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Effect of coarse aggregate on the workability of sandcrete

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Abstract

The results of an experimental study of the effect of a limited quantity of coarse aggregate on the workability of sandcrete are presented. This study has been conceived within an experimental design framework. Several parameters have been analyzed: aggregate content, aggregate size, aggregate shape and matrix strength (20- and 35-MPa matrices are cast). Statistical analysis shows that, for the 20-MPa matrix, aggregate content [gravel/sand ratio (G/S) < 0.7] and aggregate size appear to be the most influent parameters. While for the 35-MPa matrix, only the aggregate concentration has a statistically significant effect. These results show that the workability can be divided by 4 as the aggregate content increases up to G/S = 0.6. Thus, sandcrete with a small coarse aggregate content cannot be considered as a classical sandcrete whose mechanical properties, mainly compressive strength, are enhanced by an amount of gravel. Developing general use of sandcrete with coarse aggregate requires building specific mix design to respect both compressive strength and workability. © 2002 Elsevier Science Ltd. All rights reserved.

Keywords: Workability; Physical properties; Aggregate; Sandcrete

1. Introduction

Sandcrete belongs to a family of concretes, which can be used when environmental or economic constraints limit the use of coarse aggregate. In a recent past, a French National Project (Sablocrete) [1] pointed out economical and mechanical advantages of this material and provided typical applications in public works and building. In spite of advances in sandcrete technology, the use of this concrete is still limited [2,3].

This French National Project indicated how including an amount of coarse gravel in a sandcrete matrix can increase stiffness and compressive strength. The main objective is then to obtain, with a small amount of coarse gravel, a sandcrete with physical and mechanical features that are close to those of classical concrete. In order to remain economical in aggregate, the gravel/sand (G/S) ratio must be less than 0.7.

From a mechanical point of view, sandcrete with a limited content of aggregate is different from classical concrete by a gap in grading. There is a gap in particle diameter between sand and the smallest gravel. Thus, the granular skeleton cannot fulfill the principle of maximum compactness [4]. The composite results from the scattering of rigid inclusions (coarse aggregate) embedded in a continuous sandcrete matrix (sand+hydrated cement + fillers + voids). Under this assumption, several homogenisation models make it possible to estimate stiffness from properties of each phase [5,6]. Based on fracture mechanics concept, aggregate–matrix interface represents the weakest link in concrete and has negative effect on its mechanical properties. On the other hand, aggregates might stop crack propagation [7,8]. Mechanical behavior of the composite can be influenced by several aggregate parameters such as shape, size, orientation, roughness, mineralogical nature, concentration and quality of aggregate–matrix interface. From experimental studies [1,9,10], an optimum value for the G/S ratio around 0.4 was deduced. It significantly improves (from 10% to 20%) elas-tic stiffness and compressive strength. Aggregate size was also significant, whereas aggregate shape appears to be negligible.

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Table 1
Parameters and their values

Parameters	True values				Parameters	Normalized values			
f	Rounded limestone	Crushed limestone			f'	–	−1	+1	–
d	7/12 mm	10/20 mm			d'	–	−1	+1	–
g (m^3/m^3)	0.053	0.101	0.145	0.255	g' (m^3/m^3)	−1	−0.1	−0.54	+1

Mix designs for sandcrete are derived from classical Ferret's relationship [11] to account for the influence of additives (filler and microfiller) on compressive strength and considering that all sand grains are surrounded by a layer of cement paste for workability [12–14]. This latest concept can be used for sandcrete with coarse aggregate to explain the high influence of aggregate concentration on workability, as shown below in our experimental evaluation.

2. Experimental

In this experimental study, density (de) and workability (Slump test, Sl) variations with volume aggregate concentration g (m^3/m^3), aggregate shape f (rounded or crushed) and aggregate size (d) are considered. The experimental design theory [15] is used to establish an optimum experimental procedure [8,9] and to elaborate empirical models considering both experimental parameters (Input: g, f and d) and results (Output: de and Sl). True values (f, d and g) and normalized ones (f', d' and g') in [−1,+1] interval are given in Table 1. This transformation enables to analyze in the same manner both qualitative and quantifiable data [16]. In the following, all capital letters (G: gravel, S: sand, C: cement, W: water, A: additives) refer to the component weight per cubic meter of mix. When using experimental design, a priori semiempirical models are built from mathematical expansion of the outputs as following:

$$Y = a_0 + a_1 g' + a_2 f' + a_3 d' + a_4 g' f' + a_5 g' d' + a_6 f' d' + a_7 g' f' d'$$

These coefficients of the model are identified through regression analysis and all possible parameters are ordered such as to keep only the most influent (a parameter is noninfluent when its effect cannot be separated from the experimental uncertainties). In our case, 16 mixes are required to establish the mathematical formulation (four levels for g and two levels for f and d).

Two reference sandcretes are used and their 28-day compressive strengths are 20 and 35 MPa, respectively. The different sandcrete mixes are shown in Tables 2 and 3 (20 and 35 MPa, respectively). Thirty-two mixes have been cast and tested.

All mixes have been made with ASTM type III cement, 0–3-mm sand, inert limestone filler and 1% of plasticizer MBT 2000 PF. Siliceous aggregate (26.50 kN/m^3 density) of low porosity (<1%) are used and humidified by spraying before use. Aggregate grading is given in Table 4. Note that sandcrete matrix was kept constant. This means that the quantity of cement and plasticizer decreases when aggregate concentration increases. Moreover, all weight ratios remain constant for reference matrices (Table 5).

3. Results and discussion

3.1. Workability of the two matrices

Two different matrices have been considered to show the effect of coarse aggregate on sandcrete workability. The compositions are kept constant whatever coarse aggregate concentration. Compressive strength (28 day) results (Fig. 1) appear quite similar for each mixture. Compressive strength is about 21.9 and 36 MPa, respectively, considering a target of 20 and 35 MPa. Coefficients of variation are low (5.8% and 3.8%). For each mix, two slump tests are performed before adding coarse aggregate. Slump test results on the two matrices (Fig. 2) show a similar behavior for each matrix. In average, slump is about 12.5 cm for the 20-MPa matrix and about 15.5 cm for the 35-MPa matrix. Workability increases from matrix 20 MPa to matrix 35 MPa in spite of the ratio W/(C+A), which decreases between the two matrices (Table 5). Thus, variation in the workability should be sought in the cement/sand ratio. It seems that the larger the cement/sand ratio, the larger the workability. This observation confirms previous findings [12] consisting in workability increases with average distance between sand

Table 2
Sandcrete mix proportions for 20-MPa matrix

	Composition				
g (m^3/m^3)	W (l/m^3)	C (kg/m^3)	S (kg/m^3)	G (kg/m^3)	A (kg/m^3)
0	200	300	1500	0	100
0.053	188	283	1417	142	94
0.101	179.5	270	1350	268	89
0.145	172	257	1285	385	86
0.255	150	225	1128	676	75

Table 3
Sandcrete mix proportions for 35-MPa matrix

	Composition				
g (m^3/m^3)	W (l/m^3)	C (kg/m^3)	S (kg/m^3)	G (kg/m^3)	A (kg/m^3)
0	191	381	1430	0	127
0.053	181	362	1360	140	120
0.101	172.5	345	1293	267	114
0.145	165	330	1237	385	110
0.255	147	294	1102	676	98

Table 4
Rounded and crushed aggregate grading (%)

	Size fraction (mm)			
d	20–15	15–10	10–7	7–4
7/12		70	22	8
10/20	45	45	10	

particles (with W/C constant). In fact, the flow of concrete resulting from relative motion between sand particles and workability increases as particles are more distant because interactions are lower. This concept will be discussed more fully in the last part of this section.

3.2. What role for coarse aggregate?

Coarse aggregate, incorporated in a sandcrete paste, has to follow some specifications. Particularly, (1) the G/S ratio must be less than 0.7 to remain in the family of sandcrete [1] and (2) rigid inclusions (coarse aggregate) must be embedded in a continuous sandcrete and gravel must not create skeleton [1]. Thus, one has to verify if the coarse aggregate modifies the compactness/porosity of sandcrete paste. If sandcrete structure remains unchanged, whatever G/S ratio, weight effect will be only observed one. In this way, influence of coarse aggregate concentration on sandcrete density can be studied. Results show an obvious effect of aggregate concentration on density and can be modelled with a multiple linear regression analysis (for the 20-MPa matrix) as follows:$de'=2216+55.1g'$, with g' in the interval $[-1,+1]$, which with true values corresponding to [16]:

$$de = 2132 + 540g \quad (1)$$

In this fitted model, only coarse aggregate concentration appears to be very significant. Fig. 3 represents the evolution of predicted values (using Eq. (1)) as function of experimental data for the 20-MPa matrix. It appears clearly that the density increases with coarse aggregate concentration. The coefficient of correlation between these two sets of data is about .94. Now, it is advisable to verify that the increase of the density is only due to a weight effect. Thus, it can model the influence of the aggregate concentration on the density from a mixing law, given by:

$$de = d_m g_m + d_g g \quad \text{with } (g_m + g = 1) \quad (2)$$

where d_m and g_m are the density and concentration of sandcrete paste, respectively, and d_g and g are the density

Table 5
Weight ratios for the two matrices whatever *g*

	Weight ratio				
Matrix	C/S	W/C	W/C+A	A/C	W/S
20 MPa	0.2	0.66	0.5	0.33	0.133
35 MPa	0.266	0.5	0.37	0.33	0.133

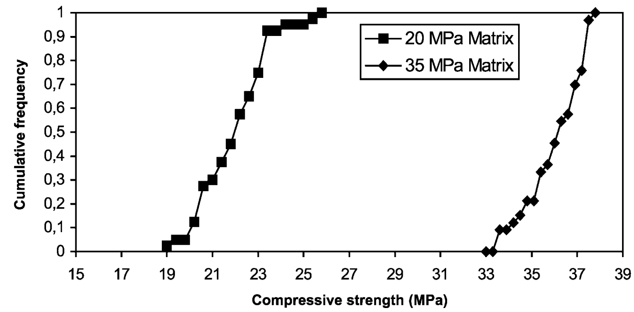

Fig. 1. Cumulative frequency of compressive strength.

and coarse aggregate concentration. A mean value of 26.50 kN/m^3 is considered for aggregate density and a value of 21.38 kN/m^3 (mean of eight mixes) for sandcrete paste density. As represented in Fig. 4, a correlation of .82 between the experimental data density and predicted density using Eq. (2) is obtained.

This result confirms the basic concept assumed in the experimental study considering that coarse aggregate has only a weight effect. The compactness of the pure sandcrete is not significantly modified by these rigid inclusions (elastic stiffness is about 70,000 MPa).

3.3. Workability of the sandcrete with coarse aggregate

Multiple regression models, identified from slump test results for 20- and 35-MPa matrices, give:

$$Sl\ (20\ MPa) = 4.87 - 3.34g' + 0.74d'$$

$$Sl\ (35\ MPa) = 7.83 - 4.94g'$$

The model for 20-MPa matrix accounts for 77% of total variance (86% for 35-MPa fitted model). Variance analysis resolves the total variability in two components (regression and deviation around fitted model) and indicates also whether estimated coefficients in the fitted model are statistically significant (at a 95% confidence level). For the two matrices, it appears that variable *g* (coarse aggregate

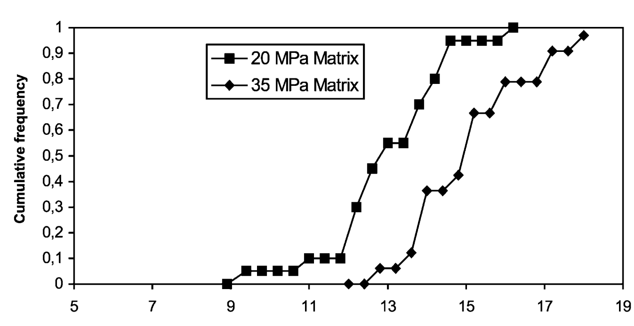

Fig. 2. Cumulative frequency of slump test.

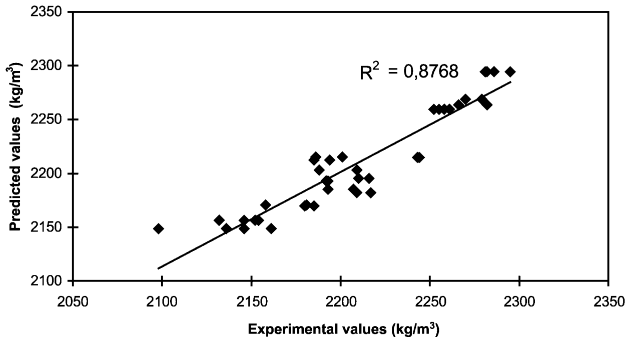

Fig. 3. Predicted versus experimental density values.

concentration) is the most significant parameter. The variable d (diameter) is second-order parameter for the 20-MPa matrix, variable f (shape of aggregate) being the least significant factor. Considering only aggregate concentration (Figs. 5 and 6) and true values, the following equations are derived:

$$20\ \text{MPa matrix}: \text{Sl} = 9.94 - 32.74g\ (r^2 = .80)$$

$$35\ \text{MPa matrix}: \text{Sl} = 15.45 - 49.17g\ (r^2 = .88)$$

These two equations are only valid for g from 0.05 to 0.25. Figs. 5 and 6 confirm the significant effect of coarse aggregate concentration on workability. Workability of sandcrete with coarse aggregate quickly decreases as the aggregate concentration increases. Even a small addition of coarse aggregate ($g = 0.05$ or $G/S = 0.1$) has an important effect. In this case, matrix whose cement/sand ratio is low seems to be more affected.

In a recent method for formulating sandcrete, Chanvillard and Basuyaux [12] use a coefficient k to account for a specific workability, k quantifies granular skeleton expansion due to a layer of cement paste surrounding each sand particles. The higher expansion of the skeleton (with increasing k), the larger the distance between sand particles, the better the workability. For sandcrete with coarse aggregate, the following formulae can be established, for a unit volume:

$$V_s p_s + k^3 (V_s + V_g) = 1$$

where p_s is sand porosity and V_s and V_g are the volume of sand and aggregate, respectively. The first term of this relationship represents volume of cement paste due to porosity and the second term represents volume of aggregate (sand + gravel) and volume of cement paste surrounding aggregate ($k^3 > 1$).

Coefficient k can be computed for each matrix versus the ratio C/(S+G) (Fig. 7) for the different mixes. Fig. 7 shows that k decreases as the total quantity of aggregate (sand + gravel) increases, whatever sandcrete matrix (20 or 35 MPa). This means that when the quantity of aggregates increases, particles are closer. Hence, coefficient k decreases.

Coefficient k evaluated for each mixture can be correlated to slump test (Fig. 8). As expected, workability of sandcrete with coarse aggregate increases as the coefficient k increases.

Thus, workability of sandcrete with limited amount of coarse aggregate may be attributed to a layer of cement paste surrounding each aggregate particle whose thickness can be estimated from coefficient k.

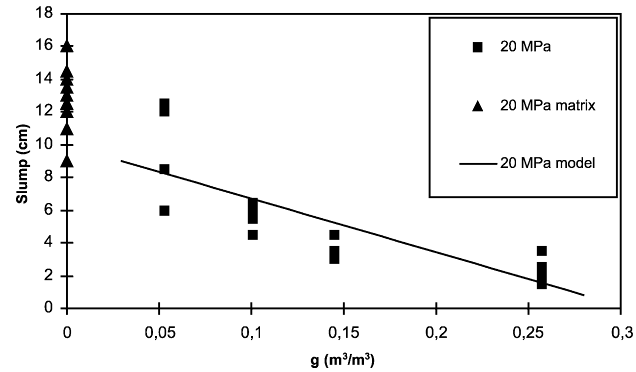

Fig. 5. 20-MPa matrix. Effect of the aggregate concentration (g) on the slump.

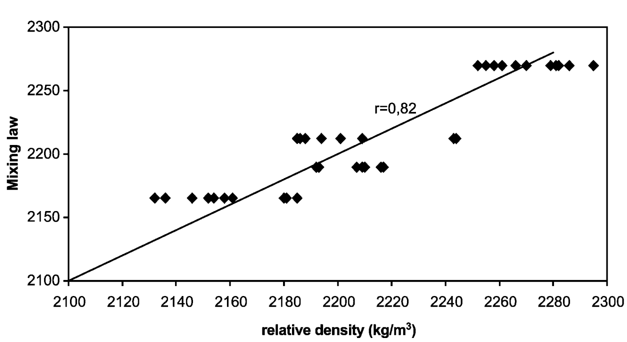

Fig. 4. Correlation between relative density from mixing law and experimental values (solid line for 1:1 ratio).

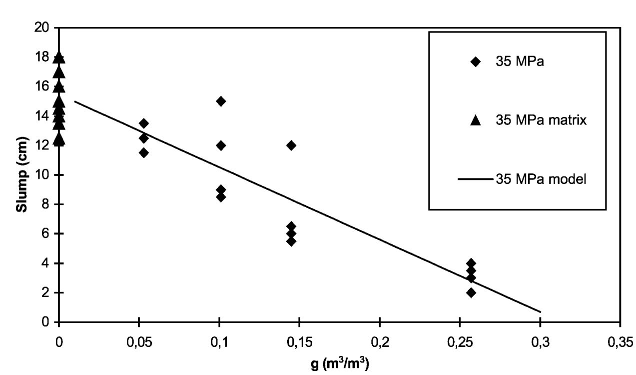

Fig. 6. 35-MPa matrix. Effect of the aggregate concentration (g) on the slump.

The coefficient of granular expansion (k) can be the basic criteria for developing a mix design method for sandcrete with limited amount of coarse aggregate and with a given workability.

4. Conclusions

The main objective of sandcrete with gravel is to obtain with a limited proportion of coarse aggregate, the same mechanical behavior as with traditional concrete. Compressive strength and elastic stiffness are effectively improved by limited addition of coarse aggregate in sandcrete matrix but it is necessary to know which parameters reduce one of the most interesting properties of sandcrete: workability.

An experimental work has been performed to study how aggregate concentration (g), aggregate shape (f) and aggregate size (d) can modify workability of sandcrete.

The following conclusions can be drawn from the present study:

1. Coarse aggregate has no direct effect on the matrix compactness. The increase of the density, which has been observed in the experimental study, simply results from a weight effect.
2. Slump is divided by 3 to 4 for $g \approx 0.25$ (G/S $\approx$ 0.6).
3. A low addition of coarse aggregates ($g = 0.05$) modifies workability. For g varying from 0 to 0.05, matrix with the lowest cement/sand ratio seems to be more sensitive to coarse aggregate addition.
4. The concept that a layer of cement paste surrounding all sand and gravel particles with varying thickness can be used to explain the influence of coarse aggregate content on workability.
5. The coefficient of granular expansion (k) can be a basic criterion for developing practical mixes.

Thus, sandcrete with limited amount of gravel cannot be considered as sandcrete whose mechanical properties (compressive strength and elastic stiffness) are improved by coarse aggregate. This concrete has rheological properties, which require specific mix design to account both compressive strength and workability. The choice of keeping same matrix highlights the very important effect of rigid inclusions scattered in a continuous sandcrete matrix on workability, gives general information for mixture proportioning but cannot provide practical mixture proportioning method. Consequently, a specific experimental study must now be performed in order to analyze how to formulate a workable sandcrete with limited amount of coarse aggregate either with low-cost additives or with a superplasticizers.

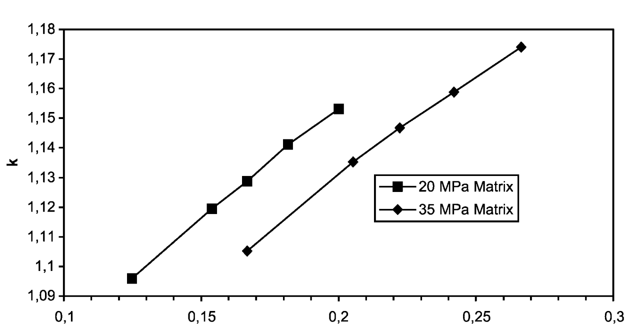

Fig. 7. Coefficient k as a function of C/G+S ratio.

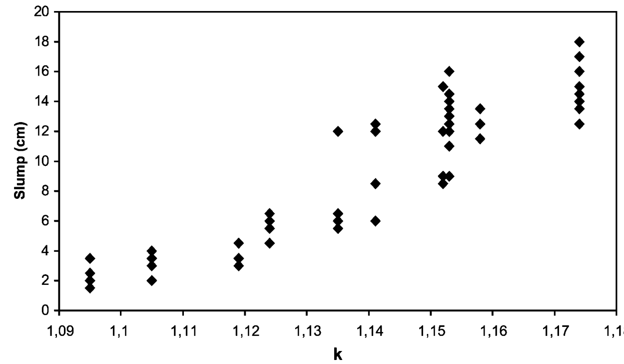

Fig. 8. Slump test experimental results as a function of the coefficient k.

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