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RE-USE OF QUARRY FINES FOR THE PRODUCTION OF BLOCKS

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Abstract
The clayey quarry fines (QF), coming from aggregate washing processes, are mixed with hemp straw (HS) to make non-bearing blocks. This study aims to obtain satisfying mechanical performances with interesting comfort characteristics by having blocks easy to handle and to manufacture. The study shows that mixes with only quarry fines and hemp straw give low mechanical performances. To enhance these results, lime and a superplasticizer are added in the mix design. By keeping a major proportion of quarry fines, the obtained mix offers mechanical strengths similar to performances of market products (gypsum blocks, cellular concrete blocks) and having interesting thermal and acoustic characteristics.

Keywords:
Quarry fines, Hemp straw, Lime, Superplasticizer, Block, Mechanical strength.

1 INTRODUCTION

In some quarries, the production and mining of aggregates includes a washing phase. At the end of the process, the washing sludge has fine concentrations varying between 150 and 750 grams per liter [Brun 1988] and has to be stored according to environmental laws for nature protection. Settling basins receive this sludge.

The washing sludge of aggregates (or quarry fines) are presently poorly re-used and need large storage capacity. Underground barriers for drinking water [De Los Cobos 1994], extruded products with cement [Brun 1988] or expandable clay [Cresswell 2007] represent some ways of re-use. Physical characteristics of quarry fines are suitable for a use in civil engineering. Through the ages, clayey earth has been used as main component of building products. Two-thirds of the worldwide population live in homes made with unfired earth. Many studies on compressed earth bricks [Hakimi 1996], [Walker 1997], [Ngowi 1997], [Venkatarama 2002], [Pkla 2003], [Kouakou 2009] adobe bricks [Quagliarini 2010], adobe walls [Hall 2004], [Jayasinghe 2007], [Bui 2009], [Venkatarama 2010] or earth-straw mixes [Prabakar 2002], [Kumar 2006], [Segetin 2007], [Santhi 2009], [Mohamed 2013] give mechanical and thermal characteristics of products made with unfired earth, stabilized or unstabilized. Unfired earth in building products is relevant for the environment and useful to reduce energy consumption and greenhouse gas emissions.

In this framework and to comply with new regulations, more materials, such as vegetable wools, animal wools or hemp concrete, have come to the building market. For twenty years, hemp concrete has been the subject of several research projects [Cerezo 2005], [Elfordy 2008], [De Bruijn 2009], [Mounanga 2009], [Nguyen 2010], [Gourlay 2011], [Glouannec 2011], [Arnaud 2012].This material contains a mix of hydraulic binders, including mainly lime, and a co-product of hemp production: hemp straw. Hemp concrete has a low dry density (350 to 900 kg/m^3) and is used as a non-bearing product for wall partition or for filling of building framing. With mechanical performances of lime and the multi-scale porosity of hemp straw, hemp concrete has mechanical characteristics up to 2 MPa in compression and an interesting hygrothermal behavior with a thermal conductivity comprised between 0.1 and 0.21 W.m^{-1}.K^{-1}. Several manufacturing techniques have been developed using hemp concrete, such as the in-situ spraying technique or the precasting of building blocks.

Moreover, in France, the use of pozzolanic lime coming from southern Europe increases the energy balance of hemp concrete. More generally, the transport is an important cause of bad energy balance for raw materials. Another cause is the energy used for production especially for materials which include binders such as cement or lime.

In this research work, quarry fines have been chosen to offer an alternative to lime. This choice allows an association between a vegetable co-product with interesting hygrothermal behavior and a clayey binder with capacity of hygrothermal control and natural thermal inertia.

This work aims to study the mechanical behavior of mixes which include quarry fines and hemp straw to produce non-bearing blocks. At laboratory scale, manufacturing constraints observed at a semi-industrial unit for making blocks have been considered. In mechanical and comfort domains, the long-term performances have been measured on laboratory samples and blocks.

2 MATERIALS

2.1 Washing aggregates fines

The quarry fines (QF) come from a limestone quarry located at Ferques in the north of France. These quarry fines are generated by the washing process necessary to obtain satisfying characteristics of aggregates according to the standard for concrete production. The average physicochemical characteristics of QF are shown in Tab. 1. QF contain a major part of limestone (62%). Clay minerals include kaolinite (12%) and illite (7%). The quarry fines are defined as Ap (low plastic clay) according to the USCS classification with a plastic index of 11% and liquid limit of 33%. At the Proctor optimum, the water content is 14% and the optimum dry density is 1860 kg/m^3.

Tab 1: Physicochemical characteristics of quarry fines.

Average mineral composition	
Limestone	62%
Kaolinite	12%
Illite	7%
Quartz	11%
Goethite	3%
Dolomite	5%
Granular distribution	
Clayey part (particle diameter < 2 µm)	17.2 %
Silty part (2 µm < part. dia. < 75 µm)	81.3 %
Sandy part (75 µm < part. dia. < 4.75 mm)	1.5 %

2.2 Hemp straw

For this study, hemp straw comes from the west of France and is usually used for sprayed hemp concrete. The granular distribution, measured by image study is shown in Fig. 1.

2.3 Lime

The chosen lime is a mix of air lime (75%), hydraulic lime (15%) and pozzolans (10%). This mixed lime (L) has been developed for the sprayed hemp concrete.

2.4 Superplasticizer

The superplasticizer has to reduce water quantity of the clay grout while keeping the consistency wished for the mix without additive (only QF + HS). In this research work, a carboxylate has been chosen with a dry extract of 30,3%. The ratio dry extract of superplasticizer / binder has been fixed to 1.3% for optimal flow.

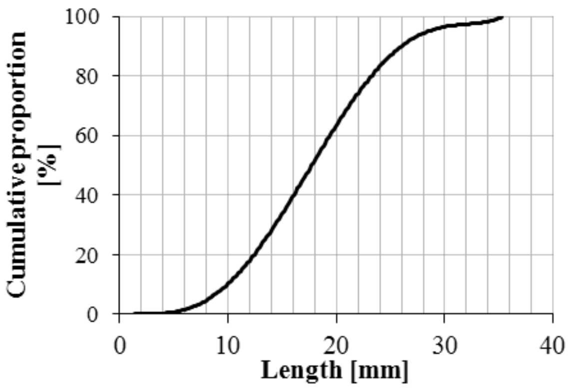

Fig. 1: Granular distribution of hemp straw.

3 EXPERIMENTAL PROTOCOL

3.1 Preparation

Laboratory samples and blocks are manufactured in a laboratory according to the manufacturing steps of an industrial site: mixing, molding, compression, unmolding and storage. The industrial process includes a mixer with a worm gear, a press with a vibration device for shaping the block, and a compressive tunnel for maintaining the matter.

The manufacturing parameters such as incorporation sequence of constituents during the mixing time have been fixed in laboratory considering industrial equipment.

For samples, a planetary concrete mixer is used. First, all the water content is put in with possibly the liquid superplasticizer. Then, the quarry fines are added, with possibly the lime, according to the mix. To homogenize the matter, the mineral part is introduced progressively to avoid the formation of little clayey balls weakly hydrated in the soil grout. This incorporation order is preferable to a first step of homogenization of dry elements followed by an incorporation of water because the soil grout is heterogeneous. The mixing time is two minutes. Finally, hemp straw is introduced progressively in the soil grout for one minute in order to obtain a homogenous matter.

3.2 Key points of mix design

The mix design is based on the ratio binder/aggregate (B/A), the ratio water/binder (W/B), aggregate proportion (kg/m^3) and final dry density (kg/m^3). The term "binder" includes the quarry fines and, according to some mixes, lime. The term "aggregate" corresponds to hemp straw. In this paper, the references of the mixes contain the ratio B/A, the ratio W/B then eventually, the lime proportion that replace the quarry fines and SP for the mixes with admixture. For example, the mix "5507L30SP" means a ratio B/A of 5.5, a ratio W/B of 0.7, a lime proportion of 30% in the binder part and the presence of superplasticizer. The wished mix has to be sufficiently fluid for a correct filling and to have satisfying mechanical performances. Several mixes have been studied with the aim of understanding the influence of the different components. The mixes are shown in Tab. 2. The dry density has been fixed to 850 kg/m^3 in order to obtain a maximum mass of block of 20 kg to easily handle the products on building site.

Tab 2: Description of studied mixes

	Components mass for 1 m^3 of final mix (kg)				
	QF	HS	Water	Lime	SP (dry extract)
5507	719	131	505	x	x
5507L15	611	131	505	108	x
5507L30	504	131	505	216	x
5507L30SP	498	131	505	213	9.2
55045L30SP	498	131	320	213	9.2

3.3 Mechanical tests

The mechanical performances have been measured under flexural and compression. For each mix, nine cylindrical samples with a diameter of 11 cm and a height of 22 cm, and six prisms of 7 cm (width) × 7 cm (height) × 28 cm (length) have been prepared. The wet mass of matter to fill in the molds is chosen to respect the aimed dry density. An extension piece is used on the mold because of the bulking. The material is compressed with a piston on a hydraulic press. After obtaining the final height, the compression is maintained for ten minutes as in the case with the compression tunnel of the industrial process. Samples are then unmolded and stored in controlled atmosphere with a climatic chamber at 20°C and a relative humidity of 50%. Weight loss is measured for all the mixes. The mechanical performances have been tested 28 days after the manufacturing. This time allows us to have a stabilization of water content and the same duration after manufacturing for all the mixes.

To validate the results obtained with the laboratory samples, blocks with similar dimensions to market products (660 mm × 500 mm × 70 mm) have been made to verify the level of flexural performances with the best mixes (Fig. 2). The same mixer and the same protocol of introduction of components than the laboratory samples were used. After vibration on a vibrating table, the compression of the matter is done by placing a load of 15 kN for ten minutes. After demolding, the blocks are stored in a laboratory room in ambient air with a temperature and a relative humidity close to characteristics fixed with the climatic chamber. These parameters have been verified by a sensor that has taken continuous measurements.

Mechanical tests are done with an electromechanical testing machine which has a force capacity of 50 kN, which gives a good level of precision for the non-bearing products. The flexural strengths have been measured on prisms and blocks. With the prisms, the three-point bending tests are done according to the French standard NF EN 12390-5 [AFNOR 2012]. The length was of 210 mm between supports and the load velocity of 4 N/s. With blocks, tests are done according to the French standard NF EN 12859 [AFNOR 2011] for the gypsum blocks. The length between supports is 566 mm and the load velocity is 20 N/s (figure 2). Cylindrical samples are used for compressive tests. The loading velocity is 5 mm/min according to the recommendations of Cerezo [Cerezo 2005]. To compare the different mixes, the research works by Nguyen [Nguyen 2010] are taken in reference. Three compressive strengths are considered, corresponding to the relative strains of 1.5%, 7.5% and the failure. If the failure is obtained before 1.5% or 7.5% of relative strains, the corresponding strengths of these strain levels will be equal to the maximum strength.

Fig. 2: Block made with quarry fines and hemp straw (mix 55045L30SP) - Three point bending test.

3.4 Thermal and acoustic characteristics

The thermal conductivity (λ), the mass heat capacity (c) and the phase shift are measured and compared with performances of conventional products. The aim is to identify the advantages of using quarry fines. To measure these parameters, a guarded hot plate with flux meters of 15 cm side is employed with samples with a length of 660 mm, a width of 500 mm and a thickness of 70 mm made from the mix having the best mechanical performances.

With this mix, the acoustic absorption coefficient is measured on samples of 10 cm diameter and 7 cm height. Acoustic absorption on materials is measured with the Kundt's tube method.

4 RESULTS

4.1 Drying

After unmolding and before tests, products are stored and dried until mass stabilization, which corresponds to a difference of less than 0.1 % between two measurements spaced of 24 hours. The following of mass evolution and the observations of the wet product make it possible to identify some phenomena linked to the combination of the quarry fines with the hemp straw.

For mixes without lime and superplasticizer, the clay minerals and the hemp straw induce large water retention.

During drying, mould has been observed on the surface of cylindrical samples after ten days of drying. With the blocks, mould is also observed (Fig. 3) and the drying time is increased because of a more important area of product.

A lime addition of 30% does not decrease the drying time, the gradient of the water content remains the same. But lime addition increases the pH from 8 to 12.4 and eliminates mould.

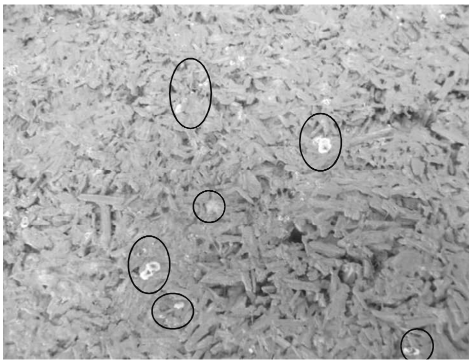

Fig. 3: Mould on blocks (enclosed areas).

With the use of the superplasticizer, the decrease of initial water content has a minor influence on the drying velocity of samples made with quarry fines, hemp straw and lime for laboratory samples and blocks (Fig. 4 and 5). For the blocks, the mass stabilization is obtained in around 45 days.

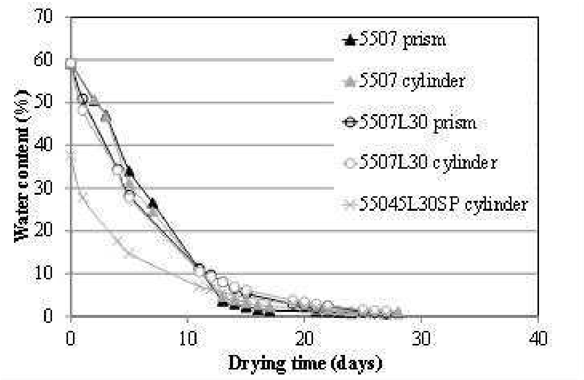

Fig. 4: Drying curves of laboratory samples.

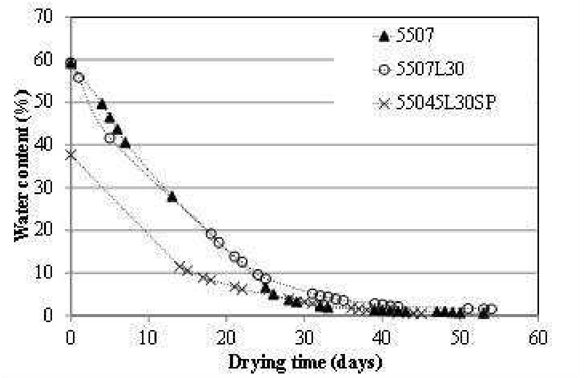

Fig. 5: Drying curves of blocks.

4.2 Mechanical characterization

Laboratory samples

Fig. 6 shows the compressive strengths of five mixes according to strains. The results are the mean values calculated on three tests per mix.

As with hemp concrete, the stress-strain curves for our mixes show a particular form with a reduced elastic phase corresponding to strains between 0 and 0.1%, then a plastic phase reaching sometimes as much as 15% of strain. Finally, the third phase and the last phase correspond to a decrease of strengths linked to the failure of clay parts.

The lime and superplasticizer have an influence on the deformability of quarry fines-hemp straw mixes. Without these elements, strains are around 15%. With 15% of lime, failure strain is unchanged. On the other hand, with 30% of lime, the rigidity of matter is increased and strain decreases, when samples are crushed, with values comprised between 5% and 10%. The superplasticizer induces an increase of strength when it is used for decreasing water content (55045L30SP). When the sample is broken, the strain of the mix 55045L30SP is around 5% (Fig. 6).

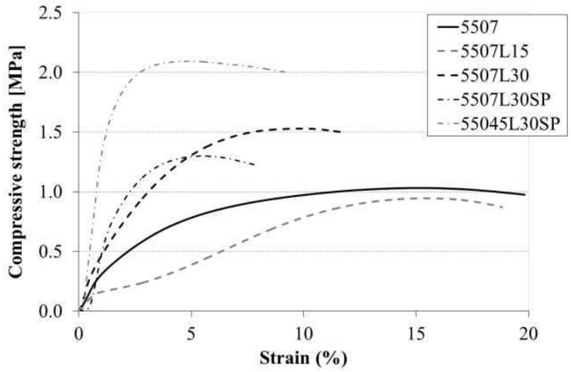

Fig. 6: Stress-strain curves of mixes.

At low deformation level (1.5%), the compressive strengths of mixes 5507, 5507L15 and 5507L30 are low with values comprised between 0.2 MPa and 0.6 MPa (Fig. 7). In contrast, the superplasticizer addition increases the mechanical performances for the same deformation level. A high gain of resistance is obtained with a reduction of initial water content (55045L30SP). A comparison between 5507 mix and 55045L30SP shows that the resistance at low relative strain (1.5%) is increased by 300%.

At the failure, the compressive strengths of samples made with only quarry fines and hemp straw are around 1 MPa with a large relative strain. A lime addition of 15% does not change the resistance level. A lime addition of 30% improves by 50% the final resistance. Increase of lime content creates more hydrates and more bridges between clayey particles. A lime proportion of 15% does not seem to be sufficient.

Despite an easier filling of the matter in the molds, the use of the superplasticizer for a similar water/binder ratio of 0.7 does not improve the compressive strength. The difference of resistance observed on Fig. 7 can be caused by the small variation of dry density between samples linked to the manufacture reproducibility.

As for low deformation levels, the presence of lime and the decrease of water/binder ratio (0.7 to 0.45), linked to the addition of the superplasticizer, increase largely compressive strengths at the failure. These results can be explained by the decrease of distances between clayey particles associated to the presence of hydrates from the lime hydration and, with the superplasticizer, by a modification of charge on clayey sheets when keeping the same consistency level.

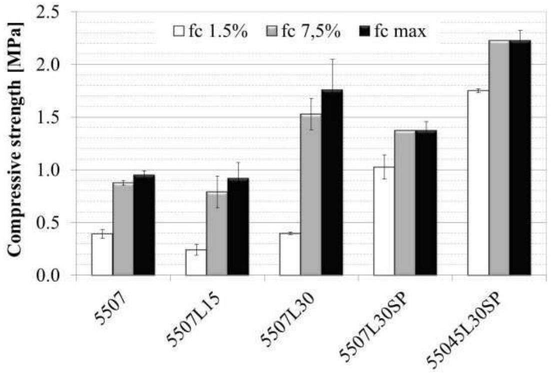

Fig. 7: Compressive strengths of mixes.

The flexural strength for the mixes made of quarry fines and hemp straw is around 0.20 MPa. The lime addition of 15% decreases slightly the flexural strength of the mixes made up with quarry fines and hemp straw (Fig. 8). A lime addition of 30% increases the flexural strength by 60% in comparison to the mixes without lime.

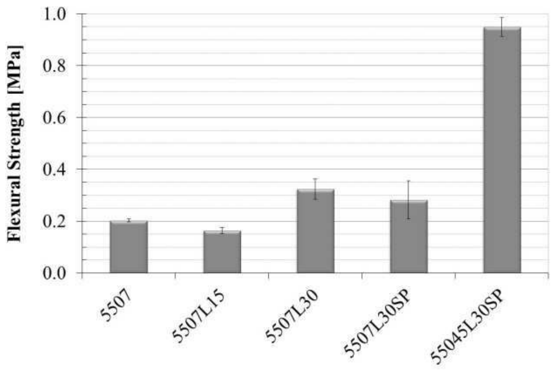

Fig. 8: Flexural strengths of prisms.

The use of the superplasticizer does not improve the flexural strength for the mixes made of quarry fines, lime and hemp straw with the same water/binder ratio as that for compressive tests.

When the water/binder ratio decreases to 0.45, the superplasticizer addition makes it possible to keep the same consistency as the consistency of the mixes made up of only quarry fines and hemp straw with W/B of 0.7. In these conditions, flexural strengths are widely increased with, for instance, an increase of 200% between the 5507L30 mix and the 55045L30SP mix.

The comparison of flexural strengths between studied mixes gives similar tendencies as compressive tests. The flexural strength is increased by 375% between 5507 and 55045L30SP.

Blocks

Three mixes have been chosen to make blocks: 5507, 5507L30 and 55045L30SP. This latter represents the best mix according to previous results on laboratory samples. Two blocks per mix have been manufactured.

The results of three-point bending tests (Fig. 9) confirm previous results with the prisms, which validates the method of manufacturing even though variations of dry density are observed between both products.

The dry density is a parameter to be considered for the flexural strengths of blocks. With the mix 55045L30SP, the flexural strength decreases by 20% at failure, when the dry density decreases by 40 kg/m^3. This is also observed for the mixes 5507 and 5507L30.

As for laboratory samples, the mix made with quarry fines and hemp straw has a low flexural strength around 0.2 MPa. A lime addition of 30% does not increase flexural performances significantly. The decrease of W/B ratio to 0.45 and the superplasticizer addition widely improves the results of three point bending tests. The results for the block 55045L30SP are comprised between the results of gypsum blocks and cellular concrete blocks. These products have been bought and tested in our laboratory to do the measurements in the same experimental conditions.

Compressive tests (Fig. 10) are also done on half blocks to verify the resistance of the products with a load corresponding to the weight of a wall. For a classic wall with a height of 2.5 meters, the number of stacked blocks is 5 and the load is around 1 kN, which corresponds to a stress of 0.022 MPa. In these conditions, the best mixes have sufficient strength but it is lower than that of market products.

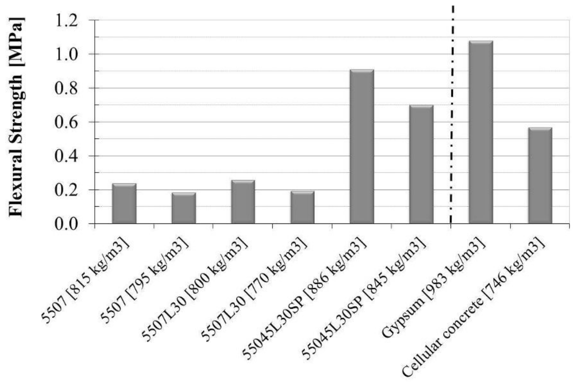

Fig. 9: Flexural strengths of blocks.

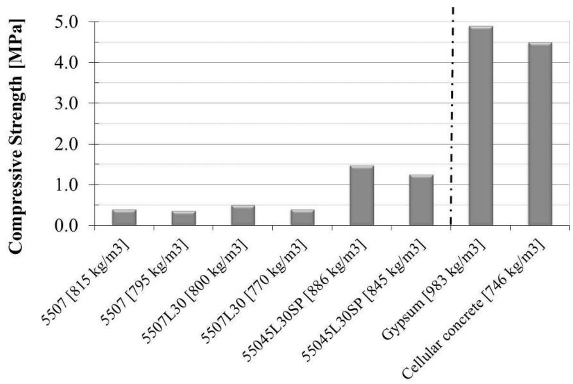

Fig. 10: Compressive strengths of blocks.

4.3 Thermal and acoustic characteristics

For this part of study, only the mix with the superplasticizer 55045L30SP is studied, which corresponds to the best mix from a mechanical point of view, and is similar for its flexural strength to market products (gypsum in particular).

Thermal performances of this mix are comprised between the performances of gypsum blocks and of cellular concrete blocks (Tab. 3). These measurements show that the association of hemp straw and clayey material gives interesting results for a partition wall with a low thermal conductivity and a satisfactory capacity of thermal inertia.

Tab. 3: Thermal characteristics of blocks.

	55045L30SP	Gypsum	Cellular concrete
λ [W/(m.K)]	0.21	0.345	0.182
c [kg/(J.K)]	1100	1120	953
ρ [kg/m3]	886	980	746
Phase shift [min]	230	191	200

On the acoustic side, the mix gives a high level of acoustic absorption for low sound emissions (250 Hz) with a value ten times greater than for gypsum blocks and five times greater than for cellular concrete blocks (Fig. 11). The hemp straw in the mix gives a good performance level thanks to its porosity.

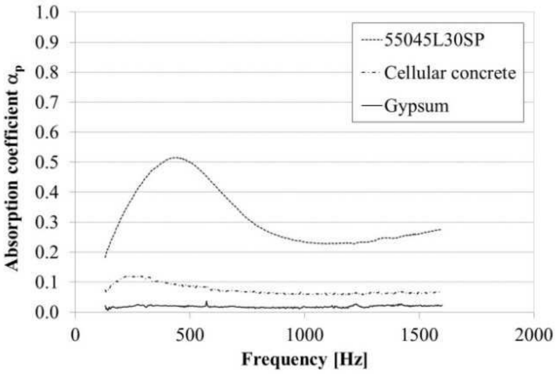

Fig. 11: Acoustic absorption coefficient of blocks.

5 CONCLUSIONS

This research work shows the capacity of quarry fines to be used in the manufacture of precast non-bearing products with an interesting size of blocks (0.33 m²) for a rapid construction of wall partitions.

With hemp straw, dry density is reduced in order to respect block handling criteria. Low mechanical strengths have been obtained for mixes made with only quarry fines and hemp straw mainly due to high initial water content and the absence of a chemical binder.

The replacement of 30% of quarry fines with lime improves the flexural and compressive strengths of the mix. Besides, with an increase of pH, the lime prevents deterioration of hemp straw.

High water content is necessary to fill the mold without difficulties but it is also the main cause of low mechanical strengths. To decrease initial water content, a superplasticizer has been used. The addition of a superplasticizer made with a carboxylate has decreased the water/binder ratio from 0.7 to 0.45. With 30% of lime, the use of a superplasticizer has given the highest improvement of mechanical performances: for blocks, the flexural strength and the compressive strength have increased by 270% in comparison to the mix with only quarry fines and hemp straw.

The use of hemp straw in the mix with clay materials makes it possible to obtain a low thermal conductivity (0.21 $W.m^{-1}.K^{-1}$) without reaching the level of an insulating material. The values are close to those of market products in gypsum or in cellular concrete. The porosity of hemp straw gives to the material an interesting coefficient of acoustic absorption at low emission frequencies, with an absorption peak at 0.5.

In conclusion, quarry fines are secondary materials which are interesting to make unfired products with good levels of performance. With these fines and hemp straw, the lime and the superplasticizer chosen in this study have been useful to limit the initial water content of the fresh matter and to obtain satisfactory mechanical characteristics. The comfort performances are equally promising and make the development of this type of products worth continuing.

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