The Use of Dredged Marine Sediment in the Formulation of Air–Foam Concrete

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Abstract
Huge quantities of sediments are dredged continuously worldwide. They are generally dumped in landfill areas, with the ensuing costs of dredging operations and in soil-groundwater pollution. The objective of this work is to study the beneficial reuse of dredged sediments in foam mortar and particularly to study the influence of the substitution of sand by dredged sediments. Air–foam concrete is an alternative to ordinary concrete, which presents the advantages of being lightweight and having low thermal conductivity. In this study, the density required ranges from 1200 to 1600 kg/m³. Air foam can be used as concrete building blocks and slabs for load-bearing and non-load-bearing structures. 20 foam mortar mixes were prepared. Sediments were introduced by replacing 15%, 30%, and 50% mass of the sand. The foam percentage was introduced from 0 to 100% volume of mortar. Workability, compressive strength, and flexural strength were measured at 7, 28, and 60 days. The foam-bubble size distribution and the effect of sediments on their stability were also studied. The results show that sediment can be used as a sand alternative for foam concrete. The air–foam concrete’s strength was increased with the substitution of sediment. This increase is linked to the density increase that is caused by the collapse of the air foam during mixing, highlighting a compromise between this material’s weight and strength.
Keywords Dredged sediment · Reuse · Air–foam concrete · Porosity · Lightweight · Compressive strength · Formulation

Statement of Novelty

Very few studies exist on the production of air–foam concrete with dredged marine sediment. We have developed an innovative type of foam concrete reusing dredged sediment as raw material. We analyzed the effect of varying the substitution ratios for sand and sediment and also of varying foam addition. The results demonstrate that sediment can be used as an alternative for sand in foam concrete.

Introduction

The accumulation of sediment in ports and rivers gradually reduces the water depth and becomes a real constraint for transport. Each year, several hundred million tons of sediment are dredged all over the world. These are characterized by high water content and large volume [1]. In France, marine sediments extracted represent 50 million m³ per year, and 6 million m³ are dredged from rivers [2]. The rivers in the Nord-Pas de-Calais region suffer from significant sedimentation due to the low flows and slopes that characterize its hydrographic network.

In the context of an economical and sustainable manner of safe disposal, reusing sediment in building materials is regarded as a prospective strategy [3, 4]. Dredging sediments (fluvial and marine) are mainly composed of fine particles and have specific physical and chemical characteristics that may be similar or different than natural aggregates like contaminants: heavy metals (Hg, As, Cr, Ti, Pb, etc.) and organic pollutants (PCB, PAH, etc.) [5]. Earlier studies have also shown that the organic materials and hazardous pollutants that are present in sediments, such as heavy metals at toxic levels, clay particles, and salt significantly affected the characteristics of final products. These elements hampered cement hydration reactions and reduced structural strength [6, 7]. Applications for the use of sediment soil such as filling materials, solid partition (in particular blocks) and construction of paving blocks have already been reported in the literature [8, 9]. These studies present adding 47.5%, 16% and 14% sediment, resulting in a compressive strength range from 1 to 3 MPa, from 14 to 17 MPa, and from 25 to 34 MPa, respectively. These studies also assess the economic benefit of the products that exposed the amount [10], showing that 30% of river sediment could be viewed as a stable source of clean sandy aggregate. It has also been demonstrated that sieving the sediments to discard their fine fraction is sufficient to recover a valuable substitute to conventional concrete aggregates and sand. Uncontaminated marine dredged sediment was dried, ground and subsequently used in partial cement replacement in the manufacture of mortars and concrete (10%, 20%, and 30%). The mechanical properties of the mortar with 20% cement replaced with sediment were better than those of a mortar made from cement CEM II/A-LL 32.5 containing a proportion of limestone similar to the sediment substitution [11].

Foam concrete is made by introducing air bubbles into fresh mortar. It is also qualified as a type of cellular concrete, lightweight concrete. Density ranges from 300 to 1800 kg/m³ [12–14]. Lightweight concrete with a density higher than 800 kg/m³ is considered as structural concrete in EN 206-1 [15]. Foam concrete is characterized by high workability, low cement content, and low aggregate need. It has also excellent thermal insulation and fire resistance, high airborne sound insulation and good compressive strength [12, 16, 17]. Foam concrete finds application in many areas, thanks to low cost, easy placement of the concrete with simple compaction, and ease of manufacture [18]. Foam concrete can have a high density range from 1200 to 1600 kg/m³ and is commonly used for the production of load-bearing structures [18]. Generally, compressive strength depends on parameters such as W/C ratio, sand/sediment particle size distribution, curing method, cement-sand ratio, and characteristics of additional admixtures [12, 19]. One of the major factors impacting compressive strength is the volume of air foam added, as it defines voids in the hardened foam concrete [20–22]. Three types of foaming agents are used to produce foam concrete, namely synthetic, protein, and organic-based foaming agents. It has been observed that for a protein-based foaming agent, the air voids were smaller and more uniform at higher foam-concrete densities than synthetic-based foaming agents [23]. Batool et al. [24] observed that formulations with a smaller range of air-void size distribution have higher thermal conductivity and lower density whereas a wider distribution of void size resulted in lower thermal conductivity. The performance of air–foam concrete produced with different foaming agents varies greatly because it is related to the stability of the foam, and this may be damaged by drainage, coalescence and ripening [25, 26].

Use of waste materials (bottom ash, waste glass, construction, and demolition waste, clay brick, etc.) as a substitute for cement or aggregate in the production of air–foam concrete is a solution of many environmental issues. It reduces reliance on conventional concrete-making materials while minimizing waste disposal problems [27–31].
### Table 1. Physical properties and chemical compositions

| Components | Sediment | Sand | Cement |
|------------|----------|------|--------|
| SiO₂       | 67.4     | 3.5  | 20.8   |
| Al₂O₃      | 1.7      | 0.9  | 4.9    |
| Fe₂O₃      | 6.6      | 1.7  | 2.2    |
| CaO        | 12.9     | 97.6 | 62.6   |
| MgO        | 1.16     | 0    | 2.8    |
| K₂O        | 1        | 0    | 1.4    |
| Na₂O       | 0.5      | 0    | 0.2    |
| TiO₃       | 0        | 0    | 0.3    |
| P₂O₅       | 0.2      | 0    | 0      |
| SO₃        | 1.2      | 0    | 3.8    |
| Specific density | 2530    | 2798 | 3160   |
| LOI (450 °C/3H) (%) | 4.74  | 1.63 | –      |
| LOI (550 °C/3H) (%) | 6.93  | 1.7  | –      |
| VBS (G/100 g DMS) | 0.2   | 0.08 | –      |
| Surface area BET (m²/kg) | 11.97 | 2.72 | –      |
| Water absorption % | 27    | 0.43 | –      |

There are few studies about air–foam concrete reusing dredged marine sediment. Further study is needed on how to formulate for target physical properties such as density and mechanical strength. We have analyzed the effects of different ratios of substitution of sand by sediment and addition of foam and optimized formulations of air–foam concrete to obtain a density range from 1200 to 1600 kg/m³ and compressive strength range from 3 to 7 MPa.

### Materials and Methods

#### Materials

We used cement CEM I 42.5 and a CEN quartz sand in the mortar formulation. The sediment used was extracted from the port of Dunkirk in France. Raw sediment, which has a high water content, was dried in an oven at 110 °C for 24 h and then passed through a 2 mm sieve.

In the study, sediment, sand and cement were characterized by physical tests described below:

- Water absorption of the sand: EN 1097-6
- Water absorption of sediment: EN 196-3
- Surface area: BET (Brunauer–Emmett–Teller) tests
- Fineness: NF EN ISO 18757 [32] using a Micrometrics Autopore IV 9505
- Organic fraction: XP P94-047 [33]
- Specific density: MICROMETRICS AccuPyc1330 helium pycnometer in compliance with standard NF EN 1097-7 [34].
- Thermogravimetric analysis was performed using nitrogen gas in a controlled environment with the argon flow (75 mL/min) at variable temperatures ranging between 105 and 1100 °C and at an increasing rate of 2 °C/min. Differential thermal analysis was also performed at ambient air and variable temperature (0–1000 °C, at a range of 5 k/min/1000).

The physical and chemical characteristics of the cement, sediment and sand are summarized in Table 1.

The sand had particle size under 2 mm and 7% fine particles. Figure 1 shows the particle size distribution of the sand and sediment. The sand had a broader range than the sediment. Sediments contain many more fine particles between 80 and 315 μm than sand.

The sediment is characterized by thermogravimetric analysis (TGA) presented in Fig. 2. The weight loss observed between 400 and 550 °C due to the combustion of carbon and organic matter (0.81%). A higher weight loss was observed between 550 and 900 °C (7.49%). This weight loss is associated with an endothermic peak due to the decomposition of calcite (CaCO₃) [35].

### Air–Foam Concrete Mixing Protocol

The preparation of air–foam concrete can be divided into three stages:

1. Prepare standardized mortar (standard EN 196-1),
2. Prepare air foam separately as shown in Fig. 3.
3. Add air foam to mortar continuously until homogeneous.

The major difficulty during the incorporation of the air foam into the mortar is obtaining a homogeneous mixture and to not burst air–foam bubbles.

The air foam is prepared as followed:

1. A liquid foaming agent is diluted with water with a dilution coefficient of 25.
2. The diluted foaming agent is transformed to air foam using an air–foam generator.

The generator used in this study was the JFG 200 foam generator from Propump Engineering—UK. It was connected to a compressed air system, which provided an airflow rate of 400 L/min with a pressure around 7 bars. These conditions produced an air foam with a density equal to 0.05 kg/m³.

The foaming agent is made with animal proteins obtained from the hydrolysis of keratin present in the horns or hooves.
of animals. These agents are recognized as being environmentally friendly. Its degree of harmfulness meets regulatory requirements.

The global process is presented in Fig. 4.

The details of the mixing proportions for 1 m$^3$ are indicated Table 1. The sand–cement ratio (S/C) and water–cement ratio (W/C) are respectively 3 and 0.6. The volume percentages added were 0%, 25%, 50%, 75%, and 100% compared to the mortar volume. For each formulation with a fixed foam percentage, the sand was substituted by sediments with a weight percentage equal to 0%, 15%, 30%, and 50% (compared to the sand weight) (Table 2).

As mentioned, the major difficulties during the incorporation of air foam into the mortar are to obtain a homogeneous mixture and not to burst the bubbles. That means that the mixing process is a very important stage of the process. During the mixing, shearing and elongation may modify the morphology of air–foam bubbles and so impact porosity and mechanical performance in air–foam concrete [26]. We did a pre-study to choose the most suitable mixing blade that gave a homogeneous mixture and minimized burst bubbles. Two types of blade were tested with the same protocol. Blade number (2) in Fig. 5 gave better homogeneity and a lower density than the standard blade (1).

The mortar mixing protocol follows the preparation of standardized mortar (standard EN 196-1) [36]:

**Fig. 1** Particle size distribution

**Fig. 2** TGA/DTG curves of raw sediments

**Fig. 3** a JFG 200 foam generator b Foam
To incorporate the air foam into the mortar, a pre-study was done to set the protocol and choose the mixing speeds. The following steps were set for the protocol in order to obtain a homogeneous mixture and to minimize burst bubbles:

1. Mix the foam with the mortar at low speed: 35 rpm for 30 s
2. Stop the mixer and scrape the bottom of the tank
3. Restart the mixer at the same speed (35 rpm) for 30 s
4. Measure the density of the mixture with the Baroïd balance.

**Protocol and Characterization Tests**

The workability of the fresh concrete was measured with a MiniMBE cone. Its dimensions were 150 mm height, 50 mm top diameter, and 100 mm bottom. The diameter of the slump is measured in two directions as shown in Fig. 6.

The density of the fresh mortar and air–foam concrete was measured with a Baroïd balance.

The compressive strength was assessed using three prismatic test samples 4 × 4 × 16 cm (NF EN 196-1 [37]).

We studied pore size distribution by measuring circularity and mean diameter of voids on optical microscope images. Due to the impossibility of capturing a clear image of the foam–mortar in its natural state by using an optical microscope with low magnification, specimens were impregnated with a yellow fluorescent epoxy as shown in Fig. 7.

First, specimens were polished, cleaned, and then impregnated with epoxy. This means that voids are filled with epoxy, which gives high contrast (Fig. 8). Then the images were processed and analyzed with ImageJ software.

The circularity factor (\(F_{\text{circ}}\)) is a function of the perimeter and surface area of each pore, defined as follows.

\[
F_{\text{circ}} = 4\pi \left( \frac{\text{Area}}{\text{Perimeter}^2} \right)
\]  
(1)

When the circularity factor equal to 1, a pore is considered as a perfect circular pore. If the circularity factor is less than 1, it is considered as irregular. After 60-days of curing, a scanner was used to analyze a 400 µm foam-concrete section.

**Porosity accessible to water** (PAW) was measured according to US standard ASTM C642-97 (cubic samples). The samples are kept under vacuum for 24 h in a vacuum bell. They are then immersed in water and kept under vacuum for 48 h. The volume of the sample is then determined by weighing it in air and in water utilizing a dispositive using hydrostatic balloon. To obtain the dry mass, the samples are dried at 105 °C (drying is achieved when the difference in mass obtained between two successive values does not exceed 0.05%).

The PAW is calculated according to the formula:

\[
\text{PAW} (\%) = \frac{M_{\text{sat}} - M_{\text{sec}}}{M_{\text{sat}} - M_{\text{eau}}} \times \rho_{\text{eau}} \times 100
\]  
(2)

The thermal conductivity of foam concrete is measured according to ISO 22007-2:2008 with the hot disk system Fig. 9. Specimens correspond to cubic size 30 mm × 30 mm × 30 mm. They were dried in a 45 °C vacuum until the mass remained unchanged. Values correspond to an average of three specimens and the accuracy is 0.001 W/m/K.

**Results and Interpretation**

**Workability**

As a first step, we studied the workability of the fresh air–foam concrete. Workability of the mortar (formulation without air–foam) and of air–foam concrete were measured using the slump spread diameter obtained with the Mini MBE cone. The method of the Mini MBE cone test is described on the section “Materials and Methods”. The following formulations have been tested:

- With percentage sediment equal to 0%, 15%, 30%, and 50%.
- With percentage volume of air foam equal to 0%, 25%, 50%, 75%, and 100%.

Slump spread diameters of the 20 formulations tested are presented Fig. 10.
Table 2  Mix proportions for 1 m³ of mortar for all formulations tested

| Formulation | Dry density (kg/m³) | Sediment (kg/m³) | Sand (kg/m³) | Cement (kg/m³) | Water (kg/m³) | Foam % | Mortar % |
|-------------|---------------------|------------------|--------------|----------------|---------------|--------|----------|
| M0% S0%     | 2200.0              | 0                | 1758.0       | 585.9          | 351.6         | 0      | 100      |
| M0% S15%    | 2166.0              | 263.7            | 1494.3       | 585.9          | 351.6         | 0      | 100      |
| M0% S30%    | 2138.5              | 527.4            | 1230.6       | 585.9          | 351.6         | 0      | 100      |
| M0% S50%    | 2049.5              | 879.0            | 879.0        | 585.9          | 351.6         | 0      | 100      |
| M25% S0%    | 1466.0              | 0                | 1171.5       | 390.4          | 234.3         | 29.9   | 70       |
| M25% S15%   | 1552.8              | 189.0            | 1071.3       | 420.1          | 252.0         | 29.6   | 70.4     |
| M25% S30%   | 1666.0              | 410.9            | 958.7        | 456.5          | 273.9         | 22.9   | 77.0     |
| M25% S50%   | 1700.0              | 729.1            | 958.7        | 456.5          | 273.9         | 22.9   | 77.0     |
| M50% S0%    | 1383.3              | 0                | 1105.4       | 368.4          | 221.1         | 36.5   | 63.4     |
| M50% S15%   | 1478.0              | 179.9            | 1019.7       | 399.8          | 239.9         | 32.8   | 67.1     |
| M50% S30%   | 1515.0              | 373.6            | 871.8        | 415.1          | 249.1         | 31.1   | 68.8     |
| M50% S50%   | 1528.0              | 655.3            | 655.3        | 436.8          | 262.1         | 30.5   | 69.4     |
| M75% S0%    | 1273.7              | 0                | 1017.8       | 339.2          | 203.5         | 40.9   | 59.0     |
| M75% S15%   | 1350.0              | 164.4            | 931.4        | 365.2          | 219.1         | 38.6   | 61.3     |
| M75% S30%   | 1428.0              | 352.2            | 821.7        | 391.3          | 234.8         | 35.1   | 64.9     |
| M75% S50%   | 1475.0              | 632.6            | 632.6        | 421.7          | 253.0         | 32.9   | 67.0     |
| M100% S0%   | 983.1               | 0                | 785.6        | 261.8          | 157.1         | 46.8   | 53.1     |
| M100% S15%  | 1312.0              | 159.7            | 905.1        | 354.9          | 212.9         | 40.3   | 59.6     |
| M100% S30%  | 1330.0              | 328.0            | 765.3        | 364.4          | 218.6         | 39.5   | 60.4     |
| M100% S50%  | 1372.0              | 588.4            | 588.4        | 392.2          | 235.3         | 37.6   | 62.3     |
Fig. 5 Mixing blades

Fig. 6 The Mini MBE cone

Fig. 7 Principle and steps for image processing
The experimental results shown that slump spread of fresh foam concrete is affected by the quantity of air foam and by the sediment content.

Firstly, slump spread increases with the air–foam percentage. This can be explained because bubbles reduce friction and make sliding easier between particles (reduction of the shear threshold). This seems to be true up to a certain limit. Formulations corresponding to M100% present a slightly increased slump spread and even a decrease (formulations corresponding to S15% and S30%).

Secondly, slump spread increases with the sediment percentage of substitution. The increase of workability due to the incremental sediment substitution can be explained by:

- The specific surface area of sediment;
- The percentage of fine aggregate of sediment being higher than in sand;
- The sediment used being dry, so water, which is supposed to be absorbed by sediment (in the case of dredged sediment) may be free.

We analyzed the results with ANOVA software in order to extrapolate experimental data and to set up a predictive model depending on air–foam percentage and sediment percentage. Figure 11 shows slump spread diameter responses in a ternary graph and Eq. (3) corresponds to the predictive equation:

\[
\text{Diameter of slump spread} = 13.29759 + 0.048860 \times \text{foam\%} + 0.046575 \times \text{sediment\%}
\]  

Equation (3) can be used to evaluate workability for a given sediment and air–foam percentages. In the equation, sediment factor and air–foam factor are positives. That indicates the increase of workability with both parameters (sediment percentage and air–foam percentage), which has been described for the experimental results. Both factors are quite
similar and indicate that sediment percentage and air–foam percentage have a similar effect on workability. These results must be analyzed with the other parameters of the specification, i.e. density and mechanical strength.

According to the slump spread values obtained, there is no need to add any type of plasticizer for the concrete formulations tested at this stage.

Compressive Strength and Density

Our purpose was to optimize formulations for density and compressive strength using sediment substitution and air–foam percentage. According to the specification and the target applications, expected densities must be range from 1000 to 1600 kg/m³ and expected compressive strength must range from 3 to 7 MPa.

Figure 12 shows the compressive strength and density of the formulations without air foam, only with sediment substitution:
- M0%S0%,
- M0%S15%,
- M0%S30%,
- M0%S50%.

Compressive strength and density decreased with incremental sediment substitution.

- The decrease of density with incremental substitution sediment can be explained by the fact that sediment density is lower than sand density (respectively 2.53 and 2.80).
- The decrease of compressive strength with incremental sediment substitution may be explained by the presence of polluting elements like Ni, Cu, and Zn which might have the greatest impact of all mineral pollutants. Their presence strongly lowers the compressive strength and decreases material density. Zn inhibits the hydration of C₃S and C₃A with a more pronounced effect on C₃S. This phenomenon is due to the formation of an amorphous impermeable film around a hydroxide (Zn(OH)₂) that inhibits the hydration process [6, 7].

Figure 13 shows compressive strength and density (experimental results) of all formulations tested:
- With percentage sediment equal to 0%, 15%, 30%, and 50%.
- With percentage volume of air foam equal to 0%, 25%, 50%, 75%, and 100%.

For each formulation with an air–foam percentage given, the incremental sediment substitution causes an increase of compressive strength and density. This trend is not in the line with the previous formulation with air foam and without sediment. For air–foam concrete, sediment bursts bubbles. Thus, density increased and then compressive strength increased. These results show that compressive strength is mainly linked to density.

In Fig. 13 the compressive strength varies from 0.42 to 13.2 MP and density between 1000 and 1700 kg/m³. Target
values for density and compressive strength were obtained for some formulations.

A function modelling the experimental results with ANOVA has been set up, which determines density with formulation parameters:

1. Air–foam percentage,
2. Sediment percentage.

As shown in Eq. (4), sediment percentage has a positive coefficient. This means that incremental sediment percentage increases density. Air–foam percentage has a negative coefficient, which means that incremental addition decreases density. The equation is in line with the previous explanation about the experimental results.

\[
\text{Dry density} = +1598.95 - 4.54098 \times \text{foam\%} + 4.65849 \times \text{sediment\%}
\]  

Equation (4)

To assess the interactive relationships between formulation parameters (foam\%, sediment\%) and the response (dry density), the 2D and 3D surface response and contour plot use Design Expert 10 as shown in Figure 14.

The same approach held for compressive strength. An equation modeling experimental results has been generated with ANOVA. From the equation we estimate compressive strength for a given value of sediment percentage and air–foam percentage.

According to the equation, sediment substitution increases compressive strength whereas air–foam percentage decreases it. These observations confirm what has been observed experimentally. For a given sediment substitution, compressive strength decreases with air foam. For a given air–foam percentage, the compressive strength increases with sediment. Nevertheless, the equation does not take into account the effect of sediment on strength for formulations without air–foam. Indeed, we observed in the experiments for the formulations without air foam that compressive strength decreases with sediment percentage as well as density. Density may be the key factor that affects the compressive strength of air–foam concrete (Fig. 15).

\[
R_c = +9.08326 - (0.095310 \times \text{foam\%}) + (0.11092 \times \text{sediment})
\]  

Equation (5)
ANOVA analysis data for compressive strength are provided in Table 3. This model is characterized by a $R^2$ equal to 0.93 and a predicted factor equal to 0.89. The model’s F-value of 94.44 suggests that the model is reliable. Values of “Prob > F” less than 0.05 indicate model terms are significant. Values greater than 0.10 indicate the model terms are not significant. In this case A (foam percentage) and B (sediment percentage) are significant model terms.

Figure 16 presents experimental results of compressive strength and density for all formulations tested. Compressive strength as a function of density is not represented by a scattered point cloud and appears to draw a single curve. This means that for one density value target, we only have one corresponding compressive strength value. Therefore operators must choose a compromise between compressive strength and density. To obtain a higher compressive strength for a density value target, cement must be added but the material cost will increase. Nevertheless, it is possible to obtain the same pair of values for compressive strength and density with different formulations (different air–foam percentage and sediment percentage). According to the specifications and constraints on site, operators can fix the quantity of sediment to reuse and will adjust the air foam to add in order to obtain the target density and compressive strength. They would obviously add sediment to increase density and compressive strength or add a larger volume of air foam to decrease the density even more.

The optimized air–foam concrete formulations that comply with the specifications (density range from 1200 to 1600 kg/m$^3$ and compressive strength range from 3 to 7 MPa) are identified in the yellow zone plot in Fig. 17. For a fixed sediment percentage, operators can immediately see the air–foam percentage to add to obtain density and compressive strength target.

**Porosity Accessible to Water (PAW)**

PAW is a very important parameter to study durability. It is measured according to the US standard ASTM C642-97 (cubic samples). The procedure is described in “Materials and Methods.”

The results shown in Fig. 18 indicate that for a fixed air–foam percentage (for each set of air–foam percentages), porosity increases with sediment addition. This observation is linked to previous results (density and mechanical strength), which show that sediment has an effect on the air foam.

The porosity of the air–foam concrete is the sum of the internal air voids (air–foam bubbles) and voids in cement paste. Density as a function of PAW is plotted in Fig. 19. Porosity accessible to water is significantly linked to dry density with a linear function. It can be represented by Eq. (6) with regression coefficient $R^2$ equal to 0.873. Using Eq. (6), we can estimate the porosity of air–foam concrete by using density values.

$$\text{PAW} \, (\%) = -36.856 \, d + 2697.6,$$

Fig. 14 The counter plots for dry density, 2D and 3D plot

Fig. 17 The counter plots for dry density, 2D and 3D plot
Fig. 15  Counter plots for compressive strength (MPa): 2D and 3D plot

Table 3  ANOVA analysis for compressive strength

| Source       | Sum of square | Df | Mean square | F-value | F-value | prob > f |
|--------------|---------------|----|-------------|---------|---------|----------|
| Model        | 180.90        | 2  | 90.45       | 94.44   | <0.0001 |          |
| Mousse%      | 113.55        | 1  | 113.55      | 118.52  | <0.0001 |          |
| Sediment%    | 67.35         | 1  | 67.35       | 70.3    | <0.0001 |          |
| Residual     | 12.45         | 13 | 0.96        |         |         |          |
| Cor. total   | 193.36        | 15 |             |         |         |          |

Fig. 16  Compressive strength 28-days vs. dry concrete density

Fig. 17  Over plot of the optimized formulation.  D density.  C.S. compressive strength
where PAW: Porosity accessible to water %; d: Maximum dry density kg/m$^3$.

**Thermal Conductivity**

The cellular structure of foam concrete contributes to a high thermal insulating property with a low thermal conductivity value. As can be seen in Fig. 20, the variation in thermal conductivity variation is similar to that of density.

For formulations without air–foam, the increase of sediment percentage decreases thermal conductivity. For formulations with a fixed air–foam percentage, the increased sediment percentage slightly increases thermal conductivity.

It seems that for a higher percentage of air foam (M75%), thermal conductivity is much more impacted by air–foam than density.

**Microstructure of Foam Concrete**

**Pore Size Distribution of Foam Concrete**

According to the literature, matrix porosity is a key parameter affecting the strength of cement-based materials [38]. However, determining the total air-void content (porosity)...
is not sufficient. Shape, size and distribution of voids may affect the concrete’s strength and durability [39, 40].

In this study, three parameters (diameter, circularity of voids and dry density) were studied to estimate porosity and durability in these materials. We calculated diameter and void circularity as follows:

- For each void, an effective diameter was calculated by measuring the void area and by assuming it as a perfect circle.
- Circularity is a value that compares the void to a perfect circle. A value equal to 1 indicates a perfect circle and a value closer to 0 indicates an elongated shape.

Table 4 shows that for the formulations without sediment (M25% S0%, M50% S0%, M75% S0%) Dmax increases with foam percentage whereas circularity seems to slightly decrease (from 0.91 to 0.85). This increase may be caused by the burst of air–foam bubbles. Contrary to the results for formulations with sediment, circularity increases (from 0.85 to 0.90) and diameter decreases (from 717.29 to 576.46). It is quite common to find that pores with smaller diameter have a better circularity (and pores with higher diameter have lower circularity). This may be due to the phenomenon called coalescence (burst of air–foam bubbles) as shown in Fig. 25.

Figure 21 shows that density decreases with increasing diameter and increases with increasing circularity. We see a high correlation between Dmean and density ($R^2 = 0.99$) and between circularity and density ($R^2 = 0.93$). These observations are confirmed by literature results, which demonstrate the influence of the shape and size of the pores on the density of foam concretes without sediment.

Table 4 shows the relationship between pore morphology (mean diameter) and thermal conductivity. In formulations with sediment, thermal conductivity increases with pore size (mean diameter). These results show that reducing the pore size does not improve thermal insulation. Figure 23 shows that in the case of formulations with sediment, compressive strength and density increase with pore size (mean diameter).
diameter). These results show that sediment burst air–foam bubbles when the mixture was fresh.

Figure 24 shows the pore size distribution of air–foam concrete for the following formulation:

- No sediment (S0%) and with an air–foam percentage equal to 25%, 50%, 75% (M25%S0%, M50%S0%, M75%S0%).
- Sediment with a substitution percentage equal to 15%, 30% and 50% at a fixed air–foam percentage of 75% (M75%S15%, M75%S30% and M75%S50%).

Pore sizes range from 50 to 800 µm.

Therefore, the addition of sediment increases density and pore diameter. For formulations without sediment and a similar density than the formulations with sediment (and a different air–foam percentage), a higher porosity and smaller pore diameter are obtained. This is due to bubbles bursting when the mixture was fresh during the mixing, as shown in Fig. 25.

Conclusion

This experimental study set up foam-concrete formulations using sediment as a substitute for sand. Key physical parameters like workability, density, compressive strength, pore size distribution and thermal conductivity were studied. The following conclusions can be drawn from the results:

- Workability is affected by air–foam addition and by sediment substitution. The effect of sediment substitution may be caused by water absorption kinetics and the sediment’s specific surface area.
- At first, for formulations without sediment, the compressive strength and density of the concrete decreases with air–foam addition. Compressive strength and density (for a fixed air–foam percentage) increases with sediment addition. The addition of sediment has a direct effect on the air–foam bubbles (i.e., bursting) when the mixture is fresh during mixing. That early effect then impacts the porosity in the hardened state.
- The thermal conductivity for a formulation with sediment and with parameters set for this experiment is around 0.5 W/m/K. Thermal conductivity increases with the air–foam addition. Therefore, thermal conductivity is linked to density.
- Air–foam addition increases average pore size diameter and reduces their circularity.
It seems that mechanical properties of foam concrete are not only affected by density but by other pore parameters such as diameter, circularity and space between bubbles. Our future research will refine this work on these effects.

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