T1

Technical report

Soil and fibre characterisation, mixes choice and mixes characteristics

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SOMMAIRE

I. Report content 4
II. Soils characterisation 4
II.1. Test performed 4
II.2. Particles size distribution 4
II.3. Methylene blue value 5
II.4. Atterberg's limits 6
II.5. Compaction parameters 6
III. Fibres characterisation 8
III.1. Fibres types 8
III.2. Absolute density 8
III.3. Water absorption 8
III.4. Tensile strenght 8
IV. Mixes choice 9
V. Mixes characteristics 10
V.1. Compressive strength 10
V.2. Thermal conductivity 10
V.3. Acoustic insulation 11
VI. Results analysis 12
VI.1. Structural mixes 12
VI.2. Thermal mixes 15
VII. Optimised mixes 17

FIGURES LIST

Figure 1. Soils particle size distribution 5
Figure 2. Proctor curves of FR soils 7
Figure 3. Proctor curves of UK soils 7

TABLES LIST

Table 1. *Used standard tests.* 4
Table 2. *Particles size distribution.* 5
Table 3. *Methylene blue value.* 6
Table 4. *Atterberg limits.* 6
Table 5. *Compaction parameters.* 6
Table 6. *Absolute density of fibres.* 8
Table 7. *Fibres water absorption.* 8
Table 8. *Fibres tensile strength.* 9
Table 9. *CobBauge mixes* 9
Table 10. *Compressive strength results* 10
Table 11. *Thermal conductivity results of structural mixes* 11
Table 12. *Thermal conductivity results of thermal mixes* 11
Table 13. *Airborne sound insulation results* 11
Table 14. *Compressive strength results of structural mixes (4, 5, 7, 8, 9 and 12)* 13
Table 15. *Soils characteristics (FR2, FR6, UK1, UK3)* 13
Table 16. *Compressive strength results of structural mixes (4, 5, 7, 8, 9 and 12)* 13
Table 17. *Compressive strength results of structural mixes (4, 5, 7, 8, 9 and 12)* 14
Table 18. *Fibre characteristics* 14
Table 19. *Compressive strength results of structural mixes (1 and 2)* 14
Table 20. *Thermal conductivity results of structural mixes (4, 5, 7, 8, 9 and 12)* 15
Table 21. *Soils characteristics (FR3, UK3, UK4)* 15
Table 22. *Thermal conductivity results of structural mixes (2 and 3)* 15
Table 23. *Thermal conductivity results of structural mixes (3, 4, 5 and 6)* 16
Table 24. *Fibre characteristics* 16
Table 25. *Thermal conductivity results of structural mixes (3, 4, 5 and 6)* 16

I. Report content

This report presents the progress of the actions planned implementation in the T1, as well as the results of these actions. This progress concerns the soils and fibres characterisation, mixes choices, mixes characterisation and the choice of the four best mixes.
For this, 12 soils and 6 fibres were selected. Concerning soils, they were named according to their origin: FR1 to 6 for French soils and UK 1 to 6 for English soils.

II. Soils characterisation

II.1. Test performed

Table 1 summarizes characterisation tests carried out on soils as well as the standards used.

Table 1. *Used standard tests.*

Characterisation type	Tests	Standard
Physical	Particles size distribution	XP P94-041
	Particles size distribution	NF P94-057
	Methylene blue value	NF P94-068
	Atterberg limits	NF P94-051
Mechanical	Proctor test	NF P94-093

II.2. Particles size distribution

The particles size distribution analysis allows to determine the dimensional distribution of grains in a material. These tests were carried out by wet sieving for the fraction greater than 80 µm and by LASER granulometry for elements smaller than 80 µm, the fines.
The results obtained are presented in Table 8 and Figure 1.

Table 2. *Particles size distribution.*

Sample	Clayed fraction (% < 2µm)	Silty fraction (2 < % < 63 µm)	Sandy fraction (63 µm < % < 2 mm)	D_{max} (mm)
FR1	1.14	10.43	46.16	50
FR2	7.64	74.38	10.70	50
FR3	12.85	65.43	12.36	50
FR4	2.55	7.75	18.22	20
FR5	9.35	81.47	8.78	50
FR6	7.97	26.01	28.05	12.5
UK1	2.72	32.26	12.87	50
UK2	7.52	44.11	41.13	20
UK3	12.83	68.93	17.80	20
UK4	5.59	58.64	16.74	31.5
UK5	3.59	35.52	18.39	50
UK6	9.05	64.20	19.54	12.5

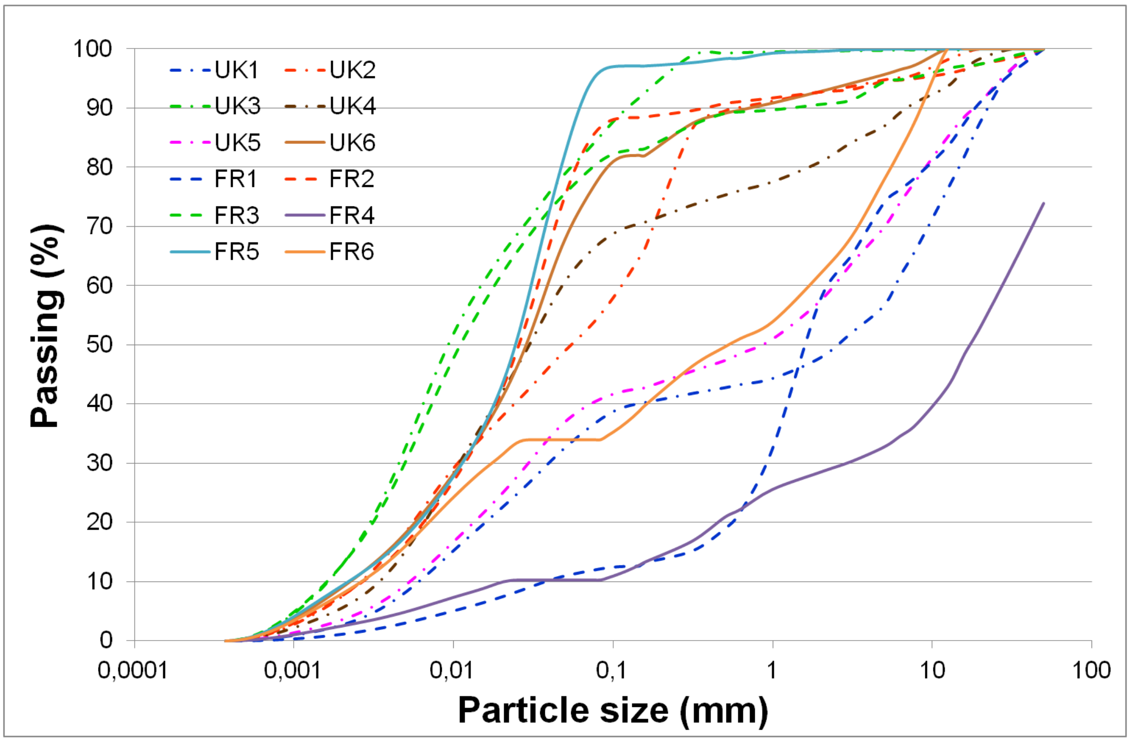

Figure 1. Soils particle size distribution

II.3. Methylene blue value

The value in the methylene blue of sediment (BV) allows to estimate the sediment clayey activity. The test is based on the particular adsorption potential of clays.
The results obtained are presented in Table 3.

Table 3. *Methylene blue value.*

	FR1	FR2	FR3	FR4	FR5	FR6	UK1	UK2	UK3	UK4	UK5	UK6
MBV (g/100 g)	0.30	0.55	5.34	0.62	0.69	0.84	0.61	1.22	3.64	0.83	0.38	0.80

II.4. Atterberg's limits

The Atterberg's limits are the reference water contents of state changes. When the water content increases, the soil passes gradually of a fragile material in a plastic material then in a viscous liquid.

The results obtained are presented in Table 4.

Table 4. *Atterberg limits.*

Soil	FR1	FR2	FR3	FR4	FR5	FR6	UK1	UK2	UK3	UK4	UK5	UK6
w_L (%)	48.9	34.1	53.3	20.1	22.7	28.9	38.5	18.6	25.7	24.8	29.6	30.4
w_P (%)	28.5	20.4	24.5	16.3	19.5	25.4	36.3	16.4	24.2	21.9	27.7	23.1
Ip (%)	20.4	13.7	28.8	3.8	3.2	3.5	2.2	2.2	1.5	2.9	2.9	7.3

II.5. Compaction parameters

The sediments compaction capacity is measured by normal Proctor test. This test consists in compacting the material with various water contents with a given energy. For every water content w is determined the material dry density ρ_d. The compaction parameters are determined from the maximum of the curve $\rho_d = f(w)$. This maximum (w_{OPN} ; ρ_{dOPN}) is the normal optimum Proctor.

The results obtained are presented in Table 5 and figures 2 and 3.

Table 5. *Compaction parameters.*

Sol	FR1	FR2	FR3	FR4	FR5	FR6	UK1	UK2	UK3	UK4	UK5	UK6
Optimum moisture content (%)	9.7	14.0	15.8	10.0	15.7	16.2	18.6	14.0	17.2	17.1	18.1	17.8
Optimum dry density ($kg.m^{-3}$)	2034	1827	1771	1916	1760	1620	1683	1777	1753	1745	1676	1709

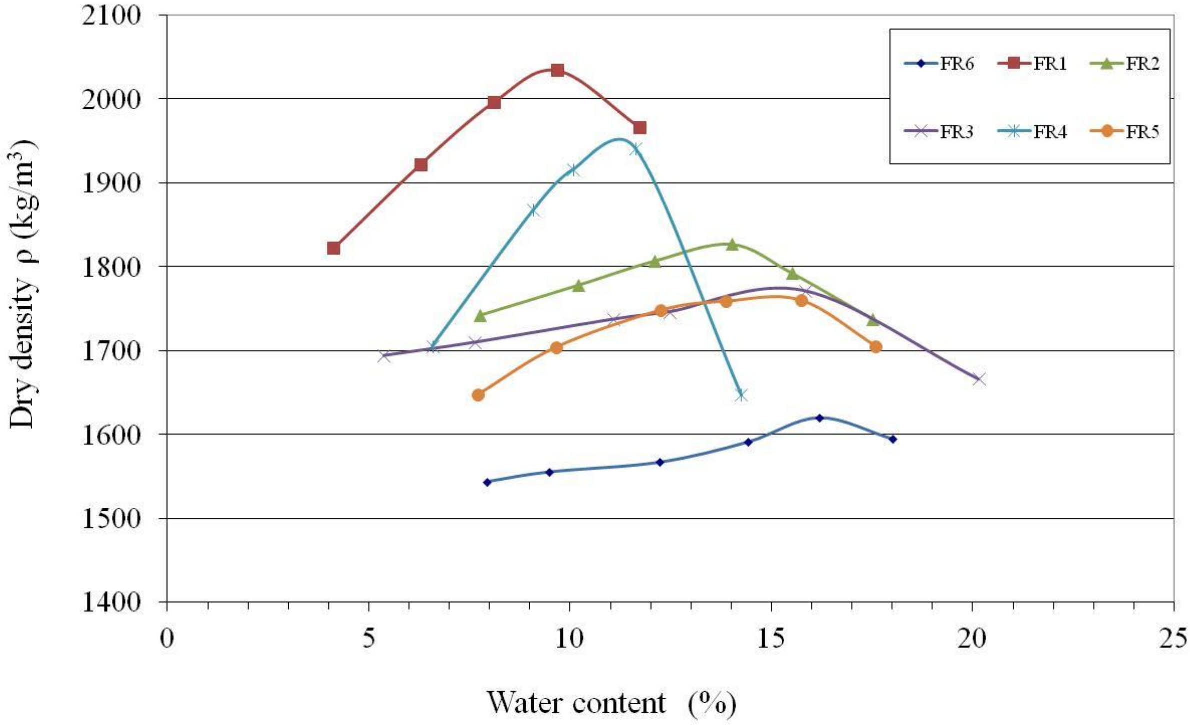

Figure 2. Proctor curves of FR soils

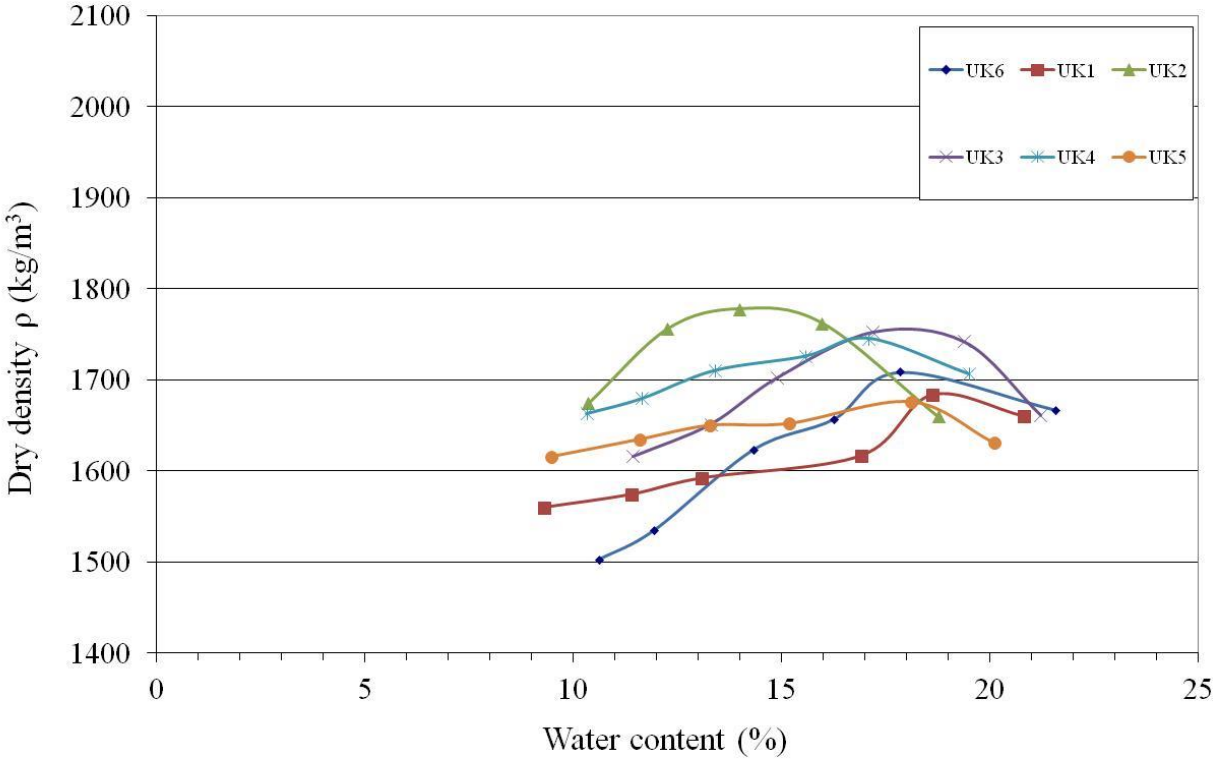

Figure 3. Proctor curves of UK soils

III. Fibres characterisation

III.1. Fibres types

With regard to the fibres, different plants were selected by their local nature, the quantity available and their current use. The selected fibres are wheat straw, flax straw, hemp straw, flax shiv, hemp shiv and reed.

III.2. Absolute density

The measurement of the fibres absolute density was carried out using an AccuPyc II 1340 type helium pycnometer of the trademark Micromeritics® (FIG. 5). It allows an accurate measurement of the solid phase volume of a known mass sample (ASTM B923, 2016).
The results obtained are presented in Table 6.

Table 6. *Absolute density of fibres.*

Fibre	Wheat straw	Flax straw	Hemp straw	Reed	Hemp shiv	Flax shiv
Absolute density ($g.cm^{-3}$)	1.182	1.337	1.391	1.390	1.410	1.455

III.3. Water absorption

The water absorption coefficient corresponds to the evolution over time of the water content of submerged fibres. This test is derived from an experimental protocol developed by RILEM group TC 236-BBM to measure the water absorption of fibres.

Table 7. *Fibres water absorption.*

Fibre	Wheat straw	Flax straw	Hemp straw	Reed	Hemp shiv	Flax shiv
Water absoprtion at 24h (%)	309	185	336	200	266	320

III.4. Tensile strenght

Tensile tests were carried out on fibres unit under ambient conditions. 10 cm length fibres were used to determine the tensile strength. This implies that flax shives and hemp shiv have not been characterised for this parameter. To prevent damage to the fibres in contact with the jaw, both ends of the fibre were protected by tape on a length of 3 cm on each side. Therefore, the initial fibre length is considered equal to 4 cm for calculating the sample bend. The fibre is then placed in the manual clamping jaws of the testing machine. The loading speed is set at 1mm / minute throughout the test.
The results obtained are presented in Table 8.

Table 8. *Fibres tensile strength.*

Fibre	Wheat straw	Flax straw	Hemp straw	Reed	Hemp shiv	Flax shiv
Tensile strength (MPa)	29	112	73	129	/	/

IV. Mixes choice

Regarding mixes, it was chosen to develop two mixes types: structural and insulating. Soils and fibres selection was made on the basis of materials properties, craftsmen experience and final objective (structure or insulation).

Concerning the water content, it was chosen to work at equivalent consistency by using two tests: the ball test for structure mixes and the puddle test for insulating mixes. Concerning the ball test, a ball of 12.5 cm diameter is dropped at 1 m high. Dry mix has to have a diameter of 17.5 cm and wet mix a diameter of 25 cm. Concerning the puddle test, 100ml of soil is poured from a height of 100mm onto glass. Dry mix has to have a diameter of 7 cm and wet mix a diameter of 14 cm.

Chosen mixes are presented in Table 9.

Table 9. *CobBauge mixes*

Mixes type	Mix	Soil	Fibre	Fibre added mass content (%)	Water content (%)
Structure	1	FR2	Hemp straw	5	25.0
	2	FR2	Hemp straw	5	28.5
	3	FR2	Hemp straw	2.5	28.5
	4	FR2	Flax straw	2.5	28.5
	5	UK1	Flax straw	2.5	31.4
	6	UK1	Reed	2.5	29.3
	7	UK3	Flax straw	2.5	37.0
	8	UK3	Wheat straw	5	37.0
	9	FR6	Flax straw	2.5	31.0
	10	FR6	Wheat straw	2.5	31.0
	11	FR6	Reed	2.5	31.0
	12	FR6	Wheat straw	5	31.0
Insulation	1	UK3	Hemp shiv	50	65.6
	2	UK3	Hemp shiv	50	107.3
	3	UK3	Hemp shiv	25	107.3
	4	UK3	Reed	25	107.3
	5	FR3	Reed	25	131.3
	6	FR3	Hemp shiv	25	131.3
	7	UK4	Reed	25	62.1
	8	UK4	Reed	50	62.1

V. Mixes characteristics

V.1. Compressive strength

Compressive strength was measured on cylindrical sample with dimensions of Ø100×H200mm. Uniaxial compression test was carried out using an IGM press with a capacity of 250 kN. The loading speed used is 0.05 kN/s.
Results obtained are presented in Table 10. Two values of compressive strength are given: the maximum compressive strength and the compressive strength at 2 % shrinkage. It is the second value which will be consider because this value is more representative of the building behaviour.

Table 10. *Compressive strength results*

Mixes type	Mix	R_{cmax} (Mpa)	$R_{c2\%}$ (Mpa)
Structure	1	3.59	1.11
	2	2.63	1.01
	3	2.07	1.45
	4	1.87	1.50
	5	1.47	0.57
	6	0.76	0.46
	7	1.07	0.97
	8	1.32	0.38
	9	1.39	0.95
	10	1.28	0.77
	11	0.93	0.89
	12	1.21	0.30
Insulation	1	0.39	0.09
	2	0.49	0.14
	3	0.73	0.34
	4	0.28	0.11
	5	0.13	0.08
	6	0.44	0.20
	7	0.47	0.20
	8	/	/

Results show that 5 structural mixes have a compressive strength at 2 % shrinkage greater than 0.9 MPa. So, these mixes can be used to build a R+1 building.

V.2. Thermal conductivity

Thermal conductivity was measured on prismatic sample with dimensions of L300×W300×H200mm. Thermal conductivity test was carried out using HFM 436 Lambda. Cold plate temperature is fixed at 0°C and hot plate temperature is fixed at 20°C.
Results obtained are presented in Table 11 and 12. In order to compare results from different partners, thermal conductivity results will be put in relationship with samples density. Indeed, even

if Plymouth and ESITC made samples according to the same operating mode, several parameters such as operator or mix variability will lead to a density variation. It has to be noted that there is no results for thermal mix n°8 because no samples were successfully made.

Table 11. *Thermal conductivity results of structural mixes*

Mix	**λ (W.m^{-1}.K^{-1})** *(ESITC)*	**ρ (kg.m^{-3})** *(ESITC)*
1	0.519	1429.0
2	0.591	1412.9
3	0.417	1423.5
4	0.668	1472.1
5	0.532	1416.1
6	0.446	1389.6
7	0.447	1419.1
8	0.332	1229.4
9	0.423	1395.7
10	0.454	1355.2
11	0.436	1429.2
12	0.271	1143.6

Table 12. *Thermal conductivity results of thermal mixes*

Mix	**λ (W.m^{-1}.K^{-1})** *(PU)*	**ρ (kg.m^{-3})** *(PU)*	**λ (W.m^{-1}.K^{-1})** *(ESITC)*	**ρ (kg.m^{-3})** *(ESITC)*
1	0.104	356.0	0.131	441.7
2	0.109	359.0	0.156	494.6
3	0.209	719.4	0.194	677.8
4	0.181	680.9	0.179	688.9
5	0.172	645.0	0.150	627.3
6	0.193	696.2	0.167	592.0
7	0.160	609.2	0.248	830.9
8	/	/	/	/

Results show that thermal conductivity of insulation mixes goes from 0.10 to 0.21 W.m^{-1}.K^{-1} and, for structural mixes, it goes from 0.27 to 0.67 W.m^{-1}.K^{-1}.

V.3. Acoustic insulation

Acoustic insulation was determined according the relationship of airborne sound insulation value:

$$R_w = 21.65 \cdot log_{10}m' - 2.3 \quad \text{(with } m' \geq 50kg/m^2\text{)}$$

This relationship is usually applied for rammed earth. To apply this, we will take a wall thickness of 30 cm for all mixes. Results obtained are presented in Table 13.

Table 13. *Airborne sound insulation results*

Mixes type	Mix	**R_w (dB)**
Structure	1	54.7
	2	54.6
	3	54.6
	4	55.0
	5	54.6
	6	54.4
	7	54.6
	8	53.3
	9	54.5
	10	54.2
	11	54.7
	12	52.6
Insulation	1	43.6
	2	44.7
	3	47.7
	4	47.8
	5	46.9
	6	46.4
	7	49.6
	8	/

Results show that airborne sound insulation of insulation mixes goes from 43.6 to 49.6 dB and, for structural mixes, it goes from 52.6 to 55.0 dB. As the current minimum requirement for internal walls is 40 dB, all mixes are meeting the regulation.

VI. Results analysis

With all these mixes, results can be used to determine each parameter role on the structural part and on the thermal part. Therefore, we will analyse structural mixes on the basis of compressive strength and thermal mixes on the basis of thermal conductivity. Results will be studied according to soil characteristics (particle size distribution, methylene blue value), fibre content, fibre characteristics (water absorption, tensile strength) and consistency.

VI.1. Structural mixes

The mechanical strength which will be used for this analysis is the mechanical strength at 2 % shrinkage as it is more representative of the building behaviour.

- ❖ Soil characteristics :

To study the influence of soil characteristics on mechanical strength, results from mixes 4, 5, 7, 8, 9 and 12 will be analysed (table 14 and 15). These results show that FR2 has the best behaviour. It seems that a soil needs to have a large amount of silty fraction (60-70%) and a little bit of each other fractions (clay, sand, gravel) to have the best mechanical behaviour. Difference between FR2 and UK1 show that soil need to have a little bit of gravel for a better mechanical behaviour. But FR6 soil show that if there is not enough silt and too much gravel, mechanical behaviour will be too low to use the soil in a structural mix. FR6 and UK1 results show that the lack of silt and clay lead to a mix with not enough binder to keep the structure cohesion.

Table 14. *Compressive strength results of structural mixes (4, 5, 7, 8, 9 and 12)*

Mix	Soil	Fibre	Fibre added mass content (%)	Water content (%)	R_{cmax} (MPa)	$R_{c2\%}$ (MPa)
4	FR2	Flax straw	2.5	28.5	1.87	1.50
5	UK1	Flax straw	2.5	31.4	1.47	0.57
7	UK3	Flax straw	2.5	37.0	1.07	0.97
9	FR6	Flax straw	2.5	31.0	1.39	0.95
8	UK3	Wheat straw	5	37.0	1.32	0.38
12	FR6	Wheat straw	5	31.0	1.21	0.30

Table 15. *Soils characteristics (FR2, FR6, UK1, UK3)*

Sample	Clayed fraction (% < 2µm)	Silty fraction (2 < % < 63 µm)	Sandy fraction (63 µm < % < 2 mm)	MBV (g/100g)
FR2	7.64	69.14	15.94	0.55
FR6	7.97	26.01	28.05	0.84
UK1	2.72	30.43	14.70	0.61
UK3	12.83	66.66	20.07	3.64

- Fibre content :

To study the influence of fibre content on mechanical strength, results from mixes 2, 3, 10 and 12 will be analysed (table 16). These results show that a lower fibre content lead to a better mechanical behaviour. It has to be noted that the R_{cmax} of 5% fibre mixes are similar or upper than 2.5% fibre mixes. This is due to the fact that samples are crushing and not cracking.

Table 16. *Compressive strength results of structural mixes (4, 5, 7, 8, 9 and 12)*

Mix	Soil	Fibre	Fibre added mass content (%)	Water content (%)	R_{cmax} (MPa)	$R_{c2\%}$ (MPa)
2	FR2	Hemp straw	5	28.5	2.63	1.01
3	FR2	Hemp straw	2.5	28.5	2.07	1.45
10	FR6	Wheat straw	2.5	31.0	1.28	0.77
12	FR6	Wheat straw	5	31.0	1.21	0.30

- Fibre type :

To study the influence of fibre type on mechanical strength, results from mixes 3, 4, 9, 10 and 11 will be analysed (table 17 and 18). These results show that flax straw lead to a better mechanical behaviour. It seems that the mix mechanical behaviour depends on tensile strength of fibre. However, mix with reed has a lower mechanical behaviour than mix with flax straw whereas reed has a tensile strength higher than flax straw. This can be due to greater water absorption of reed which can lead to a weaker bond between soil and fibre compared to flax straw.

Table 17. *Compressive strength results of structural mixes (4, 5, 7, 8, 9 and 12)*

Mix	Soil	Fibre	Fibre added mass content (%)	Water content (%)	R_{cmax} (MPa)	$R_{c2\%}$ (MPa)
3	FR2	Hemp straw	2.5	28.5	2.07	1.45
4	FR2	Flax straw	2.5	28.5	1.87	1.50
9	FR6	Flax straw	2.5	31.0	1.39	0.95
10	FR6	Wheat straw	2.5	31.0	1.28	0.77
11	FR6	Reed	2.5	31.0	0.93	0.89

Table 18. *Fibre characteristics*

Sample	Water absorption at 24h (%)	Tensile strength (MPa)
Hemp straw	336	73
Flax straw	185	112
Wheat straw	309	29
Reed	200	129

- Consistency :

To study the influence of consistency on mechanical strength, results from mixes 1 and 2 will be analysed (table 19). These results show that a viscous state lead to a weaker mechanical behaviour compared to a plastic state.

Table 19. *Compressive strength results of structural mixes (1 and 2)*

Mix	Soil	Fibre	Fibre added mass content (%)	Water content (%)	R_{cmax} (MPa)	$R_{c2\%}$ (MPa)
1	FR2	Hemp straw	5	25.0	3.59	1.11
2	FR2	Hemp straw	5	28.5	2.63	1.01

VI.2. Thermal mixes

- Soil characteristics :

To study the influence of soil characteristics on mechanical strength, results from mixes 4, 5 and 7 will be analysed (table 20 and 21). These results show that there is an issue with UK4 soil. Indeed, difference between PU and ESITC results is significant and is due to density. For the two other soils, density obtained by PU and ESITC are similar. These results show that FR3 soil lead to a better thermal behaviour than UK3 soil. It has to be noted that UK3 and FR3 have the same content of clay but a different clay activity. Moreover, sandy fraction of UK3 is higher than FR3. This can explain the higher density of UK3 compared to FR3 and, consequently, the higher thermal conductivity. It was observed also that mixes with FR3 have a better cohesion, it seems that it is due to the clay activity.

Table 20. *Thermal conductivity results of structural mixes (4, 5, 7, 8, 9 and 12)*

Mix	Soil	Fibre	Fibre added mass content (%)	Water content (%)	**λ (W.m^{-1}.K^{-1})** *(PU)*	**ρ (kg.m^{-3})** *(PU)*	**λ (W.m^{-1}.K^{-1})** *(ESITC)*	**ρ (kg.m^{-3})** *(ESITC)*
4	UK3	Reed	25	107.3	0.181	680.9	0.179	688.9
5	FR3	Reed	25	131.3	0.172	645.0	0.150	627.3
7	UK4	Reed	25	62.1	0.160	609.2	0.248	830.9

Table 21. *Soils characteristics (FR3, UK3, UK4)*

Sample	Clayed fraction (% < 2µm)	Silty fraction (2 < % < 63 µm)	Sandy fraction (63 µm < % < 2 mm)	MBV (g/100g)
FR3	12.85	63.32	14.47	5.34
UK3	12.83	66.66	20.07	3.64
UK4	5.59	55.94	19.44	0.83

- Fibre content :

To study the influence of fibre content on thermal conductivity, results from mixes 2 and 3 will be analysed (table 22). These results show that a higher fibre content lead to a better thermal behaviour. Nevertheless, it seems that a content of 50 % by weight is near to the maximum fibre content that can be use.

Table 22. *Thermal conductivity results of structural mixes (2 and 3)*

Mix	Soil	Fibre	Fibre added mass content (%)	Water content (%)	**λ (W.m^{-1}.K^{-1})** *(PU)*	**ρ (kg.m^{-3})** *(PU)*	**λ (W.m^{-1}.K^{-1})** *(ESITC)*	**ρ (kg.m^{-3})** *(ESITC)*
2	UK3	Hemp shiv	50	107.3	0.109	359.0	0.156	494.6
3	UK3	Hemp shiv	25	107.3	0.209	719.4	0.194	677.8

- Fibre type :

To study the influence of fibre type on mechanical strength, results from mixes 3, 4, 5 and 6 will be analysed (table 23 and 24). These results show that reed lead to a better thermal behaviour. This can be due to lower water absorption of reed which leads to a greater soil water content and more pore when the mix is dry.

Table 23. *Thermal conductivity results of structural mixes (3, 4, 5 and 6)*

Mix	Soil	Fibre	Fibre added mass content (%)	Water content (%)	**λ (W.m^{-1}.K^{-1})** *(PU)*	**ρ (kg.m^{-3})** *(PU)*	**λ (W.m^{-1}.K^{-1})** *(ESITC)*	**ρ (kg.m^{-3})** *(ESITC)*
3	UK3	Hemp shiv	25	107.3	0.209	719.4	0.194	677.8
4	UK3	Reed	25	107.3	0.181	680.9	0.179	688.9
5	FR3	Reed	25	131.3	0.172	645.0	0.150	627.3
6	FR3	Hemp shiv	25	131.3	0.193	696.2	0.167	592.0

Table 24. *Fibre characteristics*

Sample	Water absorption at 24h (%)
Hemp shiv	266
Reed	200

- Consistency :

To study the influence of consistency on thermal conductivity, results from mixes 1 and 2 will be analysed (table 25). These results show that there is an issue. Indeed, difference between PU and ESITC results is significant and is due to density. These results do not give a clue on the water content role.

Table 25. *Thermal conductivity results of structural mixes (3, 4, 5 and 6)*

Mix	Soil	Fibre	Fibre added mass content (%)	Water content (%)	**λ (W.m^{-1}.K^{-1})** *(PU)*	**ρ (kg.m^{-3})** *(PU)*	**λ (W.m^{-1}.K^{-1})** *(ESITC)*	**ρ (kg.m^{-3})** *(ESITC)*
1	UK3	Hemp shiv	50	65.6	0.104	356.0	0.131	441.7
2	UK3	Hemp shiv	50	107.3	0.109	359.0	0.156	494.6

VII. Optimised mixes

On the basis all mixes results and the determination of several parameter roles, four optimised mixes have to be chosen. In these four optimised mixes, we choose to have two mixes with UK soil and two mixes with FR soil. To choose the fibre type, fibre availability is one of the criteria. The four optimised mixes proposed are:

- FR2 soil, 2.5 % of flax straw, plastic state
- FR3 soil, 50 % of reed, liquid state
- UK6 soil, 2.5 % of hemp straw, plastic state
- UK3 soil, 50% of hemp shiv, liquid state