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, FD_C, FD_g, 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 can hardly 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

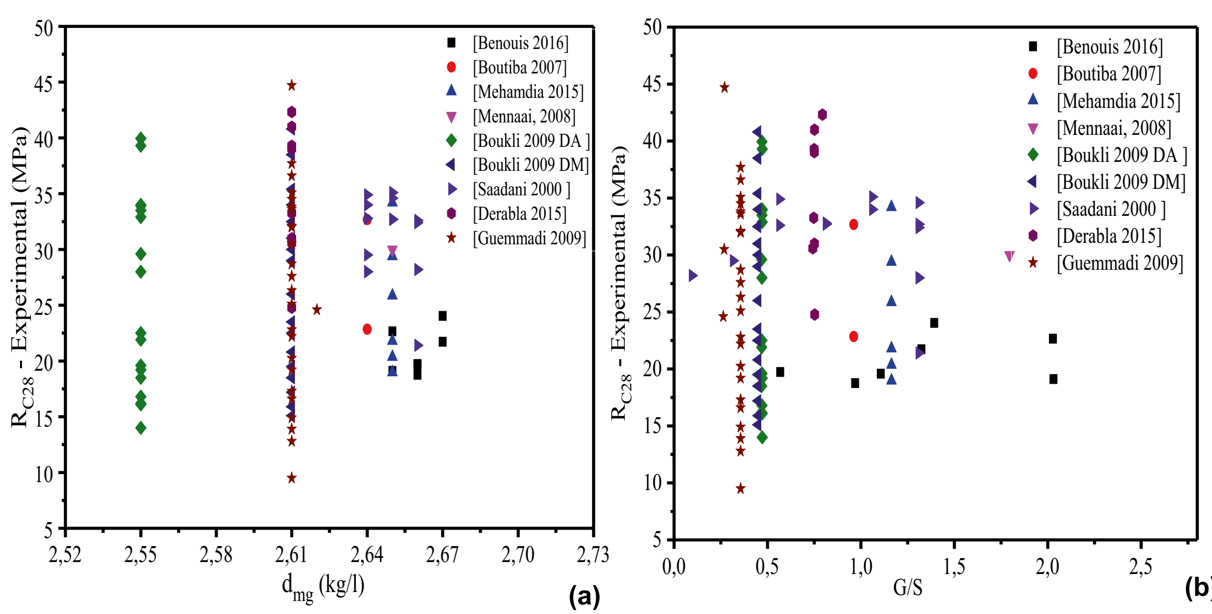

Fig. 6 Effect of the density d_{mg}, G/S of the granular mixture on R_{C28} of concretes (all collected data). **a** Effect of the density d_{mg} on R_{C28} of concretes, **b** effect of the ratio G/S on R_{C28} of concretes.

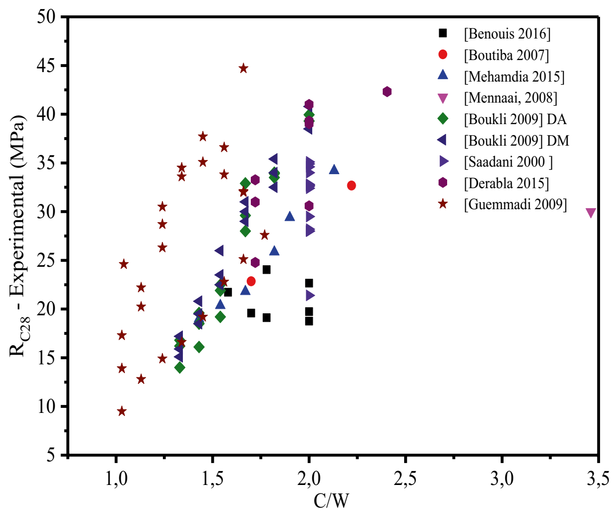

Fig. 7 Effect of the ratio C/W on R_{C28} (all collected data).

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 FMG_g, 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 FMG_g and FMG_C 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 FD_g, using Eq. (2). Then, the expression Por(d/D) was used to determine the compactness of the granular mixtures. The parameters $FD_g.\log(D/d_g)$ and $FD_C.\log(D/d_C)$ 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 FGM_g and FGM_C**, Fig. 10a and b plots the evolution of the compressive strength R_{C28} of concretes vs. the fractal dimension FD_g of the granular mixtures and the fractal dimension FD_C 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 FD_g basic granular mixtures values, whereas the corresponding values for the fractal dimension FD_C 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 FGM_g of the basic granular mixtures and the fractal granular model FGM_C of the dry concrete mixtures. They reveal that concretes may have the same fractal granular model FGM_g values for the basic granular mixtures and different corresponding values for the fractal model granular model FGM_C 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 FGM_g 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 FGM_g 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 FD_g values were used; see Fig. 10. The results were largely satisfactory and the relationship between

(See figure on next page.)

Fig. 8 Effect of the ratio C/W on R_{C28} (separate project). **a** Project of Boukli et al. (2009), **b** project of Boutiba et al. (2014), **c** project of Mehamdia and Benouis (2018), **d** project of Guemmadi et al. (2009), **e** project of Benouis and Grini (2011), **f** project of Derabla and Benmalek (2014).

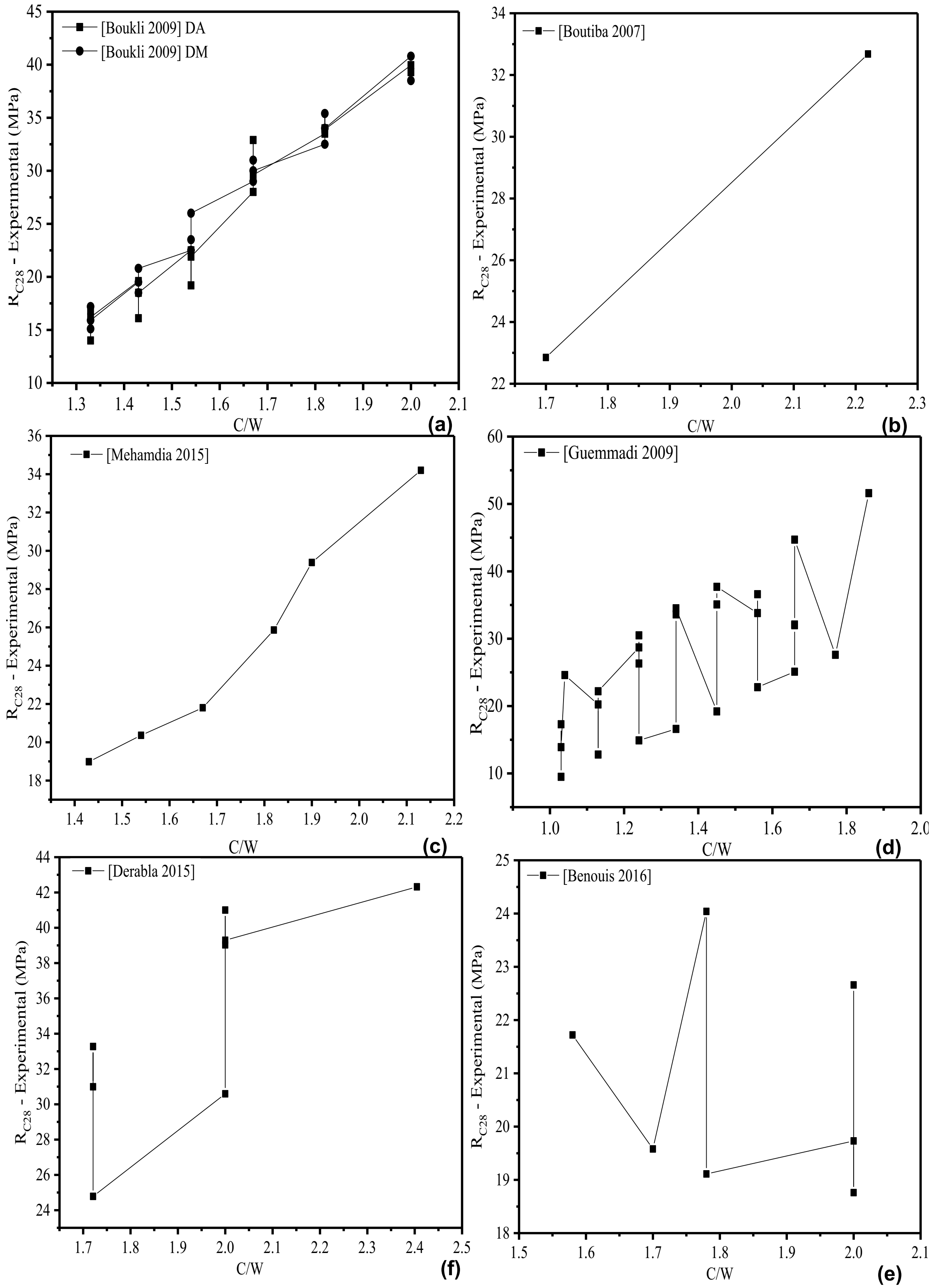

Fig. 8 (See legend on previous page.)

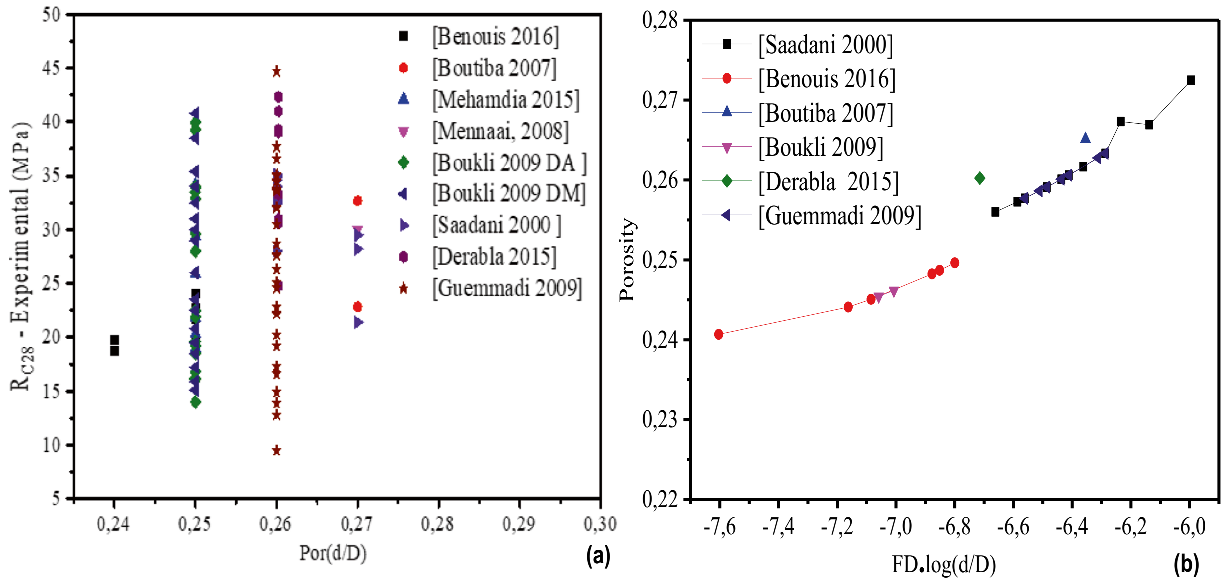

Fig. 9 Relationship between the porosity Por(d/D) of the basic granular mixture and R_{C28} of concrete. **a** Strength as a function of the porosity Por(D/d_g), **b** porosity Por (d/D) according to the model FD.log(d/D).

the fractal granular model 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 FGM_g and the cement-to-water C/W ratio for the same data collected. The use of the FD_g.log(D/d_g) parameter enabled to demonstrate the significance of the porosity/compactness of the fractal granular model 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 modelFGM_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 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 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 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 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 FGM_C 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

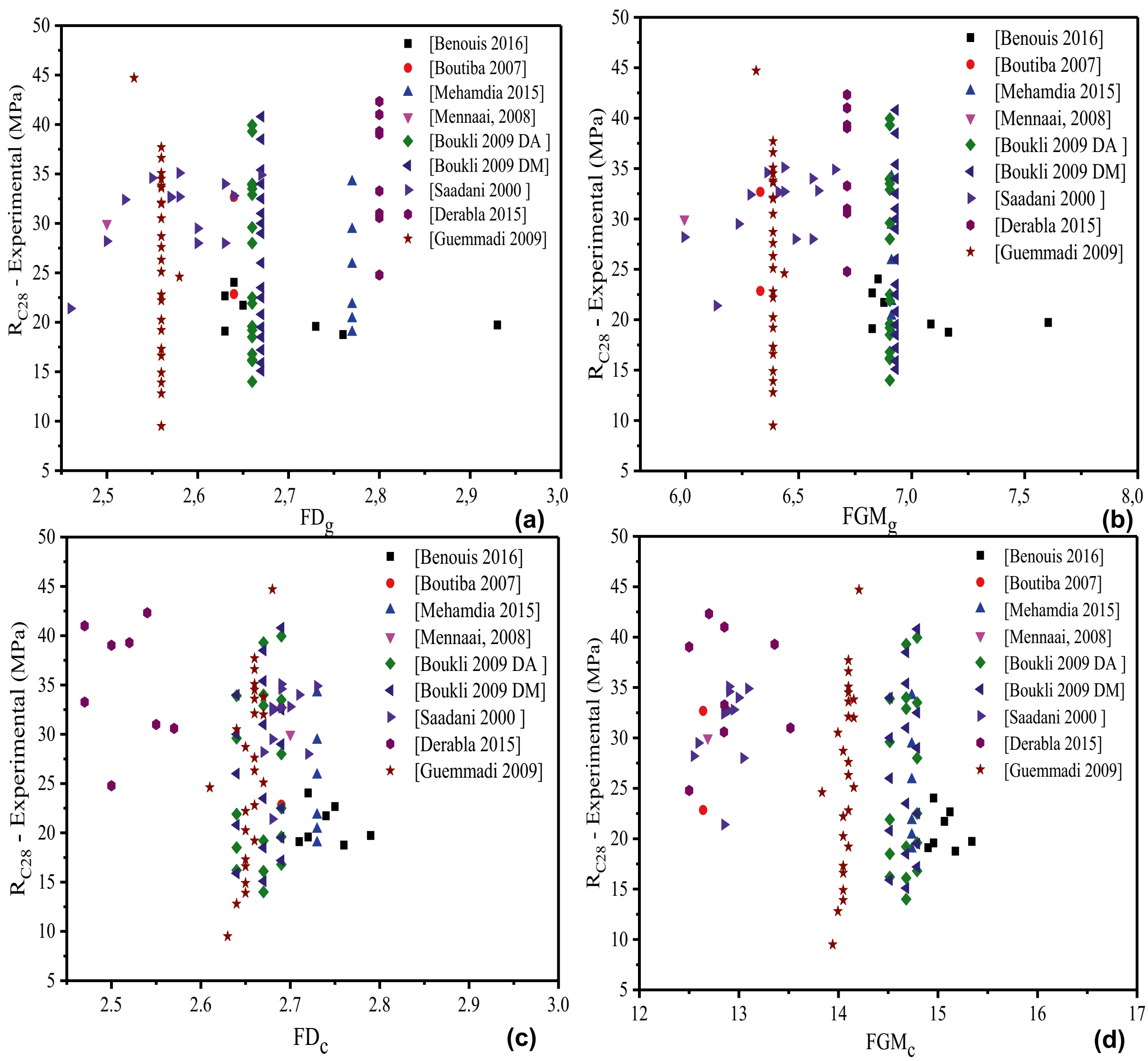

Fig. 10 Effect of the models FD_g, FGM_g and FD_C, FGM_c on the R_{C28} of concretes (all collected data). **a** Effect of fractal dimension FD_g of basic granular mixtures, **b** Effec of fractal model FGM_g of basic granular mixtures, **c** Effect of fractal dimension FD_c of the granular mix of concrete, **d** Effect of the fractal model FGM_c of the granular mix of concrete

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 FGM_g of the basic granular mixture and the fractal granular model 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 FGM_g. However, the analytical model developed here needs to be further validated by additional experimental work. The influence of the fractal granular model 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

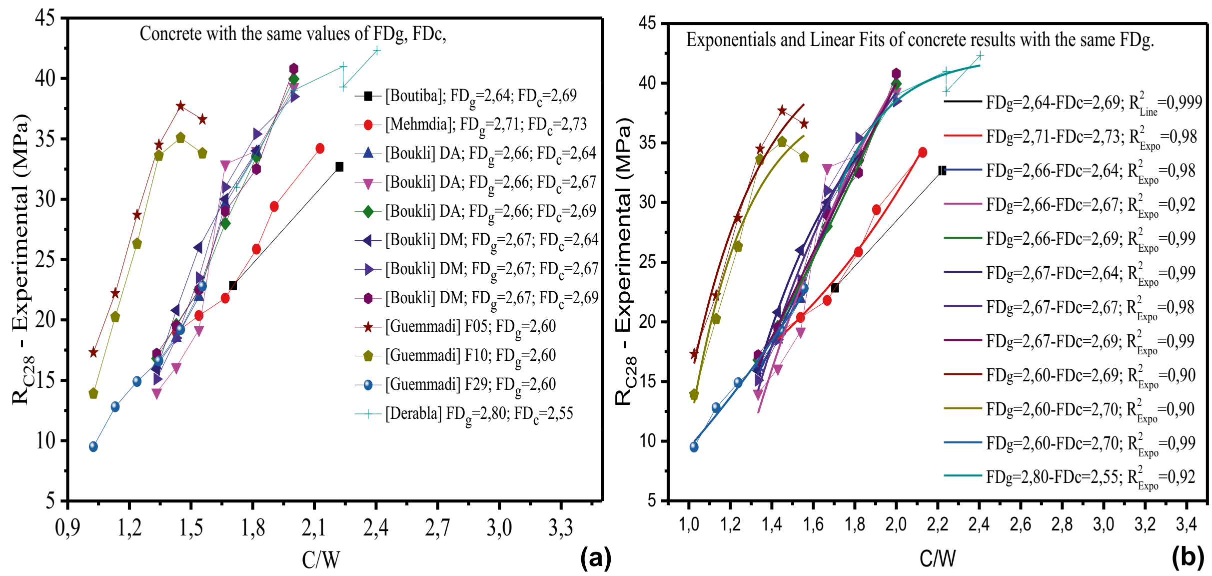

Fig. 11 Effect of the fractal dimension on the evolution of strength R_{C28} is according to the C/W, ratio. **a** Result of the effect of FD_g, FD_C; **b** linear and exponential fit correlations R^2.

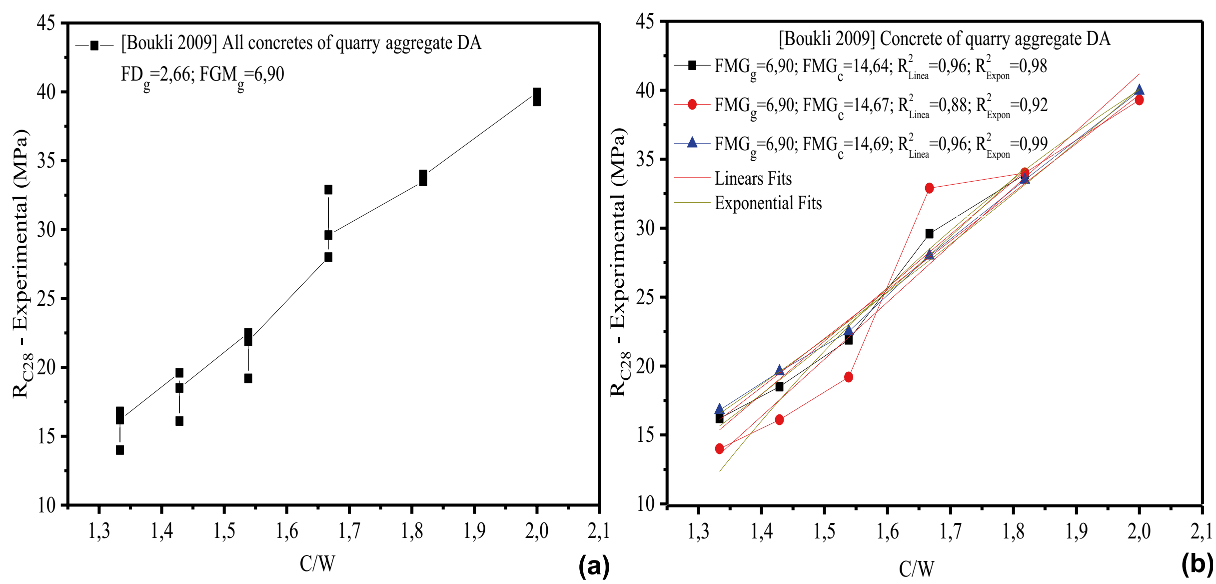

Fig. 12 Evolution of R_{C28} as a function of the ratio C/W the aggregate DA Boukli et al. (2009). **a** Results of all concretes FD_g and FGM_g, **b** results given by the models FGM_g and FGM_C.

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_g with a granular range D/d_g, 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_g and D/d_g 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

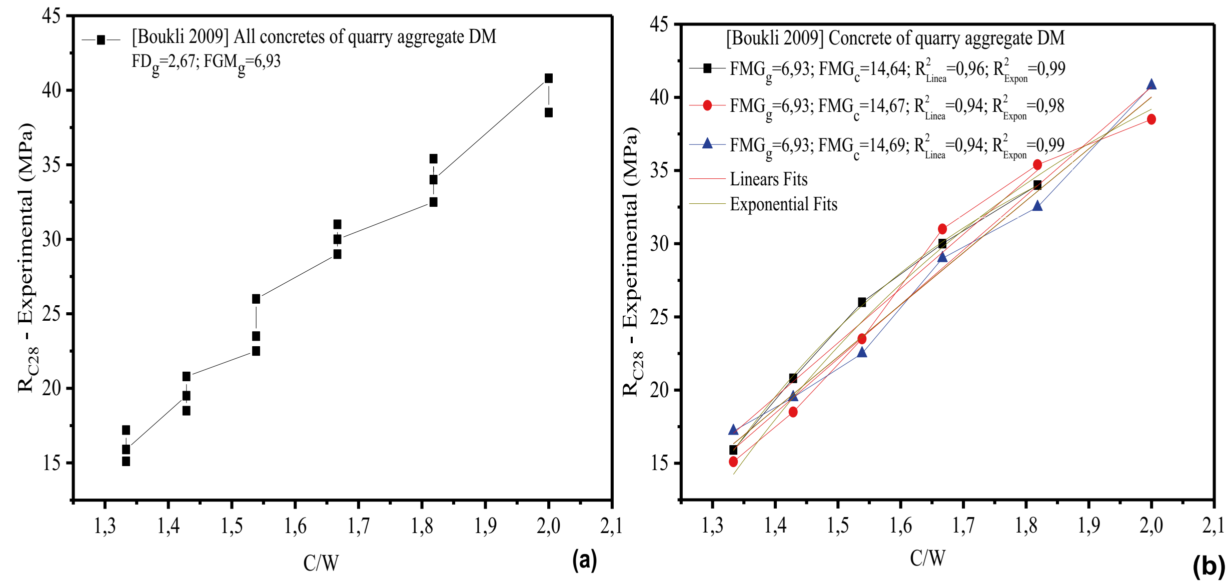

Fig. 13 Evolution of R_{C28} as a function of the ratio C/W the aggregate DM (Boukli et al. (2009). **a** Results of all concretes FD_g and FGM_g, **b** results given by the models FGM_g and FGM_C.

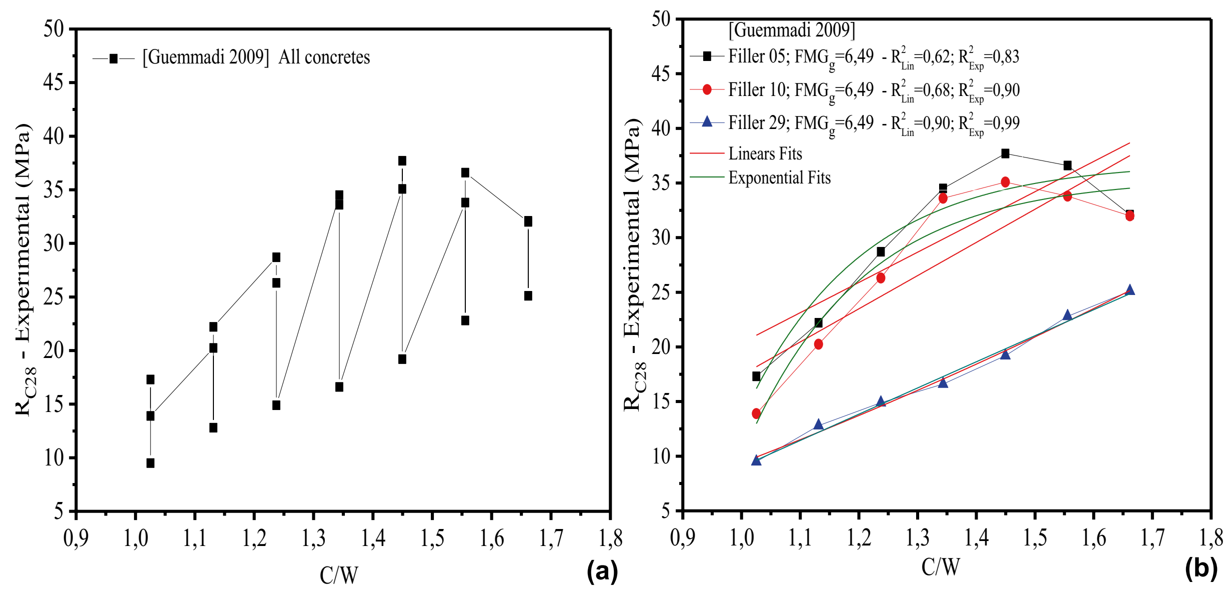

Fig. 14 Evolution of R_{C28} as a function of the ratio C/W Guemmadi et al. (2009). **a** Results obtained for all the concretes using, **b** results given by FGM_g and FGM_C.

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

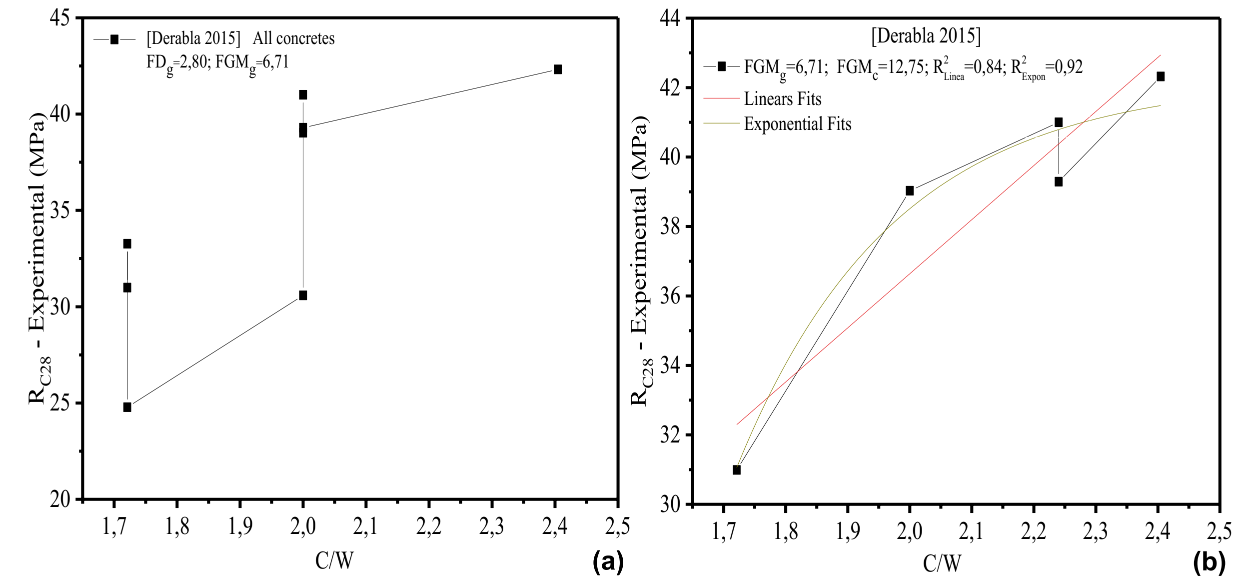

Fig. 15 Evolution of R_{C28} as a function of the ratio C/W (Derabla and Benmalek 2014). **a** Results of all the concretes obtained by FGM_g, **b** results obtained by FGM_g and (FD_C)

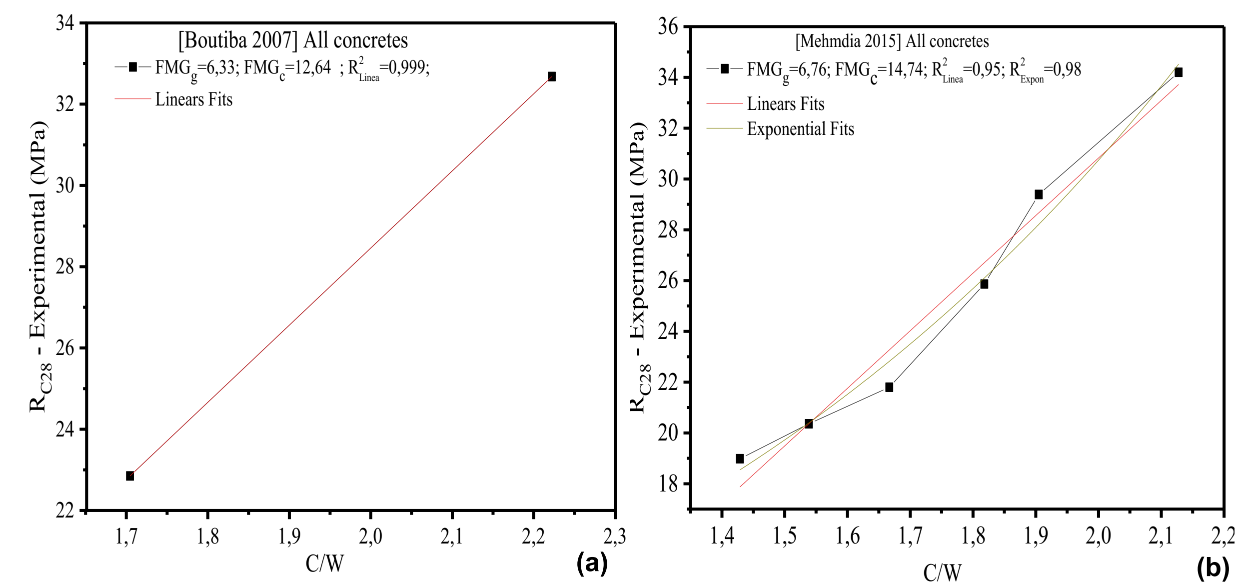

Fig. 16 Evolution of R_{C28} as a function of the ratio C/W, (Boutiba et al. 2014., Mehamdia and Benouis (2018). **a** Results given by FGM_g and FGM_C (Boutiba), **b** results given by FGM_g and FGM_C (Mehmdia).

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 R_{C28} of the concretes, as well illustrated in Fig. 17 for some selected concretes. Tables 6

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

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

Table 6 Compressive strengths R_{C28} for concrete $\mathbf{D}_{15}$, and values of the granular fractal model.

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 P-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 P-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 TP-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

Table 7 Compressive strengths R_{C28} for concrete D_{25} and values of the granular fractal model

Mixture/concrete	C/W ratio	R_{C28}(MPa)	Fractal granular model			
			FD_g	R^2	FGM_g	FGM_C
C10 QS F-D_{25}	1.78	48.16	2.68	0.99	6.69	14.57
C11 QS F-D_{25}	1.66	58.30	2.68	0.99	6.69	14.57
C12 QS F-D_{25}	1.88	55.11	2.68	0.99	6.69	14.57
C13 QS P-D_{25}	1.78	53.13	2.67	0.99	6.66	14.63
C14 QS P-D_{25}	1.88	48.46	2.67	0.99	6.66	14.63
C15 QS P-D_{25}	1.66	27.10	2.67	0.99	6.66	14.63
C16 QS TP-D_{25}	1.66	35.93	2.66	0.99	6.64	14.63
C17 QS TP-D_{25}	1.88	59.10	2.66	0.99	6.64	14.63
C18 QS TP-D_{25}	1.78	52.33	2.66	0.99	6.64	14.63
C01 DS F-D_{25}	1.66	29.09	2.64	0.98	6.59	14.52
C02 DS F-D_{25}	1.88	15.51	2.64	0.98	6.59	14.52
C03 DS F-D_{25}	1.78	36.00	2.64	0.98	6.59	14.52
C04 DS P-D_{25}	1.88	44.18	2.63	0.98	6.56	14.47
C05 DS P-D_{25}	1.78	57.59	2.63	0.98	6.56	14.47
C06 DS P-D_{25}	1.66	38.84	2.63	0.98	6.56	14.47
C07 DS TP-D_{25}	1.66	38.60	2.61	0.97	6.51	14.52
C08 DS TP-D_{25}	1.88	48.97	2.61	0.97	6.51	14.52
C09 DS TP-D_{25}	1.78	44.22	2.61	0.97	6.51	14.52

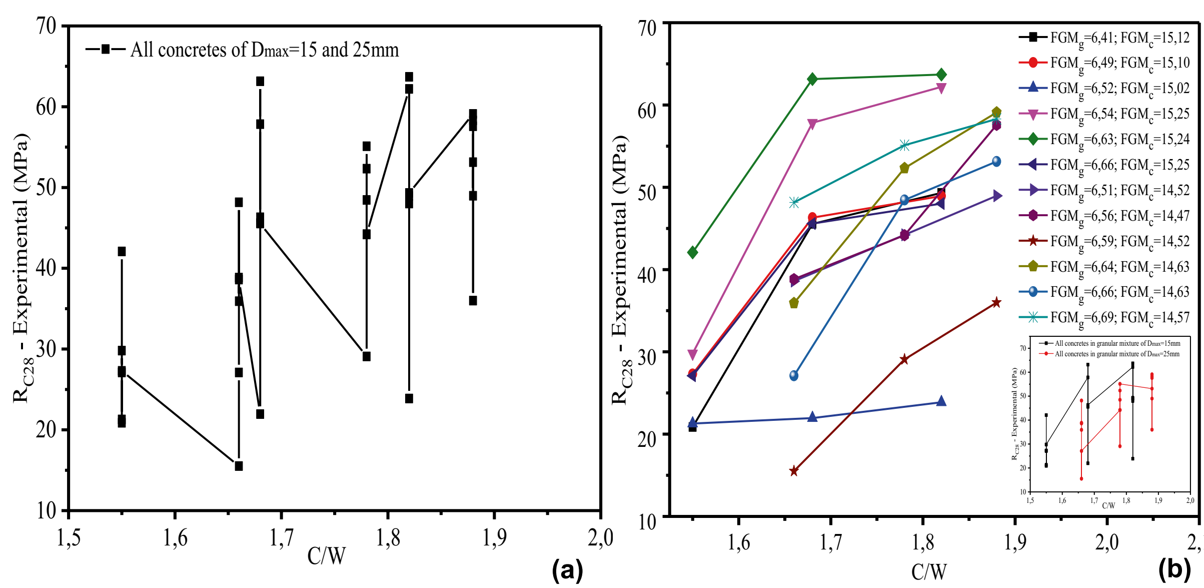

Fig. 18 Mechanical strength R_{C28} as a function of the ratio C/W for concretes D_{15} and D_{25}. **a** Results for all types of concrete, **b** results obtained according to FGM_g and FGM_C.

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,

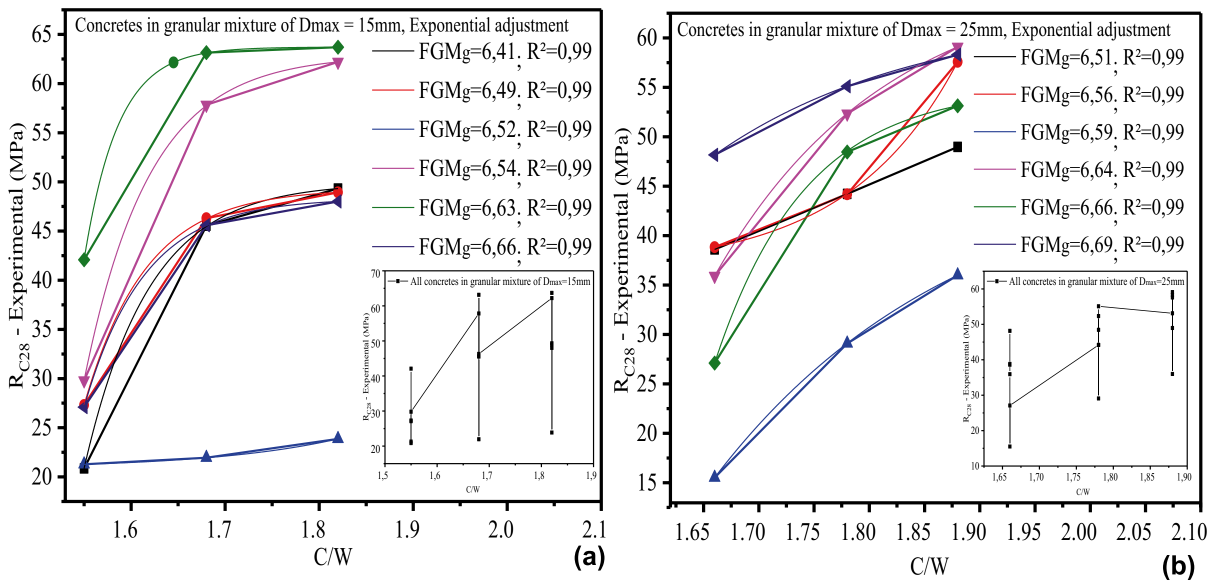

Fig. 19 Exponential adjustment of the experimental results using the models FGM_g and FGM_C. **a** Results relating to D_{15} concrete, **b** results relating to D_{25} concrete.

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:

$$R_{C28} = Y_0 + A * e^{(R_0 * C/W)}, \quad (5)$$

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

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 concretes compositions (materials used, concretes 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 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 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 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
The authors contribute to the development of a new model for concrete formulation. The main aim of this research work is to prepare a thesis for a doctorate. It is also part of the supervision and monitoring of a scientific research programme, requiring close collaboration of the authors. Both authors have read and approved the final manuscript.

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Availability of 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
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