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MECHANICAL AND THERMAL PERFORMANCE OF COB MATERIALS

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Abstract

Soil is the first construction material used by man, widely available and low energy consuming [Quagliarini 2010]. Indeed, about 30% of the current world population lives in earthen structures and, in developing countries, this rate rise to 50%, mostly rural [Houben 2006]. Moreover, earth-based materials allow an improved balance and control of thermal and acoustic indoor climate compared to industrial construction materials. However, most of earthen structures do not reach current requirements in terms of mechanical, thermal or architectural [Aymerich 2012]. To respond to these requirements, a work at scientific and craftsman levels is necessary. Cob is an earth construction type wide-spread in Normandy. In this study, the mechanical behaviour cob is studied. Two different mixes currently used for cob constructions are firstly characterized. In traditional cob, straw is usually used. Straw can act as a thermal insulation material which allows creating pleasant indoor temperatures during unpleasant weather conditions [Bouhicha 2005]. Moreover, adding vegetable fibres can reduce materials thermal conductivity [Khedariet 2005]. An important characteristic for soil-based materials is water content. Usually, in building field, the required water content is the Proctor optimum. However, cob making is done traditionally with higher water content in order to have a plastic mix. In this study, several earth-fibres formulations are developed by varying fibres' content as well as soil mixes. Mechanical and thermal behaviour of these materials is then determined and assessed according to fibres characteristics and content used and soil mixes characteristics. Results show that a higher fibre content lead to a weaker thermal conductivity of cob. This is due to a lower thermal conductivity of straw than soil and, also, to a smaller density of earth-fibre compared to earth only.

Keywords:

Earth construction; Cob; Durable material; Earth-fibre; Bio-material sources

1 INTRODUCTION

Raw earth has been and remains one of the main building materials used by men for thousands of years. Even today, more than a third of the world's inhabitants live in earthen structure. For developing countries, this percentage is 50% of the rural population and at least 20% of the urban and peri-urban population [HOU 06]. In developing countries, earth building appears as an efficient means to build short-term economic habitat for the largest number of inhabitants, the rise of local resource exploitation in building material, training technicians and craftsmen in the building, job creation.

In recent years, there has been a renewed interest in earthen building materials for reasons of restoration and repair of historic and cultural heritage buildings and for use as a low-energy material in Bio-ecological and sustainable architecture [Aymerich 2012]. The renewal of the use of soil as a building material is related to the significant reduction of the environmental impact due to the use of local raw materials and simple manufacturing processes and energy-efficient [Berge 2000; Minke 2000; Houben 2006; Minke 2006; Avrami 2008]. In addition, earth-based materials allow better balance and thermal control and internal acoustic compared with conventional building materials. This is due to their performance in terms of moisture absorption / desorption, heat storage capacity (hydrothermal regulation) and sound transmission properties [Berge 2000; Minke 2000; Minke 2006; Binici et al. 2009; Avrami 2008]. Currently, building owners and architects also choose earth as a building material because of the advantages in terms of aesthetics and sanitary quality of air [Ulrich 2013].

Earth construction was influenced by the geographical situation and the usual cultures. So many construction methods exist: adobe, compressed earth brick, cob and rammed earth. In Normandy, the most common technique is cob which is a mixture of raw earth and vegetable fibres (usually straw). The cob building technique consists in the construction of a massive wall, often bearing, implemented by piling earth-fibre balls in plastic state, possibly by using of formwork, compacted with the fork and the stick then cut to the wall. In order to ease mixing, largest elements are removed. Fibres allow to maintain the cohesion and to limit the shrinkage on drying. Usually, the mix water content is between 10 and 20% in order to obtain a compact paste (which does not crumble). Typical soil used in cob must contain about 30% gravel, 35% sand and 35% silt and clay with a variation of these parameters of more or less 10% [Akinkurolere et al. 2006].

In this study, traditional straw fibre was used. Different cob formulations will be made to evaluate the influence of different parameters (type of soil and fibre content).

2 MATERIALS

2.1 Soils

For this study, three different soils from the Lieusaint quarry were chosen: a sand (soil 1), a red clay (soil 2) and a silt (soil 3) (see fig. 1). Geotechnical properties of soils are presented in tab. 1.

In order to obtain optimum mechanical performance, the material needs to be as dense as possible. Mixtures of different selected soil will be made. According to fines content, soil 1 has the largest percentage of coarse grains. Soil 1 will be used to form the material skeleton. Given their high fines percentage (between 70 and 90%), soils 2 and 3 will act as binders between grains of soil 1. Two mixes will be made: soil 1 with soil 2 (mix A) and soil 1 with soil 3 (mix B). The mass proportion retained is 2/3 of soil 1 and 1/3 of soil 2 or 3. This allows to have two mixes with a similar particle size distribution (fig. 2) which is typical of traditional cob [Akinkurolere et al. 2006]. Indeed, these two mixes have 26% of gravel, 35% of sand and 39% of silt and clay. It should be noted that these curves differ between 0.3 mm and 80 µm.

(a) (b) (c)

Fig. 1: Soils used for the study: sand-soil 1 (a), red clay-soil 2 (b) and silt-soil 3 (c)

Tab. 1: Soils properties.

	Methylene Blue value (g/100g)	Liquid limit (%)	Plastic limit (%)	Plasticity index (%)	Proctor Optimum Moisture Content (%)	Proctor Optimum dry density (kg/m^3)	Fine fraction (%)
Soil 1	0.30	48.9	28.5	20.4	9.5	2034	13.0
Soil 2	0.91	53.5	24.5	29.0	15.5	1770	72.7
Soil 3	0.55	34.1	20.4	13.7	14.0	1827	89.5

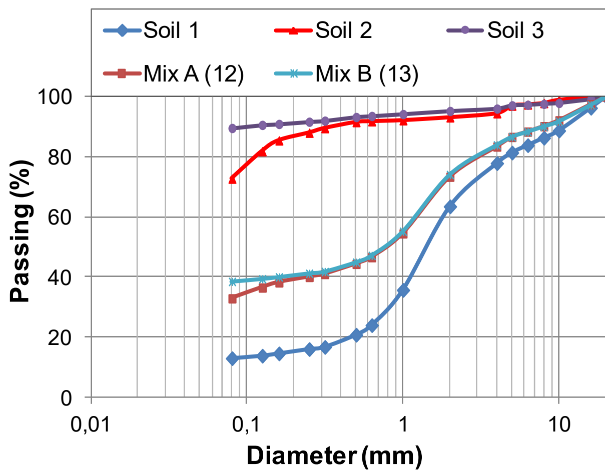

Fig. 2: Particle size distribution of the three soils and the two mixes fibres

The use of vegetables fibres has different advantages for use as reinforcing materials. First, these fibres are widely available and cheap [Akbulut 2007]. Moreover, their use in construction will be new opportunities for agricultural materials. On the other hand, their valorization allows a reduction of the environmental impact compared to mineral or polymeric fibres due to their nature renewable, biodegradable, CO_2 emissions neutrality and requiring little energy to be produced [Baley 2004].

Furthermore, the addition of randomly distributed fibres into a material provides isotropic strength [Yetimoglu 2003; Kumar 2006]. Fibres prevent cracking propagation during traction after initial deformation [Michael 2000]. Increasing fibre content allows to reduce cracks amount caused by shrinkage and to raise hydraulic conductivity of compacted soil [Miller 2004; Tang 2010].

As traditional cob, straw will be used in this study. Straw comes from Laulne (Manche). Straw properties are presented in tab. 2. Variability of straw length is explained by its agricultural development but, also, its industrial processing and the harvest method.

Tab.2: Characteristics of used straw fibres.

Diameter (mm)	Density (g/cm^3)	Length (cm)	Initial water content (%)
1-4	1.182 ± 0.073	15-50	8.4

An important characteristic of vegetable fibres is the water absorption coefficient. Indeed, this characteristic will influence, on one hand, the mix in the fresh state (absorption of available water) and, in the other hand, the long term behaviour (change in fibre volume, fibres/soil interface modification). The water absorption coefficient was determined by fibres immersion of in water during several periods (1 minute, 5 minutes, 15 minutes, 1 hour, 4 hours, 24 hours and 48 hours). After this, fibres were spun with a centrifuge at a speed of 500 rounds per minute for 15 seconds. Results show that water absorption coefficient is high for straw (see fig.3). Indeed, absorption mean value at 24 hours is 309% (each value is the average of 6 samples).

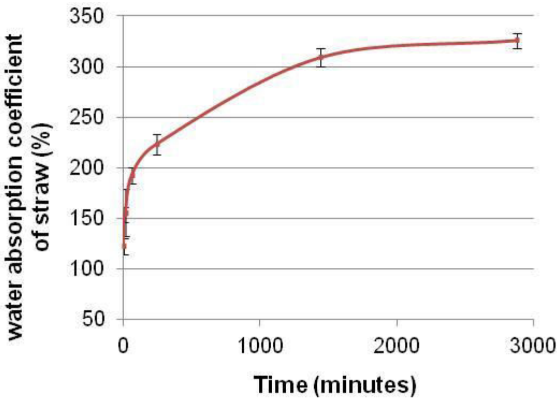

Fig. 3: Fibre water absorption coefficient through immersion time

2.2 Formulations and samples preparation

Two mixes A and B were used in this study. In order to study the influence of fibre, several mass fibre content was used: 0%, 0.5%, 1% and 2% for mechanical resistance; 0%, 1% and 2% for thermal conductivity. The straw length used was 5 cm due to samples size. Thus, fibres were cut to the required length, added randomly and mixed until getting a homogeneous composite. According to usual method, the water content used (18% for mix A and 16% for mix B) is 6% higher than mixtures Proctor optimum contents (between 11.7 % and 12.1 % for mix A, between 9.6 % and 10.2 % for mix B). All samples were stored at 20±2°C and 50±5% relative humidity. Samples were removed from the mould after 2 days to give to the sample a sufficient initial strength to stand alone. Initial mass (after manufacture) and mass after unmolding were measured in order to know the water content over time.

3 METHODS

3.1 Mechanical strength

Samples used for bending strength were 70mm x 70mm x 280mm prismatic samples. Broken samples were, then, used for unconfined compressive strength test. Mechanical strengths were obtained using a testing machine IGM with a capacity of 50 kN in accordance with AFNOR **[NF EN 12390-3]** (speed of 0.05KN/s for compressive test) and AFNOR **[NF-EN-12390-5]** (speed of 0.3 mm/min for bending test) [Magniont 210]. Samples were tested when the mix water content was below 1.5 %.

3.2 Thermal conductivity

Concerning thermal conductivity, transitional method is often used for heterogeneous materials with high moisture content. For this method, a heat source is installed in soil and the soil temperature variations are stored according time. As this method requires a short measurement time, change of the structure over time can be negligible. The hot -wire method is one of the most commonly used for measuring the thermal conductivity of unsaturated soil [Tang 2005].

In this study, KD2 Pro device (Decagon Devices, INC) was used with TR-1 sensor. The standard used was **[*ASTM* D 5334-08]**. Measurements were made on a cylindrical sample with a diameter of 152 mm and a high of 152 mm. For each sample, the experimental protocol consists to:

- Drill 9 holes of 2.4 mm diameter and 100 mm depth (sensor dimensions) on one side of the sample (fig. 4). According to the standard **[ASTM D 5334-08],** the sample should have a cylindrical shape of which diameter should be at least 10 times greater than thermal sensor diameter and length at least 20% greater than the probe length. In this study, distance between holes is 30 mm and the sample height is 152 mm which satisfy standard criteria. Using 9 holes allows to determine homogeneity of the sample.

- Install the sensor in the sample: before inserting the thermal sensor, a thermal paste is used to coat the sensor surface in order to improve the contact sensor/sample. Measurements will be made after inserting the thermal sensor inside the sample trough the pre-drilled hole. It is necessary to ensure that the sensor is fully inserted.

- Measure: after sensor installation, the measurement begins. The thermal conductivity is displayed directly on the device screen after 5 minutes of measurement.

- Repeat on 9 different points. This allows to have an average value on the whole sample for each water content.

- Vary the samples water content. For this, samples are dry during one day and put in an air-tight container during 2 days to homogenize the sample. Therefore, a minimum of 3 days is needed between each water content measurement. The water content was controlled by weighting the mass of the sample regularly.

Fig. 4: Device for measuring thermal conductivity

4 RESULTS AND DISCUSSION

4.1 Cob mechanical strength

Fibre role in compressive strength

Figure 5 shows the stress-strain curve of mix B obtained with several fibre contents.

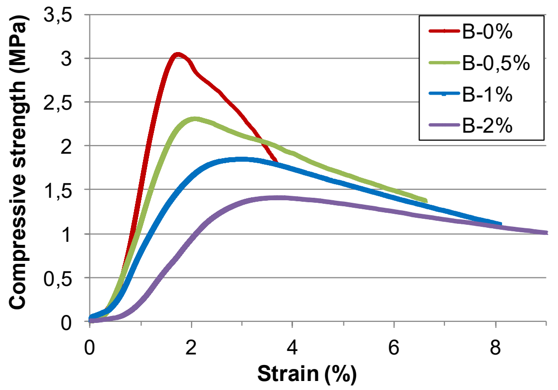

Fig. 5: Stress-strain curves of mix B with various fibre contents.

As the study on earthen concrete done by [Hibouche 2013], the stress-strain curve presents globally 4 distinct domains:

- A first domain near the point of origin which has a concave shape characteristic of the porous materials. This is due to two factors: contact homogeneity between sample and loading device; closure of micro-cracks naturally present in the sample.
- A second domain where the slope of the stress-strain curve reach its maximum. This corresponds to an approximate deformation of 1.5%. This domain is used to establish the Young modulus. It has to be noted that this is a module measured in large deformations.
- A third domain corresponding to material plasticisation which is characterised by a stress-strain slope which continuously softened up to the maximum stress value corresponding to the simple compressive strength.
- A fourth domain, known as the post-peak domain of resistance, which corresponds to the material behaviour after rupture. It has to be noted that rupture is ductile for mixes with fibres, which confirms that straw fibres maintain some post-rupture cohesion.

Compressive strength results of mixes A and B with different fibre content are presented in figure 6. Results show that compressive strength decreases as fibre content raise for both mixtures. This was also observed in previous studies [Bouhicha 2005; Avrami 2008; Quagliarini 2010; Piattoni 2011]. According to Quadrini *et al*.[Quagliarini 2010], straw is weakly adherent to the earth matrix. This explains that, at the beginning of loading, straw can slide and have no positive effect on compressive strength. Moreover, a fibre addition will decrease the mix density and, thus, reduce the compressive strength.

Concerning mix B, an addition of 1% fibre to the soil leads to a decrease of strength about 33% and 2% leads to a decrease about 53%. Concerning mix A, the decrease is about 7% for 1% straw and 20% for 2% (tab. 3). Under a fibre content of 2%, mix B has a better compressive strength than Mix A. Previous studies on earth mixes with straw found that, for a fibre content of 0.5%, the compressive strength is between 2 and 2.5 MPa [Houben 1990], [Binici 2005], [Bouhicha 2005] [Quagliarini 2010], So, values obtained for mix A and B are similar to these values.

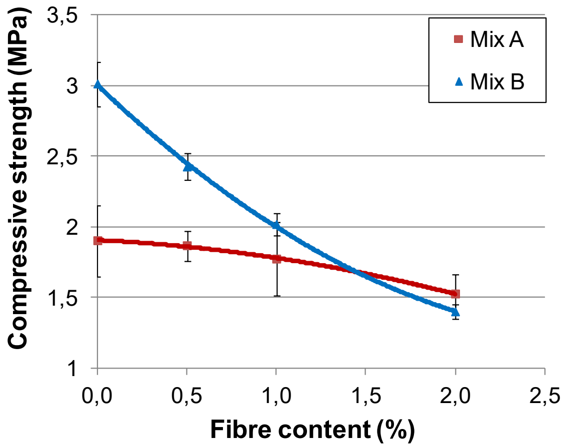

Fig. 6: Compressive strength of the two mixes with various fibre content.

Tab. 3: Compressive strength values of the two mixes with various fibre content.

Fibre content (%)	Compressive strength of mix B (Mpa)	Compressive strength of mix A (Mpa)
0	3.01 ± 0.16	1.90 ± 0.25
0.5	2.42 ± 0.09	1.86 ± 0.11
1	2.02 ± 0.08	1.77 ± 0.25
2	1.40 ± 0.05	1.52 ± 0.13

Fibre role in bending strength

Bending tests were carried out when samples mass was stable. It will be assume that the displacement is representative of the sample maximum deflection. Thus, the bending frame and the specimen crushing are neglected. During tests, it has been observed that cob mix (soil mix with fibre) is more deformed than soil mix and that, after breaking at 70% F_{max}, cob mix is still in a single piece whereas soil mix breaks in two pieces.

Bending strength results of 7 × 7 × 28 cm samples are presented in figure 7. Results show that mix B has a better bending behaviour than mix A for all fibre contents tested. This is due to a higher density for mix B and to the mix A higher Methylene Blue which can lead to more shrinkage and small cracks. According to previous studies, presence of reinforcing fibres can improve [Ghavami 1999; Bouhicha 2005; Binici 2005] or reduce [Avrami 2008; Piattoni 2011] the bending strength of soil. Results from Bouhicha (2005) can be explained by the use of longer fibres (10-20cm) for the same samples which lead to an oriented optimal direction. For mix A and B, it is clear that a fibre addition leads to a bending strength decrease of mixes as for [Avrami 2008] and [Piattoni 2011]. Without fibre, bending strength of mixture B is 0.58 ± 0.03 MPa, this value decreases 38% to 0.36 ± 0.01 MPa with an addition of 2% of fibre. An addition of 2% of fibre to mixture A reduces the bending strength about 26% from 0.38 ± 0.06 MPa to 0.28 ± 0.03MPa.

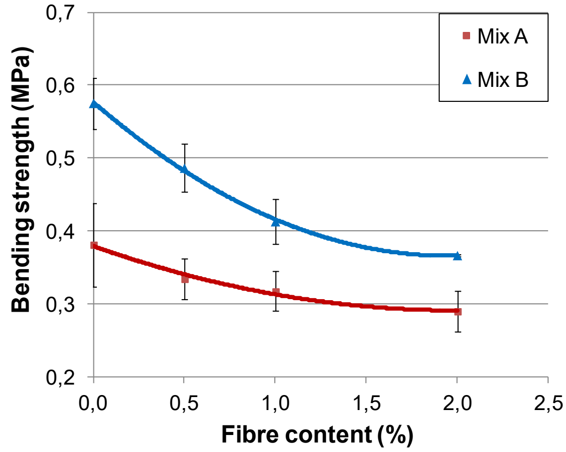

Fig. 7: Bending strength of the two mixes with various fibre content.

4.2 Thermal conductivity

Results for thermal conductivity are presented in figure 8 and 9. These results show that thermal conductivity is linked to water content as found in previous studies [Tang 2005, Hibouche 2013], the thermal conductivity decreases during drying. This can be explained by the fact that water evaporates and is replaced by air which has a lower thermal conductivity than water 0.025 ($W.m^{-1}.K^{-1}$) instead of 0.6 ($W.m^{-1}.K^{-1}$). However, it has to be noted that, above a water content of around 6%, the thermal conductivity decrease is lower. This can be due to shrinkage which increases slightly the sample dry density. This lead to a competition between two phenomena which have opposable effect on thermal conductivity.

Moreover, results show that a higher fibre content leads to a lower thermal conductivity as seen by [Al Rim et al. 1999], [Ledhem et al. 2000] and [Khedari 2005]. Indeed, straw fibres have a thermal conductivity between 0.055 and 0.065 $W.m^{-1}.K^{-1}$ [Sutton 2011] compared to soil thermal conductivity. Figure 10 shows the evolution of thermal conductivity at the equilibrium (in storage conditions) according to dry density of the two mixes. An addition of fibre introduces an additional porosity and, thus, leads to a lower dry density of the soil/fibre mix. Results show that this porosity lowers thermal conductivity as seen by [Laurent 2014]. Values obtained for mix A (0.72 ± 0.08 $W.m^{-1}.K^{-1}$ with a density of 1560 kg/m^3) and for mix B (0.91 ± 0.07 $W.m^{-1}.K^{-1}$ with a density of 1580 kg/m^3) with 2% fibre content is similar to characteristics observed in a 19th century cob house (0.76 ± 0.12 $W.m^{-1}.K^{-1}$ with a density of 1660 kg/m^3) [Laurent 2014].

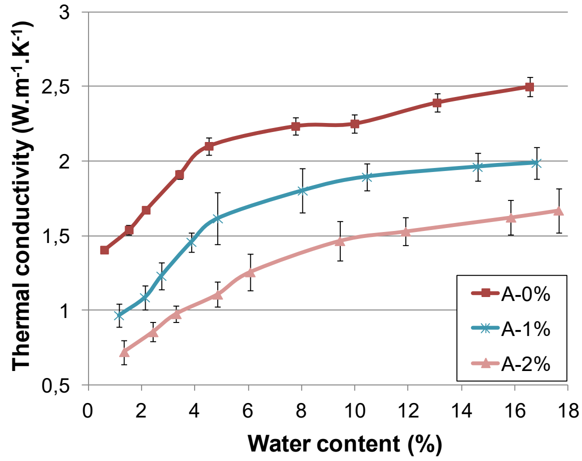

Fig. 8: Thermal conductivity changes of mix A with various fibre content according to the water content.

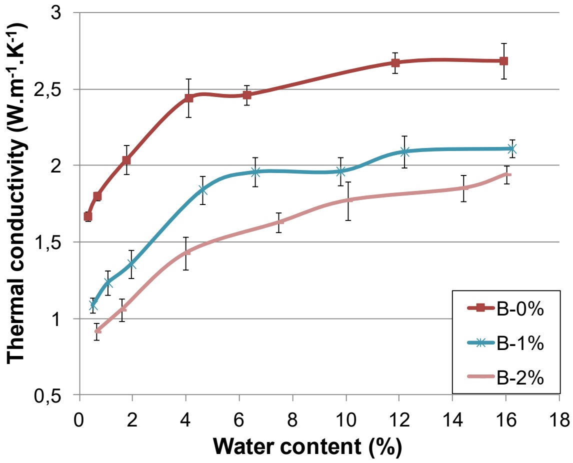

Fig. 9: Thermal conductivity changes of mix B with various fibre content according to the water content.

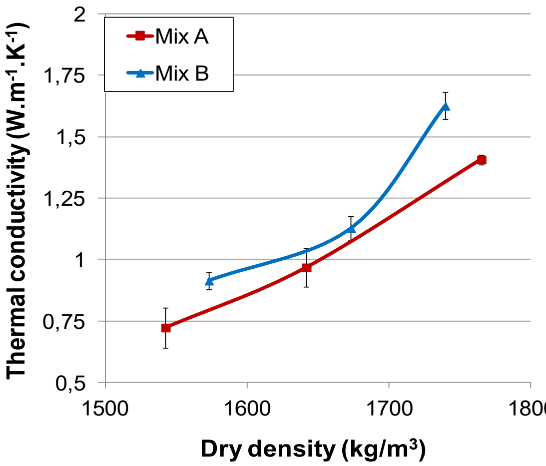

Fig. 10: Thermal conductivity of the two mixes with various fibre content according to dry density.

5 CONCLUSIONS AND PERSPECTIVES

In this study, the mechanical and thermal behaviour of two soil mixes with various fibre content was presented. A length of 5 cm was used for straw fibre due to samples size. The water content used was 6% above the optimal Proctor water content as usually used in construction site. After 2 days from the manufacture day, samples can be unmould without bending. The objective of 2 days of storage is to give the sample an initial resistance sufficient to stand alone without mould. All samples were then stored at 20 ± 2 ° C and 50 ± 5% relative humidity. Mechanical tests were carried out when the sample water content was stable. Results obtained show that:

- An addition of straw fibre reduces the compressive and bending strength of the material. It has to be noted that the fracture is ductile for fibre-reinforced mixes. This highlights the straw fibres effect which maintains a post-fracture cohesion. Therefore, fibres improve material toughness by helping to prevent rapid propagation of fracture crack of the earth matrix.
- Thermal conductivity decreases when fibre content increase. This is due to the lower density of the material and to the low conductivity of fibre.

In order to lower the thermal conductivity of cob, several studies show that the use of hydraulic binders can improve λ between 0.1 and 0.3 $W.m^{-1}.K^{-1}$ and allow a decrease of λ during the curing time [El Rawi 1997; Laurent 2014; Wang 2016]. Therefore, the use of hydraulic binders can be a solution to improve thermal conductivity and mechanical strength of cob.

This study has focused on the mechanical strength and the thermal behaviour of cob. Further tests such as water vapour permeation, water absorption and desorption will be studied to evaluate the influence of water on the behaviour of the cob.

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