# ENVIRONMENTAL-CLAY-BASED CONCRETE

AUTHORS

**Mariette MOEVUS-DORVAUX**
**Lucile COUVREUR**
**Laetitia FONTAINE**
**Romain ANGER**
**Patrice DOAT**
CRAterre / AE&CC / ENSAG, France

**Lionel RONSOUX**
DGCB / ENTPE et MATEIS / INSA Lyon, France

**Yves JORAND**
**Christian OLAGNON**
**Sandrine MAXIMILIEN**
MATEIS / INSA Lyon, France

SUMMARY

The C2D2- Environmental-Clay-based Concrete research program, funded by the French Ministry of Ecology for three years, brought together eight partners: research laboratories, material producers, constructors, technical center and educational experimentation center.
The challenge was to propose innovative solutions to transform raw earth, a complex and highly variable raw material, into genuine environmental clay-based concretes whose implementation and final properties are controlled.
Research has focused on cement concrete and industrial ceramics technology transfer towards a clay-based concrete: the control of granulometry, the use of dispersants and superplasticizers, coagulation techniques to harden the material and enable a rapid removal of the formwork. Exciting developments have been made, like the understanding of the impact of dispersants on the microstructure and final properties of the material.
The economic partners had the ambition to commercialize innovative products. A fluid clay-based concrete was formulated from argilo-calcareous fines derived from aggregate washing; an abundant resource so far unused. This clay-based concrete was recently implemented on two construction sites, produced in a batching plant, transported in a mixer truck, poured and vibrated like a cement concrete. This is one of the pioneer experiences in France for an earth-based concrete.

## INTRODUCTION

Earth is a phase changing natural material, locally available with low grey energy and recyclable. These qualities make it a building material full of future promise.
Physics and mechanics of divided matter are rapidly expanding fields. The rapid onset of nanosciences offers a new lighting on the mechanical, thermal, hygrometric and rheologic behavior of the earth material, especially in the finest physico-chemical scales of clays.In addition to this contribution of theoretical knowledge is a very developed industrial know-how for the implementation of materials which offer many common points with earth, a genuine clay-based concrete. Thus, applied methods to the manufacturing of always more performing cement concretes are transferable to the earth material. On the other hand, the specialized market of earth construction is growing rapidly. Added to this is an increasingly strong societal demand which leads eg clay brick industrial companies to offer raw bricks. Aggregate quarries wish to value their large volumes of quarry coproducts (argilo-calcareous fines). Conditions are then met to establish a national earth industry that relies on extensive scientific and technical bases.
The scientific challenge lies particularly in a better understanding of the physical phenomena occuring during earth material's lifecycle. Water plays a major role in the mechanical and hygrothermal behaviour of raw earth, which is still poorly understood.

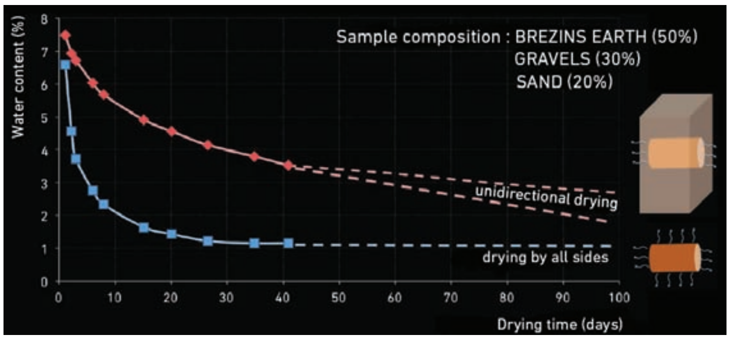


Fig. 1 Drying kinetics of rammed earth samples

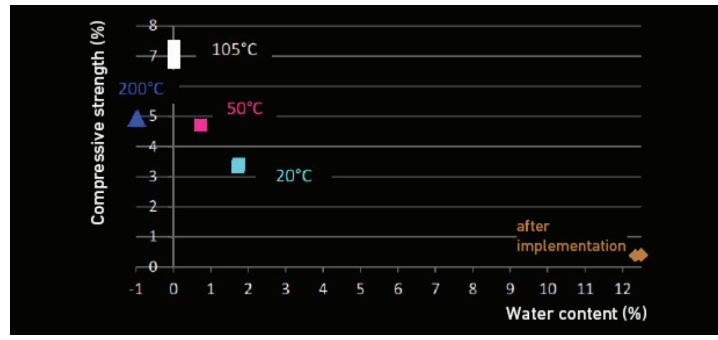


Fig. 2 Evolution of earth of Brezin's compressive strength with residual water content

## 1. STATE OF THE ART OF RAW EARTH CHARACTERISTICS

An assessment of the state of knowledge of the properties of raw earth in construction was made on the basis of scientific papers, test reports and technical publications. This work was presented at the symposium TERRA 2012 and is fully available in the final report of C2D2-BAE project (Moevus, 2014; Moevus et al., 2014). Only reliable data given with the details of characterization processes have been selected. 143 bibliographical references published between 1949 and 2012 were quoted. Few reliable experimental data are available concerning earth material for construction. The studies often involve one single earth type and concentrate in only a few properties. Very few standards are available for earth construction, and most involve masonry in Compressed Earth Bricks (BTC) which are cement stabilized.

Earth has an elasto-plastic behavior. Measurements for the elastic modulus and intrinsic compressive strength are delicate and require experimental precautions which are rarely taken (Morel et al., 2007). The compressive strength is usually comprised between 1 and 5 MPa. Generally, earth has a better water vapor retention capacity compared to common construction materials (concrete, plaster...) (Eckerman et al., 2007). Water contained in soil can evaporate and condense depending on external conditions. This contributes to a building's indoor comfort through hygrometric regulation (Allinson and Hall, 2010). Earth has a water vapor permeability close to that of terracotta and light concretes. (Hall and Allinson, 2009). The thermal conductivity of earth depends mainly on its density and lies in the same range as other building materials of the same density (Laurent, 1987). Earth alone is not an insulating material, but fibered earth can be used as insulation with thermal conductivities approaching 0,1W/m/K with a volumic weight of 500kg/m$^3$. Earth provides a significant thermal inertia that is amplified by the latent energy of water vaporization and condensation inside the material.

Hygrometric, mechanical and thermal properties of earth all depend upon the same main parameters: total porosity, pore size distribution, clay content, clay specific surface and their cation exchange capacity and granular packing. The porous network determines the adsorption-desorption of water and water vapor transport phenomena; the amount of water in the soil corresponds to a suction value that determines the capillary forces within the microstructure. Of this suction depend partially the macroscopic mechanical properties. The presence of water also influences the thermal properties of earth. Currently, the links between the porous network and macroscopic properties are not clearly established: there is no predictive model allowing to relate compressive strength to microstructural parameters.

## 2. INFLUENCE OF WATER ON MECHANICAL AND THERMAL PROPERTIES

In order to fill the data gaps identified by the state of the art, an experimental campaign was conducted. It led to a better understanding of the influence of density, porous network organization and hygrometry on mechanical and thermal properties. Three different natural soils were analyzed (brown earth from Brézins, red earth from Royans and argilo-calcareous fines AC0100 from Carrières du Boulonnais).

### 2.1. DRYING KINETICS OF THE EARTH MATERIAL

The drying kinetics of cylindrical samples (Ø 16cm ; H 32cm) of rammed earth has been measured during 40 days. The samples were placed in a room at ambient temperature and relative humidity. A first group of samples (in blue on Fig.1) could dry freely by all surfaces. A second group (in red) was swathed with cellophane, allowing water to evaporate only by the sample's flat surfaces, in order to reproduce drying conditions of a 32cm thick wall. Water content was measured by mass difference before and after drying at 105°C. Extrapolations until 100 days are proposed on fig.1. This results highlight the time needed for a rammed earth wall to dry: between 4 months and one year to reach an equilibrium state. In the case of rammed earth, relatively few water is needed to implement the material in a humid state (here 8%). The challenge for pouring a fluid clay-based concrete lies in the control of the amount of water needed for its implementation in a liquid state and in the material's ability to harden before complete drying.

### 2.2. HYGROMETRIC BEHAVIOUR OF THE EARTH MATERIAL

Earth absorbs more or less moisture depending on the temperature and relative humidity. Adsorption isotherms indicate, for a given temperature, the water content of the material once the equilibrium state is reached. The adsorption isotherms of the three selected soils were measured from fragments of earth samples implemented through molding. The curves obtained at 20°C are very similar, with a water content of about 0,5% at 20% relative humidity, and about 1% at 70% relative humidity. Much more important variations can be expected under real conditions where temperature and humidity vary at the same time.

### 2.3. MECHANICAL BEHAVIOUR ACCORDING TO HUMIDITY

The influence of the water content upon the mechanical properties was estimated for rammed earth from Brézins samples. Compressive strength have been measured after drying at 20°C, 50°C, 105°C and 200°C. The water content was measured by loss of mass after drying at 105°C. With this definition, the water content is considered to be zero for samples dried at 105°C, even if there is still free water held by

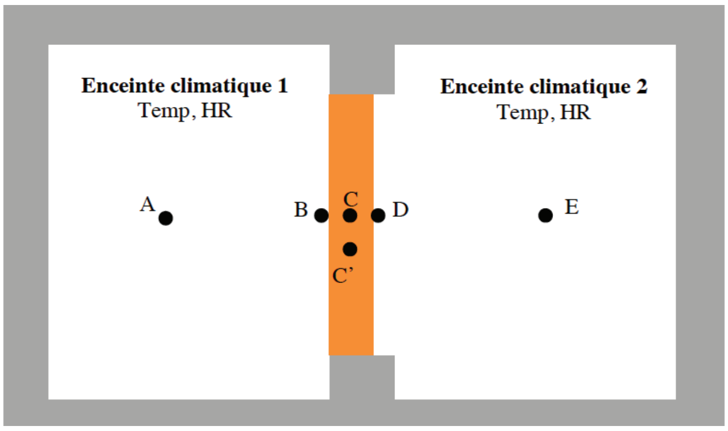


Fig. 3 Position of the wall sample and temperature sensors in the climatic chamber

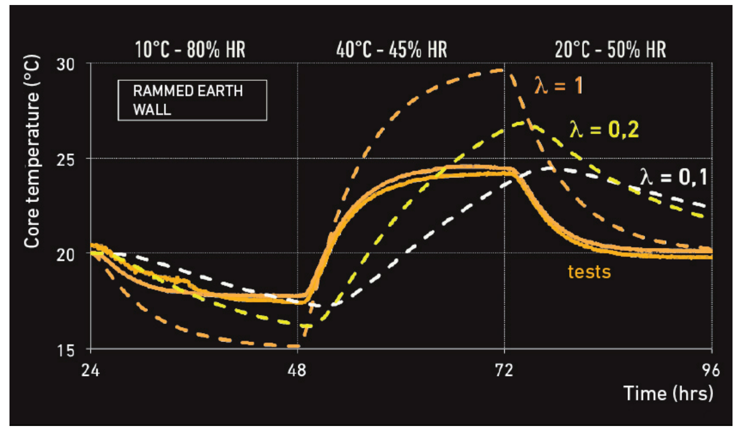


Fig. 4 Temperature measured within the wall (solid line) and simulated (dotted lines)

clays, and it can be negative for more elaborate dryings. At 200°C all types of clays are dehydrated but they are not dehydroxylated (free water is no longer present but water from constitution still is).
The graph below (fig. 2) describes the evolution of compressive strength according to water content The drier the material, the higher the mechanical strength is. It is known that the capillary bridges betwen the particles significantly contribute to the cohesion of soils (Gelard, 2005). The finer these capillary bridges are, the higher the capillary strength and the suction inside the porous material.
The compressive strength measured after a 200°C drying is below the one reached after 105°C drying, but is still equivalent to the strength achieved after a 50°C processing, thus relatively high. This indicates that the capillary strengths are only partly responsible of the internal cohesion of the material. Additional mechanisms to capillary strengths contribute to the mechanical strength such as Van der Waals interactions, friction between the grains which is also sensitive to water content, and probably crystallization of dissolved salts.

### 2.4. SCALE 1 HYGROTHERMAL TESTS

Walls were made by the CARACOL company during the Grains d'Isère Festival in 2011 at Grands Ateliers in Villefontaine. One of them was made of rammed earth from Brézins to measure the hygrothermal behavior of a representative typical rammed wall from the Dauphiné region. Tests were made at the ENTPE. The wall is positioned at the interface between two climate chambers. One chamber has a stable atmosphere (20°C, 50% RH) while the atmosphere in the second chamber is imposed following 4 levels: (20°C, 50% RH) (10°C, 80% RH), (40°C, 45% RH) and (20°C, 50% RH). The temperature and hygrometry are measured within the wall (sensor C on fig.3). A finite elements modeling was performed using data from conductivity and density of the material, without taking into account the influence of water. As shown on fig. 4, the difference between experiment and simulation is important: the temperature variation measured within the wall is 2 times lower than that planned by the calculations. This significant difference may be explained by phase changes of water contained in the material.
The current statutory calculations ignore the effects of water phase changes. Recent investigations have demonstrated the importance of the coupled hygrothermal processes for an accurate assessment of the thermal behavior of earth buildings (Chabriac et al., 2014).

## 3. CASTABLE CLAY-BASED CONCRETES

### 3.1. DISPERSANT EFFECT ON THE VISCOSITY OF CLAY SUSPENSIONS

The effect of various clay dispersants upon the viscosity of natural earth muds was compared. The used dispersants are the HMP (sodium hexametaphosphate), PAA (polyacrylic acid), the Darvan C and Darvan 7 (sodium polymethacrylate). They were selected for their different action modes.
Having studied various dispersants on four very different clay powders, we note that the addition of a dispersant reduces the suspension viscosity and greatly reduces the flow threshold. This thinning effect is observed for the fine fractions of all 3 soils, despite very different clay compositions and other ferric impurities: illite and kaolinite for AC0100 fines, kaolinite for the red earth, and illite and muscovite for the earth from Brézins. This result is rather surprising, since we find that the effects of dispersants are very similar on different suspensions, while their mode of action and/or their molecular weight are very different. This point deserves to be studied in more detail, but in a practical point of view, this indicates that the use of a dispersant on these materials is quite robust.

### 3.2. DISPERSION EFFECT ON THE MICROSTRUCTURE AND ON MECHANICAL PROPERTIES

A practical consequence of clay dispersion is an increase by a factor between 1.5 and 2 of mechanical compressive strength (see fig. 5). This result was verified for several soils and dispersants. A microstructure analysis by mercury porosimetry shows a modification of the porous network in the case where clay is dispersed. Grains (sand, gravels) contained in the earth material are bound together by a clayey phase, which internal cohesion is enhanced as a result of a better organization of clay particles, when using dispersant at the time of implementation.
These results were presented at the symposium TERRA 2012 (Ronsoux et al., 2013) and are the subject of an extended scientific publication (Moevus et al., 2015).

### 3.3. FORMULATION OF A CLAY-BASED CONCRETE USING ARGILO-CALCAREOUS FINES

A clay-based concrete formula has been developped using argilo-calcareous fines which are coproducts from aggregate quarries. This concrete was formulated and produced to manufacture the exposure modules in the Maison des Marais built in 2013 at Saint Omer, Pas de-Calais. The requirements for this material were : a good surface quality and strength, particularly at the edges, aesthetic layers which

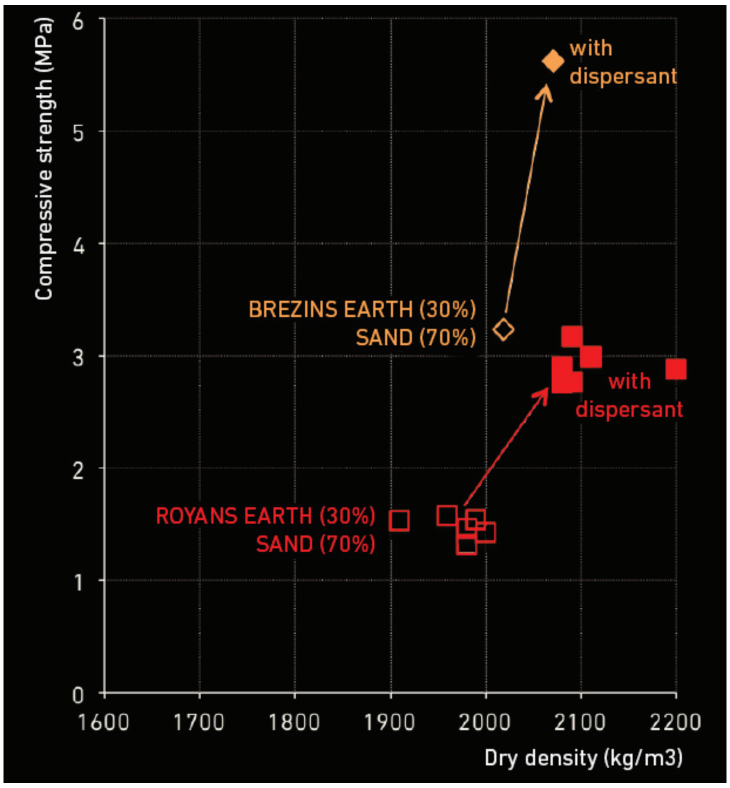


Fig. 5 Dispersing effect on compressive strength of two different soils

present different shades, compressive strength > 1.5MPa, slump class S4, rheologic behaviour stable during 1h30. The formula used for the site is 90kg/m³ of cement, 225kg/m³ of argilo-calcareous fines, 878kg/m³ of sand, 864kg/m³ of gravels, 4.5kg/m³ of dispersant, 217kg/m³ of efficient water. It was decided to add a small amount of cement in order to remove the material from the formwork faster. 60m³ of this clay-based concrete have been produced in a concrete plant, transported by a mixer lorry and poured into formworks with a lifting pump. The material is not subject to cracking during drying. The compressive strength after a 28-day curation and a 7-day drying at 20°C is 3.6MPa, for a density of 2209kg/m³.

An ATEx demand has been obtained upon the CSTB in order to validate the implementation of loadbearing walls with the same product at the Maison intergénérationnelle project in Manom, Moselle. The building has been realised in 2014 (see fig. 6).

Other clay-based concretes have been formulated and implemented for different applications during the 3-year BAE project: slabs with high thermal inertia, renovation sites (recovery of crackings in rammed earth walls and leveling at a rammed earth barn), bearing walls, etc.

## CONCLUSION

Thanks to this research program, significant results have been achieved, paving the way for future research and development works.The state of the art of the characteristics of the raw earth is already used as a basis to write professional rules for earthen construction. The influence of water content on mechanical performance of raw earth was characterized by compressive tests on raw earth samples. The strength increases from the humid state after the implementation up to the dry state. After drying at 200°C all types of clays are dehydrated: the compressive strength level is that of the level achieved after a 50°C processing. Despite of the loss of capillary bridges, compressive strength stays relatively high, because of additional mechanisms contributing to the mechanical strength (friction between the grains, and probably crystallization of dissolved salts). Hygrothermal tests realized on a rammed earth wall placed in a device with two climate chambers highlighted the importance of water phase changes in the hygrothermal behavior of raw earth and of clay-based concretes, which is not takeninto account in the current statutory calculations. The effect of various dispersants upon the viscosity of natural earth muds was compared. Whatever the type of product used the addition of a dispersant reduces the suspension viscosity. The practical consequence of clay dispersion is an increase by a factor 1,5 to 2 of compressive strength. This result was linked with the material's microstructure evolution. In order to substitute the industrialized plasticizers with natural ones, some research was conducted on the use of tannins as dispersant but these molecules are not enough controlled to enable them to be used in construction. This issue warrants more profound analysis.

A fluid clay-based concrete was formulated from argilo-calcareous fines derived from aggregate washing; an abundant resource so far unused. This new environmental clay-based concrete was recently implemented on two construction sites like a cement concrete with current and well controlled means. No cracking occured during drying. This is one of the pioneer experiences of last few years in France for an earthen concretes. Keys of its success: an optimized granulometry, an adapted dispersant and a low percentage of cement (3%) to allow a rapid removal of the formworks. In order to find an alternative to the use of hydraulic binders, the idea of an in situ polymerization / reticulation of clay mud is currently being studied within the framework of a doctoral thesis started in November 2013.

## BIBLIOGRAPHICAL REFERENCES


Allinson, D., Hall, M. (2010). *Hygrothermal analysis of a stabilised rammed earth test building in the UK.* Energy and Buildings.

Chabriac, P-A., Fabbri, A., Morel, J-C., Laurent, J-P., Blanc-Gonnet, J. (2014). *A Procedure to Measure the in-Situ Hygrothermal Behavior of Earth Walls.* Materials.

Eckermann, W., Röhlen, U., Ziegert, C. (2007). *Auswirkungen von Lehmbaustoffen auf das Raumklima.* 0, Venzmer, H.: Europäischer Sanierungskalender 2008 Beuth Verlag.

Gelard, D. (2005). Identification et caractérisation de la cohésion interne du matériau terre dans ses conditions naturelles de conservation. Thèse INPG, Université de Grenoble, 198 p.

Hall, M., Allinson, D. (2009). *Analysis of the hygrothermal functional properties of stabilized rammed earth materials.* Building and Environment.

Laurent, J-P. (1987). *Propriétés thermiques du matériau terre.* Cahiers du CSTB.

Moevus, M., Anger, R., Fontaine, L. (2014). *Hygro-thermo-mechanical properties of earthen materials for construction: a literature review.* Terra 2012, Apr 2012, Lima, Peru.

Moevus, M. (2014). *State of the art of the raw earth characteristics. Final report of BAE project.*

Moevus, M., Jorand, Y., Maximilien, S., Olagnon, C., Anger, R., Fontaine, L., Arnaud, L. (2015). *Earthen construction: an increase of the mechanical strength by optimizing the dispersion of the binder phase.* Materials and structures.

Morel, J-C., P'kla, A., Walker, P. (2007). *Compressive strength testing of compressed earth blocks.* Construction Building Materials.

Ronsoux, L., Moevus, M., Jorand, Y., Maximilien,S., Olagnon, C. et al. (2013). *Poured Earth as concrete.* Terra 2012, Apr 2012, Lima, Peru.

Fig. 6 Implementation of the clay-based concrete developed in Manom's building site