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DESIGN OF A NEW SOIL CONCRETE AS AN ECO-MATERIAL: EFFECT OF CLAY AND HEMP FIBERS PROPORTIONS

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Abstract

This study presents a series of soil concrete mix that is made of excavated soils, cement, lime and hemp fibers. An experimental program was carried out on the testing samples of soil concrete with different proportions of clayey soil and hemp fibers. This program focuses on several properties of soil concrete, such as compressive strength, autogenous shrinkage, drying shrinkage and water mass loss with time. The obtained results show that the compressive strength of soil concrete increases even after 28 days, and can be reduced significantly with increasing the proportion of clayey soil. The effect of clayey soil on the properties tested of soil concrete is more than that of hemp fibers. In addition, drying shrinkage associated with water mass loss allows to describe the drying process of soil concrete.

Keywords: soil concrete; hemp fibers; compressive strength; autogenous shrinkage; drying shrinkage; water mass loss.

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1. Introduction

The ecological aspect of building structures and the sustainable development is nowadays of high importance in the construction domain. Therefore, building material containing a proportion of various ecological composition is a good idea. Soil concrete is defined as an ecological building material since it uses a high content of clayey and sandy soils that are excavated directly at construction sites, and a small content of binders. The aim of producing ecological concrete is to reduce CO_2 emission, energy consumption in industry by limiting the use of cement and natural resources. For instance, building made of low cost raw soils represents real interest since the acoustic and thermal properties of these materials are improved in comparison with ordinary concrete [1]. The stabilization of soil in concrete can be realized by using different types of binders as lime and cement [2, 3]. The addition of cement increases the evolution of the mechanical properties of concrete but can induce shrinkage and cracking [4].

The use of natural fibers as hemp is particularly interesting as it minimizes the volume of waste in landfill. It is renewable and environmentally friendly [5]. Moreover, hemp is naturally produced, do

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not require much energy to process, do not require maintenance and consumes CO_2 to grow, making the hemp concrete as a carbon negative building material. The addition of hemp fibers can also reduce the density, shrinkage and cracking of soil concrete and improve the thermal properties [6, 7]. The acoustic and thermal properties of soil concrete could be better than ordinary concrete, which are explained by the use of clayey soil and hemp fibers [8].

Concrete volume change is an unavoidable phenomenon, from very early age to long-term behavior [9] and more particularly with soil concrete containing a high proportion of fines aggregates [10, 11]. Autogenous shrinkage is defined as a concrete volume change occurring without moisture transfer to the environment. It depends mainly on the composition of concrete and develops more rapidly with time than drying shrinkage [12]. Drying shrinkage depends on the age of the beginning of drying and external parameters such as relative humidity and specimen size. Thus, the understanding of shrinkage process and more particularly drying shrinkage, known as the main cause of micro and macro cracking, is essential.

In this study, the design of soil concrete mix is presented, which made of clayey soil, sandy soil, hemp fibers, cement and lime. A series of soil concrete mix has been proposed for considering different proportions of clay soil and hemp fibers. In the laboratory, an experimental program carried out on the testing samples of soil concrete. The experimental data allow to determine the compressive strength at 7, 28 and 180 days, autogenous shrinkage, drying shrinkage and water mass loss with time of soil concrete. The obtained results are also used to evaluate the effect of clayey soil and hemp fibers on these physical and mechanical properties of soil concrete.

2. Experimental program

2.1. Materials used

In this study, the soil concrete was made of different compositions, such as soil, cement, lime and hemp fibers. The soils used were excavated at two construction sites in Bordeaux city, France during the execution of underground. These soils can be classed into two principal types: (a) clayey soil, (b) sandy soil.

a. Clayey soil

In the laboratory, some tests such as the Atterberg limits, particle-size analysis and the methylene blue were carried out on the samples in order to determine the type of used clayey soil (Fig. 1) according to the unified soil classification system in the American standard ASTM D2487-17 [13].

The experimental results are synthesized in Table 1 for the parameters of soil: liquid limit W_L, plastic limit W_P, plasticity index I_P, granulometric composition, and VBS that is the methylene blue value of the total soil. These results show that the used soil can be defined as low plastic clay (CL) and has a high content of silt particles.

b. Sandy soil

In the laboratory, some tests such as the particle-size analysis, methylene blue, specific density and fineness modulus were performed on the samples in order to determine the type of used sandy soil. Fig. 2 presents the sandy soil after grinding by a rubber hammer.

The experimental results are synthesized in Table 2. These results show that the used soil can be defined as poorly graded sand with gravel according to the unified soil classification system in the American standard ASTM D2487-17 [13].



Figure 1. Clayey soil after grinding



Figure 2. Sandy soil after grinding

Table 1. Characteristics of used clayey soil

Test	Criterion	Value	USCS* [13]
Atterberg limits (%)	Liquid limit WL	51.74	Low plastic clay (CL)
	Plastic limit WP	30.08	
	Plasticity index IP	21.66	
Particle-size analysis (%)	Clay (< 0.002 mm)	25.06	
	Silt (0.002 – 0.06 mm)	55.94	
	Sand (0.06 – 2 mm)	19	
	Gravel (> 2 mm)	0	
Methylene blue	VBS	5.72	Lean clay (CL)

*USCS: The Unified Soil Classification System is a soil classification system used in engineering and geology to describe the texture and grain size of a soil.

Table 2. Characteristics of used sandy soil

Test	Criterion	Value	USCS* [13]
Particle-size analysis (%)	Silt (0.002 – 0.06 mm)	0.64	
	Sand (0.06 – 2 mm)	72.54	
	Gravel (> 2 mm)	26.82	
Blue methylene	VBS	0.67	Sandy soil
Specific density (kg/m^3)		2.33	
Fineness modulus		2.57	Poorly graded sand with gravel (SP)

c. Hemp fibers

In this study, hemp fibers were used as an additional composition for improving the tensile strength of soil concrete. The hemp fibers have been often used among the natural fibers with low price, such as like sisal, jute, rice husk, flax, bamboo, banana fiber, oil palm fiber, sugarcane bagasse, wood fiber, etc [14]. The diameter of these fibers is less than 2 mm, and the length ranging from 5

to 25 mm. The density of hemp fibers is about 100 kg/m^3 in the ambient conditions. The thermal conductivity is equal to $\lambda = 0.05$ W/m.K. The tensile strength varies between 300 and 1100 MPa. The hemp fibers are highly hydrophilic and can absorb water up to 2.5 times of their mass.

d. Cement

The Portland cement CEM V/A (S-V) 42.5N according to the European standard EN 197-1 was used as the first binder of soil concrete. This cement has been chosen since it has two important criterias as clinker ratio and CO_2 impact. The compositions of the cement are provided by the manufacturer and presented in Table 3. In the tested soil concrete mixes, the cement content has been used ranging from 125 to 155 kg/m^3.

Table 3. Composition of cement

Cement	Main composition (% by mass)			Additional composition
	Portland clinker	Blast furnace cinder	Fly ash	
CEM V/A (S-V)	40 – 64	18 – 30	18 – 30	0 – 5

e. Lime

In the soil concrete mix, the lime can also be used as the second binder in order to reduce the cement content. In this study, the pure natural lime named 100 NHL5 according to the European standard EN 459 was used that has no additives. The specific density of the lime used is 700 kg/m^3. In the tested soil concrete mixes, the lime content has been used about 40 kg/m^3.

2.2. Soil concrete mix

The design of soil concrete mix aims to increase the clayey soil content while decreasing the sandy soil content. For this purpose, the clayey soil content was varied from 0%, 20%, 30% and 40% in the mass total of the soil, named 0A, 20A, 30A and 40A, respectively. For each clayey soil content, the volume fraction of hemp fibers was mixed ranging 0%, 0.6% and 1.2% in mass, named 0F, 0.6F and 1.2F, respectively. In this study, 12 soil concrete mixes studied were presented in Table 4. In fact, when increasing the proportion of clayey soil from 0 to 40%, the cement content can be reduced from 158.1 to 126.6 kg/m^3, meanwhile the water content must increase for the workability in the mixing. The casting of concrete mixtures has been realized by vibration, as normal concrete, to obtain the requirement of workability on construction sites. After mixing soil concrete, the consistence was measured by the slump test and ranging from 65 to 165 mm in function of the proportion of clayey soil and hemp fibers.

2.3. Compression test

The compression test aims to determine the compressive strength of soil concretes that were made of different mixes as presented in Table 4. The Young's modulus of soil concretes can be also determined from the stress – strain curve. The results of this test can be used to assess the effect of clay and hemp fibers on the soil concrete compressive strength at the target age.

This test was carried out on the cubic samples with the dimensions of 100×100×100 mm. Fig. 3 shows the compression test that carried out on a typical sample of soil concrete. During the test, four devices were installed at the center of the lateral faces of each sample, two devices for measuring the vertical displacement, and two another for measuring the horizontal displacement. The axial load was applied on the sample with the constant speed of 0.5 mm/minute.

Table 4. Soil concrete mix studied in the laboratory

No	Soil concretemix	Clayey soil (kg/m^3)	Sandy soil (kg/m^3)	Cement (kg/m^3)	Lime (kg/m^3)	Hemp fibers (kg/m^3)	Water (kg/m^3)	Slump (mm)
1	0A0F	0.0	1386.8	151.8	45.0	0.0	330.6	165
2	0A0.6F	0.0	1306.2	144.3	42.8	12.0	314.2	162
3	0A1.2F	0.0	1238.2	138.0	40.9	22.9	300.6	157
4	20A0F	247.8	991.4	135.6	40.2	0.0	398.9	105
5	20A0.6F	241.4	965.7	133.3	39.5	11.1	392.1	148
6	20A1.2F	236.6	946.7	131.9	39.1	21.9	388.0	95
7	30A0F	368.3	859.5	134.4	39.9	0.0	417.6	95
8	30A0.6F	356.3	831.5	131.2	38.9	10.9	407.7	65
9	30A1.2F	345.3	805.7	128.3	38.1	21.3	398.7	140
10	40A0F	501.1	751.7	137.1	40.7	0.0	466.1	125
11	40A0.6F	476.6	714.9	131.6	38.8	10.9	447.3	73
12	40A1.2F	454.4	681.6	126.6	37.6	21.0	430.5	105

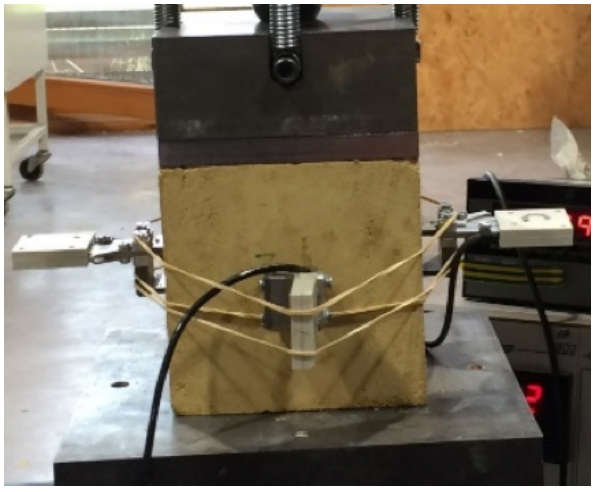
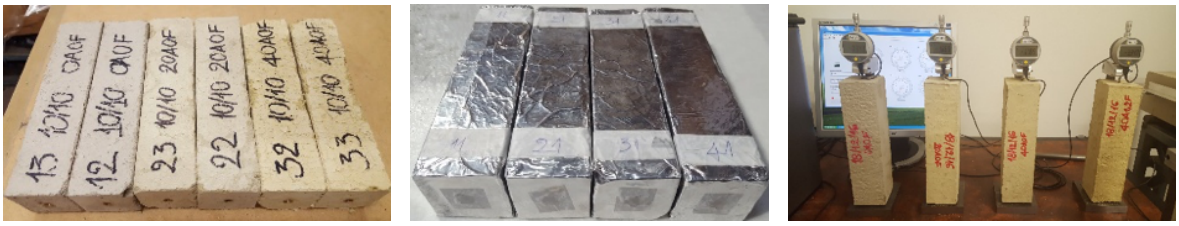


Figure 3. Compression test on the cubic sample of soil concrete

2.4. Shrinkage and water loss measurements

As soil concrete presents a high volumetric change that can cause the infiltration of water and impact its durability, the measurements of shrinkage were carried out on the prismatic samples of the dimensions 40×40×160 mm exposed to controlled ambient conditions with the temperature of 20°C and the relative humidity of 60%. All samples were overlaid by a thin plastic sheet at the top of sample mold during 24 first hours in order to prevent water loss. Then, the samples were demolded, including two types: (i) uncovered samples for drying shrinkage test and mass loss test (Fig. 4(a)); (ii) covered samples by self-adhesive aluminum paper for autogenous shrinkage test (Fig. 4(b)).

Fig. 4(c) presents the shrinkage test that was carried out on uncovered samples for determining the total shrinkage of soil concrete. The longitudinal deformation of each sample is measured by a displacement device (LVDT). The shrinkage of each sample is calculated by the ratio between the



(a) Uncovered samples of soil concrete (b) Covered samples of soil concrete (c) Shrinkage measurement

Figure 4. Shrinkage and mass loss measurements of soil concrete samples

absolute deformation and the length of sample. The shrinkage of each soil concrete is the average value of three samples. In this study, six soil concrete mixes having three proportions of clayey soil ranging from 0%, 20% and 40%, and two proportions of hemp fibers of 0% and 1.2% were measured the shrinkage and mass loss in function of time. There were the total of 36 samples tested. At the same time, the mass loss was measured on the uncovered samples for a better understanding of drying shrinkage phenomenon. The measurements of mass loss were performed by the electronic balance with 0.01 gram readability. The mass loss is calculated in percentage by the ratio between the water loss mass by evaporation and the initial mass of sample.

3. Results and discussions

3.1. Compressive strength of soil concrete

For each soil concrete mix, three cubic samples with the dimensions of 100×100×100 mm were tested to determine the average value of the compressive strength, as well as the standard deviation and the coefficient variation. The experimental results of compressive strength are presented in Figs. 5, 6 and 7 for 12 soil concretes at 7, 28 and 180 days, respectively. In this study, 36 sets of soil concrete samples were tested.

At 7 days, 12 sets of tested soil concrete samples show that the average values of compressive strength range from 0.5 to 1.2 MPa (Fig. 5). The compressive strength of soil concrete decreases significantly with increasing the proportion of clayey soil. The effect of hemp fibers on the compressive strength is only observed for the soil concrete without clayey soil (100% sandy soil). This effect is negligible for soil concrete having clayey soil.

At 28 days, the average values of soil concrete compressive strength range from 1.0 to 2.4 MPa (Fig. 6). The same remarks are idenfied on the effect of the proportion of clayey soil and hemp fibers. The compressive strength can be reduced to 1 MPa with beyond 20% clayey soil. Meanwhile, it can be reduced from 0.5 to 0.8 MPa with the hemp fibers contents of 0.6 - 1.2%. The effect of hemp fibers on the compressive strength may be due to the lower density and the modification of the soil concrete structure and pore distribution by introducing voids and discontinuity.

At 180 days, the compressive strength of soil concrete increases about two times in comparison to that at 28 days. The average values of compressive strength range from 2.5 to 5.1 MPa (Fig. 7). The evolution of soil concrete compressive strength occurs in more time in comparison to ordinary concrete that is normally characterized the mechanical properties at 28 days. Fig. 8 shows the evolution of compressive strength of 12 soil concrete mixes during 180 first days. The obtained results allow to quantify the effect of curing time on the compressive strength of soil concrete. These results show

that the compressive strength of soil concrete increases even after one month. This is an important mechanical property of soil concrete. In the short term, the compressive strength of soil concrete is mainly associated to the cement hydration. Meanwhile, in the long term, it may be provided by the hydration reaction and the pozzolanic reactions between clay minerals and calcium hydroxide formed by the cement hydration [15].

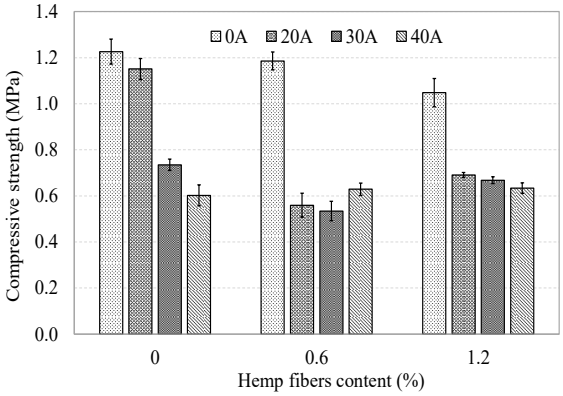


Figure 5. Compressive strength of soil concrete at 7 days

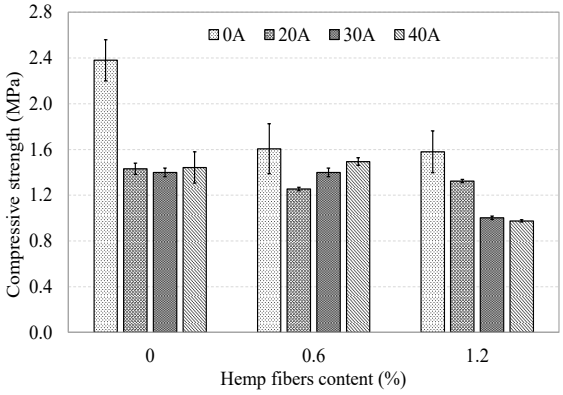


Figure 6. Compressive strength of soil concrete at 28 days

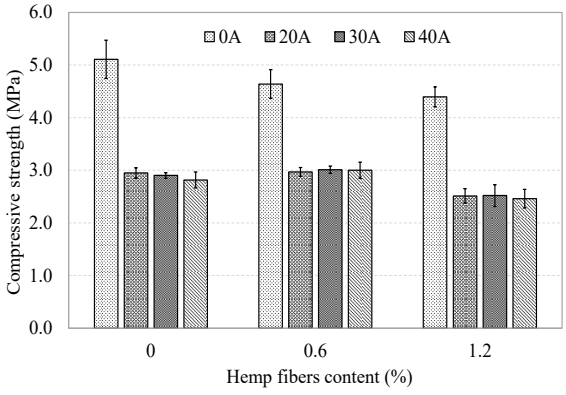


Figure 7. Compressive strength of soil concrete at 180 days

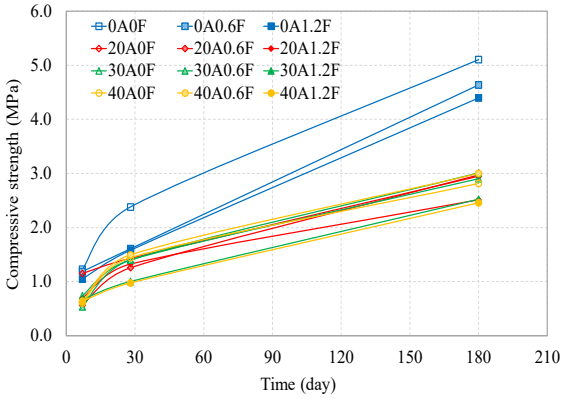


Figure 8. Evolution of soil concrete compressive strength with time

The measured compressive strength of soil concrete is low ranging from 1.0 to 2.4 MPa at 28 days compared with ordinary concrete. The range of compressive strength is acceptable regarding the application of this kind of concrete which is used as a filling concrete and not for assuring high load capacity (e.g. wall, block, etc.). This is due to low cement content, the higher porosity of soil concrete constituted of fine grained mixtures and the higher water content required to achieve an acceptable workability.

3.2. Young's modulus of soil concrete

Fig. 9 shows the typical diagram of stress – strain that presents the relationship between compressive strength and both longitudinal and horizontal deformations of the soil concrete mix named

40A1.2F having 40% clayey soil and 1.2% hemp fibers at 7, 28, and 180 days. Young's modulus is calculated by the slope of the curve between 10% and 30% of ultimate compressive strength. The obtained results show that the Young's modulus of soil concrete increases with a high rate even after 28 days. The elastic modulus of tested soil concrete increases from 2 GPa at 7 days to 8 GPa at 180 days. The stress-strain curves of soil concrete show also a higher ductility with increasing the proportion of clayey soil. Moreover, the addition of hemp fibers as reinforcement in soil concrete can prevent horizontal deformation during compression loading.

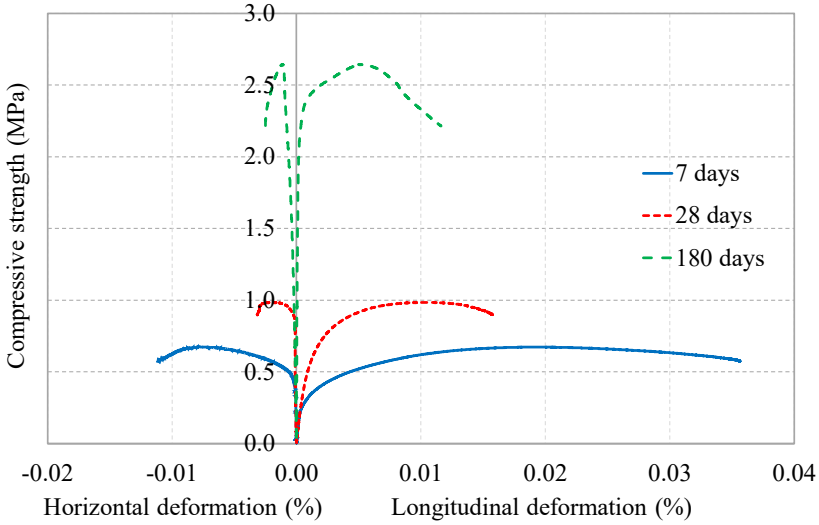


Figure 9. Compressive strength in function of longitudinal and horizontal deformations of soil concrete

3.3. Shrinkage of soil concrete

Fig. 10 presents the evolution of autogenous shrinkage of soil concrete having 0%, 20%, 40% clayey soil and 0%, 1.2% hemp fibers during 70 first days. The autogenous shrinkage of soil concrete increases with a high rate during the three first days and decreases gradually in function of time. Autogenous shrinkage occurs independently of external water loss and is a result of chemical shrinkage and self-drying shrinkage. The reduction of humidity in the pore system causes water–air meniscus that subjects the pore walls to considerable stress and leads to substantial self-drying shrinkage. The obtained results show that the autogenous shrinkage of soil concrete without hemp fibers increases with the proportion of clayey soil. The autogenous shrinkage of soil concrete having 40% clayey soil and 0% hemp fibers (40A0F) at 67 days increases about four times in comparison with that of soil concrete having 20% clayey soil (20A0F) and 0% clayey soil (0A0F), 1900 μm/m versus 450 μm/m. The addition of 1.2% hemp fibers causes a slight increase of autogenous shrinkage for soil concrete having 20% and 0% clayey soil (20A1.2F and 0A1.2F). However, the autogenous shrinkage of soil concrete having 40% clayey soil and 1.2% hemp fibers (40A1.2F) decreases significantly in comparison to that of soil concrete having 40% clayey soil and 0% hemp fibers (40A0F). This difference may be related to the variation of the global porosity between soil concrete mixes and the water absorption of hemp fibers [16, 17]. The autogenous shrinkage of soil concrete having 1.2% hemps fibers is in the range of 600 – 800 μm/m.

In general, the drying shrinkage is defined as the contracting of a hardened concrete mixture due to the loss of capillary water. This shrinkage causes an increase in tensile stress, which may

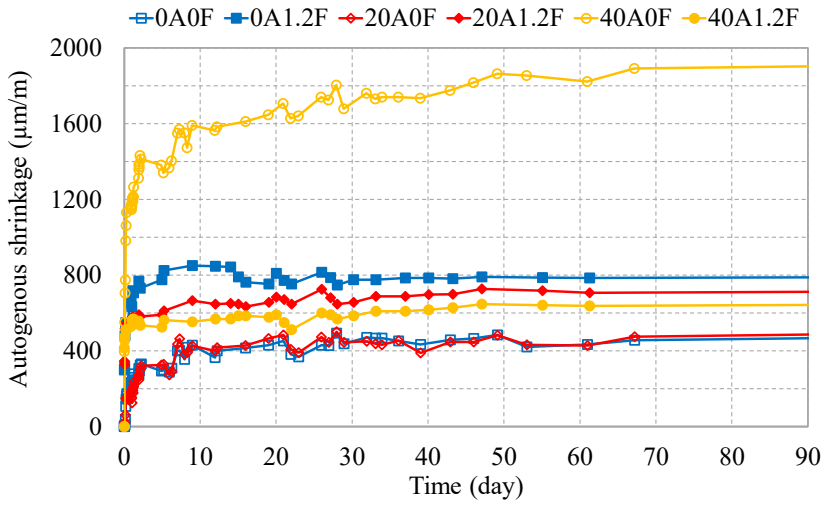


Figure 10. Autogenous shrinkage of soil concrete with different contents of clay and hemp fibers

lead to cracking, deterioration of concrete structure, before the concrete is subjected to any kind of loading. Fig. 11 presents the evolution of drying shrinkage of soil concrete having 0%, 20%, 40% clayey soil and 0%, 1.2% hemp fibers during 70 first days. The drying shrinkage is calculated by the subtraction of the autogenous shrinkage from the total shrinkage. The drying shrinkage of soil concrete increases quickly at the beginning and later stabilizes between 10 and 15 days. The effect of the proportion of clayey soil on the drying shrinkage is significant. For example, for soil concrete having 40% clayey soil and 1.2% hemp fibers (40A1.2F) the drying shrinkage reach a high value about 11800 µm/m, corresponding to approximately 8 times higher than that of soil concrete having 0% clayey soil (0A1.2F and 0A0F). The effect of hemp fibers on the drying shrinkage depends also on the proportion of clayey soil in the of soil concrete mix. In fact, the drying shrinkage increases significantly for soil concrete of 40A1.2F in comparison with that of 40A0F having 40% clayey soil

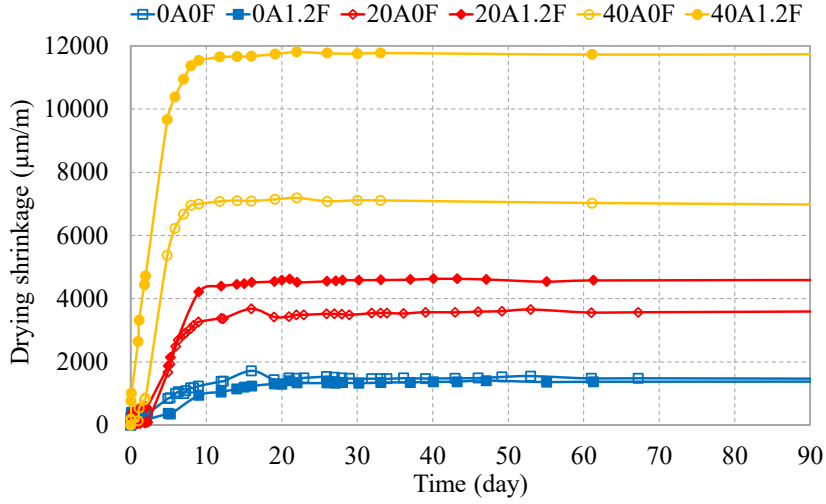


Figure 11. Drying shrinkage of soil concrete with different contents of clay and hemp fibers

and 0% hemp fibers. This may be due to modification in pore system structure and transfer properties that modify the water evaporation at the surface of soil concrete.

3.4. Water mass loss

The water mass loss of soil concrete was also measured at the same time of the measurement of drying shrinkage. The obtained results are presented in Fig. 12 for soil concrete with 0%, 20%, 40% clayey soil and 0%, 1.2% hemp fibers. The variation of water mass loss transcribes the diffusion capacity of the material. The mass loss is important during 15 first days and later stabilizes. The water mass loss with time shows similar trend as the drying shrinkage. The water mass loss increases when rising the proportion of clayey soil, which could explain the increase of drying shrinkage. The addition of hemp fibers causes the increase of the water mass loss for soil concrete having 0% and 20% clayey soil (0A1.2F and 20A1.2F). Meanwhile, it causes the decrease of the water mass loss for soil concrete having 40% clayey soil (40A1.2F).

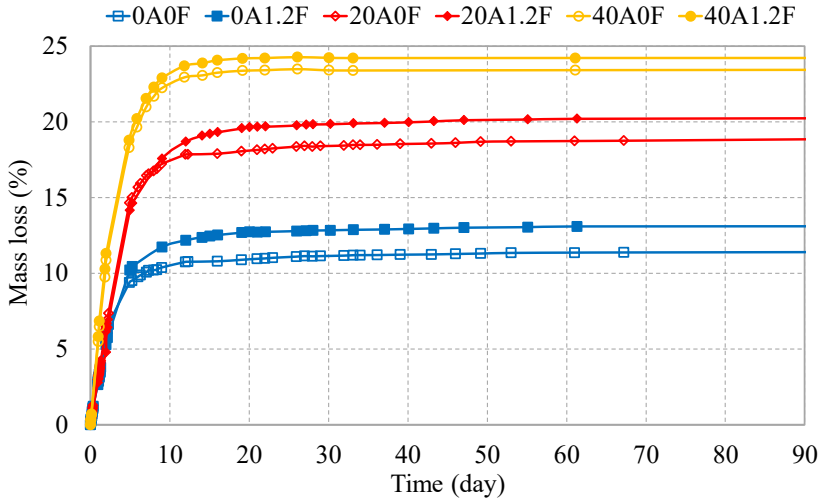


Figure 12. Evolution of water mass loss of soil concrete

The water mass loss has a good correlation with the drying shrinkage of tested soil concretes. Fig. 13 presents the relationship between these two parameters for six tested soil concrete mixes. There are some phases that can be distinguished in Fig. 13. In the first phase called “dormant zone”, the water loss without shrinkage is observed on the tested samples of soil concrete. In fact, the water content gradient in soil concrete due to drying generates a stress gradient, so a high tensile stress at the sample surfaces exposed to the atmosphere and causes cracks. The surface area to volume ratio is an important factor in this phase. During the second phase, the gradients become more pronounced, the cracks at the surface remains unchanged. The drying shrinkage is proportional to water mass loss (linear zone), with a slope that reflects the fineness of the porous network. In the last phase, a stabilisation phase is observed with a lower shrinkage rate. Soil concrete shrinkage is higher in comparison to ordinary concrete due to the lack of coarse aggregates that inhibit the total shrinkage and the higher porosity related to incorporating clayey soil and high water content.

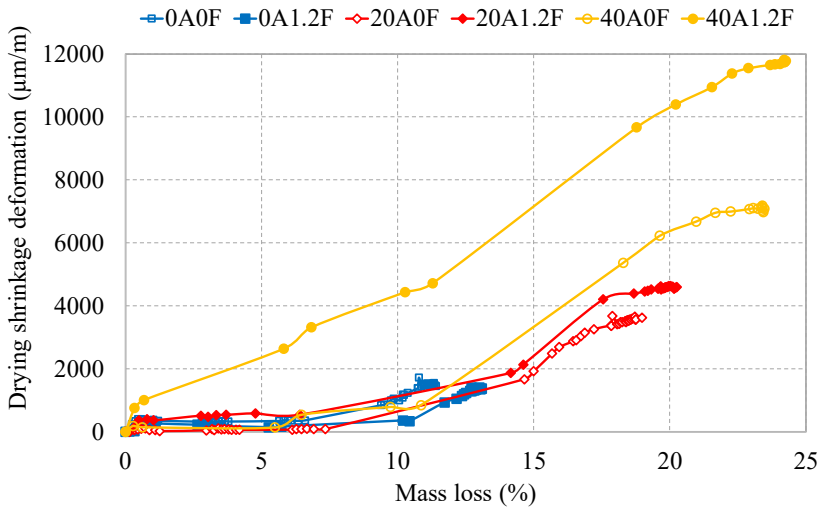


Figure 13. Correlation between drying shrinkage and water mass loss of soil concrete

4. Conclusions

The present study aims to consider a series of soil concrete mixes with different proportions of clayey soil (0%, 20%, 30%, 40%) and hemp fibers (0%, 0.6%, 1.2%). The experimental results allow to evaluate the effect of clayey soil and hemp fibers on several physical and mechanical properties of soil concrete, such as compressive strength, Young's modulus, autogenous shrinkage, drying shrinkage and water mass loss.

For tested mix, the compressive strength of soil concrete ranges from 1.0 to 2.4 MPa at 28 days and increases even after one month with the average values ranging from 2.5 to 5.1 MPa at 180 days. The results show that the compressive strength of soil concrete decreases when increasing the proportion of clayey soil and hemp fibers, which could be related to increasing concrete porosity. The effect of clayey soil is higher than hemp fibers. The hemp fibers cause a slight reduction of compressive strength that is due to lower density and modification of soil concrete structure and pore system by introducing voids and discontinuity.

The soil concrete deformation due to autogenous and drying shrinkage increases significantly when rising the proportion of clayey soil, especially with the use of 40% clayey soil of the total mass of soils used. The drying shrinkage increases reaches important value for soil concrete having 40% clayey soil, which corresponds to about 8 times higher than that without clayey soil. The addition of 1.2% hemp fibers influences slightly the shrinkage of soil concrete that has less than 20% clayey soil. Meanwhile, it causes a significant increase of drying shrinkage for soil concrete having 40% clayey soil. Thus, the obtained results show that it recommends to use less than 40% clayey soil and 1.2% hemps fibers in order to design the soil concrete mix as a building material.

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