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How to use in-situ soils as building materials

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Abstract

Using in-situ soils for building constructions is attractive in the sustainable development because these materials have low embodied energy and present an interesting hygro-thermal behavior. Several researches have been recently carried out to study soil materials. However, the variability of soil characteristics on each construction site makes that the use of an unique construction technique (soil concrete, rammed earth, adobe, …) becomes difficult to satisfy several exigencies of the modern regulations (mechanical, thermal performances, durability and earthquake resistance), and the economic criterion.

This paper introduces firstly a strategy which can facilitate the use of in-situ soils for building constructions. Relevant techniques corresponding to several in-situ soil types are proposed. Then, the application of the proposed approach is showed with a case study on a building project using a soil concrete. Several aspects are investigated: material optimization, architectural design, structural-thermal performances and life cycle analysis.

Keywords: soil material, soil concrete, mechanical characteristics, dynamic characteristics.

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1. Introduction

Local materials are in-situ materials which are directly available on site. They are used by humanity from centuries as earth (rammed earth, adobe, cob,…), stone (dry stone masonry and rubble stone masonry), and wood. The construction techniques using in-situ materials are still widely used today in developing countries, thanks to their lower construction costs in comparing to conventional constructions (such as reinforced concrete or metal structures). The reason is that conventional materials are not always available in these countries and must be imported, that significantly increases the cost. In addition, the labor cost is not expensive, so the use of in-situ materials has a positive social aspect by providing work to local workers.

However, in developed countries, most of these materials were dropped consistently over the past six decades for two main reasons. First, the labor cost in these countries is very important, which is not favorable for the constructions requiring important labor. Then, the current design regulations are established mainly for industrial conventional materials. There are few standards for non-industrial materials due to the lack of scientific knowledge. Nevertheless, the past few years have witnessed a renaissance of local materials in developed countries, mainly due to the urgent demands of sustainable development. Soil material gradually found its place on construction sites because it is taken and manufactured directly on site, which provides low embodied energy [1]; and walls constructed with soil material have an interesting hygro-thermal behavior. From the economic view point, using the in-situ soil as construction material is also interesting for the builder because the fee to evacuate the in-situ soil before the construction is costly (this is the case in France for example).

Several traditional techniques exist today to use soil as construction material: rammed earth, compressed earth blocks, adobes, cob. The main binder in those cases is clay. For new constructions, other hydraulic binders can be added (cement, lime or both) especially when the soil does contain enough clay or the clay type is not adapted for the earth construction technique chosen. The most difficult point in using of in-situ soil as construction material is the variability of soil characteristics on each construction site. So using of an unique construction technique (rammed earth, adobe, …) becomes difficult to satisfy several exigencies of the modern regulations because each soil type is adapted for a construction technique.

The strategy proposed is to create a “repertory” of several soil types and the corresponding adapted technique(s). The soils will be classed following their characteristics: size distribution, clay amount, clay type. And for each soil type, several techniques and several compositions were tried to find the most adapted techniques.

A repertory has been developed in the Research & Development programs of Filiaterre company (France), in collaboration with the research laboratories. A large number of soil types was taken on the construction sites of the Filiaterre company and then studied in laboratories, on several aspects: mechanical, thermal properties, durability, seismic design. For each soil, several techniques were tested and one or two techniques have been selected for the construction. This paper illustrates the using of a soil as an “eco-concrete” for dwellings.

2. The case study

2.1. Puddingstone soil and their presence in Alpes-Maritimes (France)

The puddingstone soil is widely present in the Alpes-Maritimes region (Southern France), so there is a promising perspective for a sector of "puddingstone constructions" in this region. The size distribution of the puddingstone soil is presented in Tab. 1.

Table 1: size distribution of the studied soil

< 0.002 mm	0.002 -0.063 mm	0.063 - 2 mm	> 2 mm
0.5%	2.5%	30%	67%

2.2. *Project "Domaine des Galets"*

The object of this study is a program realized by Filiaterre which uses the in-situ puddingstone soil for the construction. Fig. 1 shows an overview of the project. The main elements include three buildings (for five dwellings) numbered buildings A, B, C whose the first two are identical. They were built in 2013 in Nice City by using the puddingstone concrete. In addition, many secondary elements were also built by using this material, such as: the arches supporting the terraces, garages and retention basin. All these elements are vaulted shape. This paper focuses on the building B which can represent the project. The architectural plans of the building are given in Fig. 2. It includes a Ground-Floor (GF) and the first floor containing a mezzanine. While all the elements of the GF are made of puddingstone concrete, the elements of the first floor are made of wood, with the exception of the facades (Fig. 2).

Fig. 1 : Overview of the project.

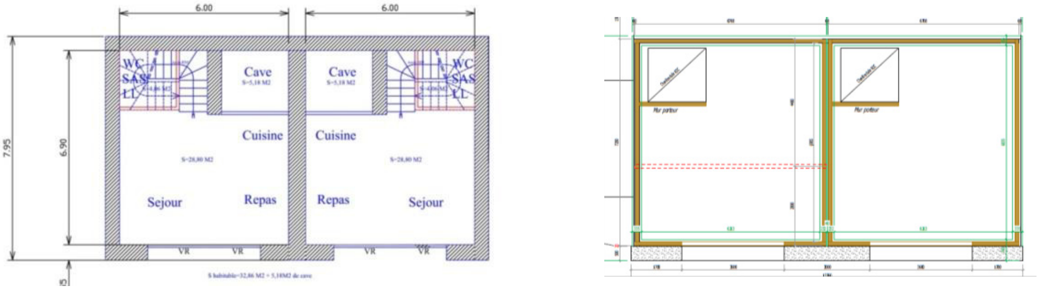

Fig. 2 : Architectural plans of the studied building. Left: Ground-Floor: walls and vaults made by puddingstone concrete. Right: First Floor: wooden walls, excepting the façade.

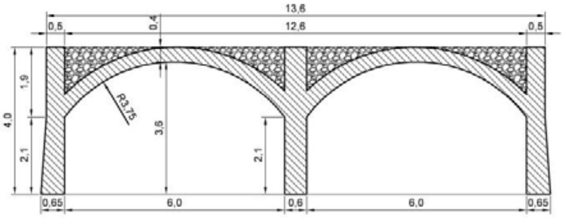

Fig. 3 : Detail of the arch made by puddingstone concrete

A cross section of the vaults of the studied building is shown in Fig. 3. There are two arches of 6 m opening. These arches are supported by three walls: two external (left, right) and one interior. The two external walls are two buttresses with a thickness varying from 0.5 m at the top to 0.65 m at the down. The inner wall has a constant thickness of 0.6 m. The opening of the arches is also the transverse space of the building.

3. Material characteristics

3.1. Formulation of the puddingstone concrete

The presence of clay in the puddingstone soil is low (<0.5%, Tab. 1), a binder should be added to produce the building material. The added binders can be cement, lime or clay. The manufacturing is similar to that of conventional concrete to reduce the production time. An optimization study was performed [2] to investigate different possible compositions for the puddingstone concrete: type and rate of added binders; amount of water; modification of the grain size distribution. Mechanical tests were then carried out in laboratory for each composition; the results were compared to current regulation demands. Finally, the chosen composition for the project “Domaine des Galets” was a cement (CEM II 32.5R) amount of 10% (by weight) and water/cement ratio of 1, which gave the maximum compressive strength.

3.2. Compressive strength

Tests on the standard specimens

In a first step, standard cylindrical specimens (16cm-diameter x 32cm-height) were manufactured to investigate the mechanical properties of the material. To ensure the hypothesis of a homogeneous specimen, gravels bigger than 50 mm have been eliminated by using a 50mm-sieve. Before compression tests, the specimens were surfaced on the upper side by cutting with a specific saw. Then, uniaxial compression tests were carried out to determine the Young's modulus and the compressive strength.

To determine the Young's modulus, a loading-unloading cycle was performed. Three extensometers were used to measure strains in the central part of the specimen (Fig. 4) [3]. Then, the specimen was loaded until the failure to determine the compressive strength. The mean values of compressive strength and Young's modulus were 8.2 ± 0.15 MPa and 13600 ± 300 MPa respectively.

Fig. 4: Compression test on a (16D x 32H) specimen

Fig. 5 : Cutting the puddingstone concrete column

Tests on representative volume element (RVE)

Due to the presence of an important amount of big gravels in the puddingstone soil (up to 80 mm), more important size of the specimen was necessary. This could show influences of the specimen size on the obtained mechanical characteristics.

Two RVE specimens were manufactured: first, a cylindrical column of 30 cm-diameter and 110 cm-height was made. Then, this column was cut in two specimens with a chainsaw (Fig. 5). So these specimens had a slenderness ratio of 1.83. The specimen height was limited to 55 cm due to the maximum height of the press.

Uniaxial compression tests were carried out on VRE specimens by using a Schenck press with a force sensor of 2500 kN (Fig. 6). Three displacement sensors (LVDT) were used to measure strains in the central part of the specimen. The bottom steel plate is movable to facilitate the installation of the specimens since the specimens were heavy and could not bring in hand. The compression tests were controlled in displacement with a speed of 0.01 mm/s.

Fig. 6: Compression test on a (30 cm-D x 55 cm-H) specimen

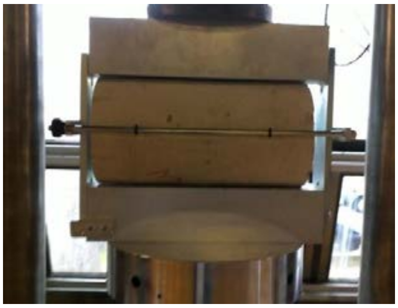

Fig. 7: Splitting test on cylindrical specimen

The mean values of the compressive strength and the Young's modulus of the VRE specimens were of 12 ± 0.57 MPa and 15600 ± 400 MPa, respectively. This shows that in the case of puddingstone concrete, VRE specimens have a compressive strength 1.5 times greater than that of the 16 cm-diameter specimens. Indeed, big gravels play a favorable role, significantly increases the compressive strength of the material. Consequently, mechanical characteristics determined from “small” specimens should be corrected by a coefficient.

The puddingstone concrete at 10% of cement by weight corresponds to 170 kg cement by m^3. For ordinary concretes, the cement amout is 300 - 400 kg/m^3. This explains why the puddingstone concrete’s compressive strength is lower than that of ordinary concretes. However, for residential low rise buildings (1 - 3 stories), the puddingstone concrete’s strength is acceptable.

3.3. Tensile strength

The splitting tests were performed on cylindrical specimens of puddingstone concrete to determine the tensile strength (Fig. 7). The mean tensile strength obtained by splitting tests was of 1.2 ± 0.1MPa.

In this case the puddingstone concrete, the results showed that from the compressive strength of the material, its tensile strength can be estimated according to the expression (1):

$$f_t = 0{,}6 + 0{,}06 f_c \qquad (1)$$

where: f_t and f_c are respectively the tensile and compressive strengths of the material. No testing has been performed on VRE specimen to determine its tensile strength. Therefore, following equation (1), the tensile strength of the VER can be estimated of 1.32MPa.

4. Life cycle analysis (LCA)

4.1. Occupation phase

Dynamic thermal simulations were performed for the studied building. Their details will not be presented here. Thanks to a bioclimatic architecture (thick walls in puddingstone at 1st story to have a good thermal inertia; wooden structure at 2nd story to have a good isolating; wide glazing door in southern façade to have an important solar input), the primary energy consumption of the building during the occupation phase is of 40 kWh/m^2/year, which corresponds to a low consumption category.

4.2. Embodied energy

In the past, the embodied energy (energy necessary for the transformation, transport; from the extraction of primary material to the finished product) of the buildings was usually neglected, because it was low by comparing to the energy consumption during the occupation phase. However, with the rising in thermal performance of the modern buildings (low energy consumption or positive energy), the embodied part becomes considerable in the life cycle of a building.

A LCA investigation was carried out [4]. Two buildings were studied: the first was the building B of the present project and the second was a “virtual” building which had the same architectural plans, but constructed by conventional materials which were currently used in France for individual houses: cement bricks for the walls, reinforced concrete for floor. The thickness of the walls in cement bricks was the current thickness for this type of construction (25cm), however, the thickness of insulation layers of the “conventional” building was calculated in order that the same walls in the two buildings provide the same thermal resistance. This means that two buildings have the same energy consumption for the occupation phase. The life cycle was assumed to be 50 years.

The results showed that, although the actual building (building B) consumed a more important quantity of materials (40%) due to the important thickness of its walls, it had an energy consumption less than 60% of the virtual conventional building. The CO_2 emission of the actual building was also less than 60% of the actual conventional building. The results also showed that the embodied energy of the actual building was at 10% of the total energy consumed during the building’s life cycle. This means that the embodied energy is not negligible for the recent constructions.

5. Assessing the seismic performance

First, the dynamic characteristics of the building were identified by the in-situ measurements. This enables to understand the dynamic behavior of this type of construction and then to validate a numerical model. Then, a numerical model of the building, using the finite element method (FEM) was developed and validated by comparing with experimental results. Based on the numerical model, a simulation of the seismic action was carried out according to the European standard Eurocode 8 [5]. This helps to study the response of the building in case of earthquake and then to evaluate the seismic performance of this type of construction.

5.1. Modeling the building using FEM

In order to study the behavior of the structure under the seismic loading and then to assess its vulnerability, the “Robot Structural Analysis” software was used (Fig. 8). The walls were considered to be embedded in the soil at the foundation surface. Two materials defined in this model were the puddingstone concrete and wood. The puddingstone concrete includes the vaults and walls of the 1st story and the facades of the 2nd story; other elements of the 2nd story were in wood. The characteristics used for these two materials are presented in Tab. 2.

Tab. 2 : Characteristics of the materials used

Characteristics	Puddingstone concrete	Wood
Density (kN/m^3)	22	5.5
Young's modulus (MPa)	15600	9000
Poisson's ratio	0.2	0.03

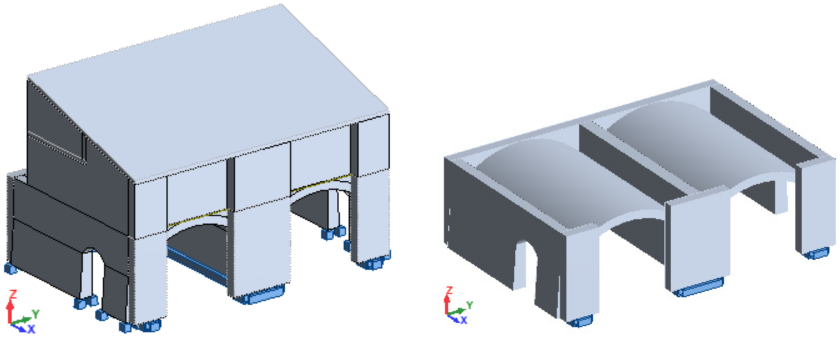

Fig. 8: Numerical model. Up: the entire structure; Bottom: walls and vaults in puddingstone concrete of the 1st story

Following the modal analysis obtained by the model, the first natural frequencies of the structure were: f_1 = 28.08 Hz and f_2 = 36.13 Hz. At the first natural frequency (f_1 = 28.08 Hz), the modal mass in the y-direction (M_y = 76.1%) was dominant compared to modal masses in other directions (M_x = 0% and M_z = 0%). So the first natural frequency corresponds to the first vibrating mode in the y-direction. Also, the second natural frequency corresponds to the first vibrating mode in the x-direction (M_x = 76.46%; M_y = 0% and M_z = 0.2%).

5.2. Validating the numerical model by in-situ vibrational measurements

When the building was in the end of the construction, in-situ vibrational measurements were carried out. The triaxial accelerometers were used (Fig. 9) to measure the acceleration of the building under the “ambient noise” (caused by the micro-earthquakes, ocean waves, …). More details about in-situ vibrational measurements can be seen in [6] or [7] for example.

Fig. 9 : Vibrational measurements by triaxial accelerometers.

From the accelerations recorded in function of time (20 min for each measurement) and after a signal processing, the natural frequencies of the building could be identified. The difference between the two first natural frequencies identified by experiments and that of the numerical model was less than 5%, which showed that the model relevancy was acceptable.

5.3. Assessing the earthquake performance

A seismic loading was simulated in the model according to the demands of Eurocode 8. The ground of the construction project was in class A according to the classification of Eurocode 8. The building is located in a medium seismicity zone (the highest seismicity zone of France Metropolitan). The reference ground acceleration of the class A for this seismicity zone is $a_{gr} = 1.6$ m/s^2. The Eurocode 8 acceleration spectrum was used and the quadratic combination method was adopted to combine the vibrational modes.

The puddingstone concrete's behavior was assumed to be linear-elastic. Therefore, it is necessary to limit the response of the puddingstone concrete elements in the elastic range. The compressive and tensile strengths were obtained by laboratory tests. In this case of the puddingstone concrete, the elastic limit in compression and tension were assumed to be 60% of the strengths, which was often used for conventional concretes.

For all cases of load combinations, the maximum compressive and tensile stresses were of 0.34 and 0.37 MPa, respectively, although the elastic limit in compression and tension were 7.2 and 0.8 MPa, respectively. This corresponds to safety factors of 21 and 2, respectively for the compressive and tensile stresses. Therefore, the earthquake performance of the structure is verified.

6. Conclusions and perspectives

The difficulty of constructions using in-situ materials is that they must satisfy several exigencies of the modern regulations which are established for conventional materials. This paper showed how a recent project using in-situ soil to make a soil concrete which can meet the modern exigencies. The earthquake performance was also studied which consisted of a numerical modelling and in-situ experiments to validate the model. The results showed that the studied building could satisfy seismic demands following Eurocode 8.

The results for LCA showed also that thanks to using an in-situ material, the embodied energy of the studied project was lower than that of a virtual conventional building. This led to a reduction of 60% of energy consumption and CO_2 emission for a life cycle. The embodied energy of the studied building was 10% of the total energy consumption in its life cycle, which was not negligible.

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