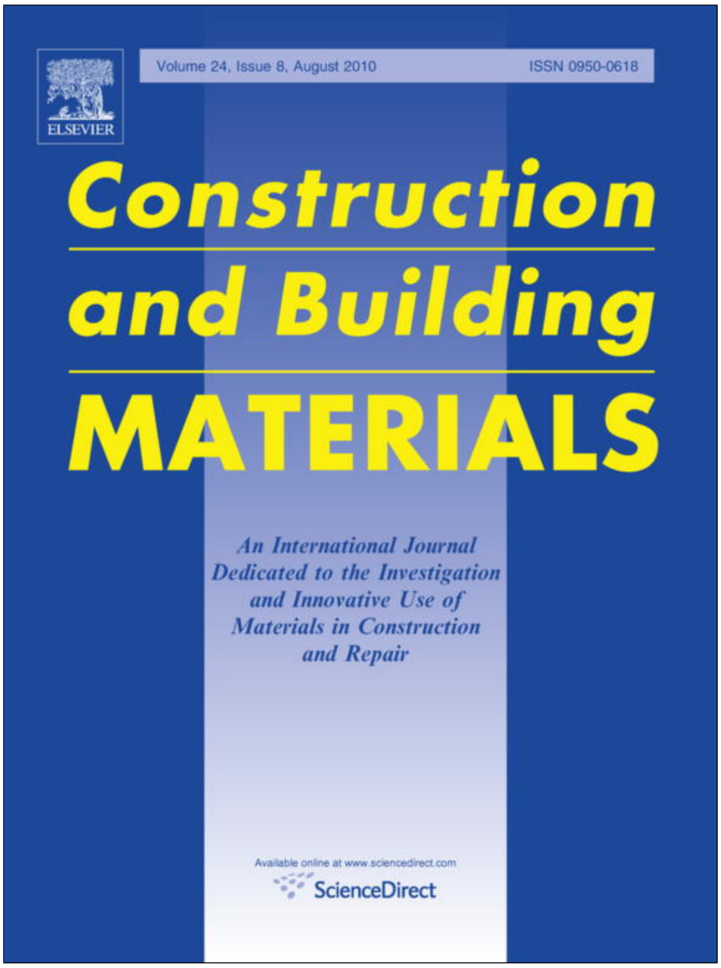
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Clay-based composite stabilized with natural polymer and fibre

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ABSTRACT

The research objective is the stabilization of soils with natural polymers and fibres to produce a composite, sustainable, non-toxic and locally sourced building material. Mechanical tests have been conducted with a clay soil supplied by a Scottish brick manufacture. Alginate (a natural polymer from the cell walls of brown algae) has been used as bonding in the composite. Sheep's wool was used as reinforcement. Tests done showed that the addition of alginate separately increases compression strength from 2.23 to 3.77 MPa and the addition of wool fibre increases compression strength a 37%. The potential benefit of stabilization was found to depend on the combinations of both stabilizer and wool fibre. Adding alginate and reinforcing with wool fibre doubles the soil compression resistance. Better results were obtained with a lower quantity of wool.

1. Introduction

1.1. Sustainability as a goal

Increasingly, humankind's intervention in the planet's eco-system is threatening the prospect of a sustainable future. There is a view that the conflict between mankind's aspirations and the planet's resilience to accommodate them arose during the heady days of the industrial revolution when there was an abdication by design, engineering, and manufacturing, from learning guided by nature's self-perpetuating systems of ecological evolution. Studying and collaborating with nature, asking how nature would solve our design problem is a step towards reversing this abdication.

Sustainability requires resources to be conserved, the environment to be protected, and a healthy environment to be maintained. The World Commission on the Environment and Development suggested the following definition for sustainable development: "sustainable development is the development that responds to the needs of the present, without abandoning the ability of future generations to supply their own needs". The influence of sustainable development on culture, economy, and ecology is of global significance, but there are specific measures for particular regions [1].

Raw earth was one of the first building materials to be used by man. The earliest examples of variously shaped earth "bricks" and of "plasters" are found in the Near/Middle East (dating from X Millennium B.C.). Earth materials were also used in stone constructions, for instance as a constituent of bedding mortars and plasters, and as a filler between stones. Earth was also combined with parts of plant and grasses parts for building huts, as witnessed, for example, by the archaeological findings from the Nuragic civilisation in Sardinia dating back to as early as the Middle Bronze Age (XIV Century B.C.) [2].

Though raw earth has today been surpassed by modern materials that ensure much better performance, in many developing countries, where modern technologies are simply too costly to implement, it continues to be an important building material [3].

The ancient earth building technique known as rammed earth produces dense, load-bearing walls by dynamically compacting moist sub-soil between removable shuttering to create an in situ monolithic compressed earth wall that is both strong and durable. Modern rammed earth construction is enjoying much renewed interest throughout the world as a highly sustainable alternative construction material [4–6]. In areas of certain developed countries [7], such as the south-west region of the United States and Western Australia, rammed earth is widely used.

The main drawback of raw earth is its affinity for water. Most earth buildings are in fact found in arid regions where rainfall is low. The purpose of stabilizing earth-based materials is to improve their mechanical properties and their resistance to the detrimental effects of water by adding a variety of natural (e.g. straw) or man-made (e.g. cement and lime) products. In recent years, a considerable level of interest in earth as a construction material has developed within the United Kingdom driven by its rediscovery as an environmentally friendly building material. The damp, temperate climate of the United Kingdom is quite far removed from environ-

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ments such as those of the arid regions mentioned above. Consequently the environmental performance criteria for buildings there is also very different because problems associated with moisture ingress and dampness are widespread.

1.2. Unfired clay buildings in the UK

Unfired clay materials provide a sustainable and healthy alternative to conventional masonry materials, such as fired clay and concrete block, in both non-load-bearing and low rise load-bearing applications. Environmental benefits include significantly reduced embodied energy, thermal mass and regulation of humidity. Traditional earth construction techniques, including cob, mud-block, wattle and daub, and rammed earth, has a long and largely successful history in the UK [8].

Materials may be taken from sustainable resources (low grade clay and overburden) and are readily re-used, re-cycled or harmlessly disposed on end use. Though the use of traditional vernacular techniques, such as cob, has raised the profile of earthen architecture, wider impact on modern construction is likely from modern innovations such as extruded masonry units.

There are an estimated 500,000 occupied earth buildings in the UK, most built before the 20th century [9]. Earth is primarily used for wall, and occasionally, floor construction. Walls are thick solid construction, in contrast to modern masonry walls, which are generally comprised of two thin leaves with an insulated cavity between.

There are many existing references on the interest in UK about earth construction techniques and unfired bricks. Unfired bricks are nowadays used and mechanical characteristics can be found in [10–15]. Unfired bricks characteristics are sometimes improved adding stabilizers such as cement [16]. Several scientific studies analyse various aspects of thermal insulation [17–19], but all of them stress the environmental benefits associated to this type of building construction materials [20].

1.3. Compressive strength of earth material: literature review

There are many different techniques to use earth as a raw material. Adobe is a natural building material made from sand, clay, and water, with some kind of fibrous or organic material (sticks, straw, dung), which is shaped into bricks using frames and dried in the sun. It is similar to cob and mudbrick. Adobe bricks are unfired sun-dried clay units, whose dimensional stability and control of shrinkage cracks can be achieved by adding organic fibres. Similar to bricks in shape, but bigger in size, they can be stabilized with lime or cement. Clay is the major binder in traditional adobe. Earth used in traditional adobe production must contain approximately 30% clay. To obtain the final dried material, the blocks must be cured for 15–21 days prior to utilization in a site sheltered from sun and rain.

The rammed earth is a clay soil (earth) compacted into a formwork. The earth composition varies greatly but contains no organic component and sufficient clay, which acts as a binder between the grains, a mixture of silt, sand, gravel and stones with a diameter of a few centimetres. Compaction is performed using a water content considered optimum, i.e. that provides the highest dry density for a fixed compaction energy. For traditional rammed earth, the only binder is clay, it is referred to as “unstabilized rammed earth”. Modern rammed earth appeared in western countries after industrialisation when other binders were added, such as cement, hydraulic or calcium lime [21]. They are called “stabilized rammed earth”. The main advantage of stabilizing the rammed earth is to increase its durability (with respect to water attack) and mechanical performance (compressive strength).

Compressive crushing strengths between 0.6 and 2.25 MPa for unstabilized soils are shown by Jiménez Delgado and Cañas Guerrero [22]. According to Spanish standards [23]. Morel et al. [24] summarizes previous studies focused on the mechanical behaviour of unstabilized rammed earth characteristics, showing compressed earth blocks that have been made using a manual press present compressive strengths in a range of 1.5–3 MPa and densities from 1763 to 2160 kg/m^3. Higher strengths are achievable using hydraulic presses and/or higher cement contents, but compressive strengths in the range 2–3 MPa are most typical.

In situ measurements to validate laboratory results were done by Bui et al. [21] in a rammed earth house erected near Thiers (France) and chosen as the subject of the study. The densities obtained were 1980 kg/m^3 and compression tests 1.65 MPa.

Stabilizers such as lime, cement or bitumen, are added to improve particular properties [25]. In countries such as Papua New Guinea clay soils are stabilized with native materials: various percentages of volcanic ash (VA), finely ground natural lime (L), cement and their combinations. The influence of stabilizers and their combinations are evaluated by Hossain et al. [25]. Compressive strength in this case varies between 0.39 and 3.1 MPa. According to Ngowi [26], the strength of the cement-stabilized bricks is 70% higher than the bricks stabilized with lime, as the strength of lime mortar is only a third of the cement mortar.

Atzeni et al. [2] added stabilizers such as hydraulic cements, hydrated lime and polymers (acrylic latex and an aqueous solution of naphthalene–sulphonate), thus increasing compression resistance from 0.9 (unstabilized) to 5.1 (polymer impregnated). Bahar et al. [27] improved to 4.5 MPa with an addition of 10% of cement and up to 6.5 MPa with an addition of 20% of cement as stabilizer. Spanish standards [23] indicate maximum values of 3.6 MPa with lime stabilization and 6.6 MPa with Portland stabilization. Specimens sizes vary widely from cubes $5 \times 5 \times 5$ cm, cubes 10 cm, cubes 15 cm to prismatic $100 \times 100 \times 30$ cm or $30 \times 30 \times 60$ cm.

2. Research objectives

The research objectives are to capture and test the essential, natural qualities of traditional materials through research into enhanced combinations of essential components such as mixtures of soil with natural fibres (wool) for strength and with plant-derived polymer binders (alginates extracted from seaweed) all presently under-explored for their potential as building materials that respond environmentally, contain no synthetic toxins, and may be employed through conventional as well as advanced technology and design. In our study we chose alginate as a natural polymer, which is locally sourced and is a product of the first stage of extraction of alginate from seaweed.

Our research interest was to produce a composite, sustainable, non-toxic and locally sourced building material. As mentioned above, clay-based construction materials are vulnerable to water and therefore inappropriate to the wet climate. Currently the common response is to stabilize mud with cement, tar, synthetic sealers, etc. – all of which change moisture absorption and desorption properties of natural earth and therefore its phase structure and ability to create indoor environment beneficial to human health.

In this research earth is used as a building material and mixed with natural polymer extracted from seaweed and animal fibre – in this case raw, unprocessed wool, to form a composite stabilized against water erosion, with enhanced binding force, increased compressive strength.

All the components in our composite material are non-toxic and readily available in the UK and many other parts of the world. The possibility to build cheaply, using prefabricated panels made of locally available (and non-toxic) materials has an immediate potential in sustainable housing development. The aim is to establish the feasibility of deployment of naturally occurring forms of construction and abundant, and/or replenishable local materials such as soil, wool, and seaweed in the building industry in the UK and beyond. The goal of mass production of local, sustainable and non-toxic building materials will be of major consequence in the future of our planet.

3. Materials

3.1. Properties of the soil

Any soil is basically a mixture of mineral particles (solid), air and water, and is defined by parameters such as Atterberg limits, clay content and chemical analysis. The soil under study was supplied by a brick manufacturer, ERROL Brick Company, based in Perth Scotland, UK. Main characteristics are shown in Table 1.

3.2. Fibre

Plenty of natural materials available have been used as soil reinforcement improving certain engineering properties of soil such as jute, coir, sisal, bamboo, wood, palm leaf, coconut leaf truck, coir dust, cotton and grass etc. Research works are concentrating on limited varieties of materials [28] like bamboo, jute, and coir and other materials are presently left without consideration in the field of soil reinforcement.

Several investigations have been carried out on the addition of coconut and sisal fibre, which have shown very promising results. The addition of 4% of fibres (weight ratio), reduced significantly the occurrence of visible cracks and gave high ductility in soil blocks [29].

Table 1
Soil characteristics.

Physical characteristics		Procedure
Composition %		Sample dried at 110 °C
Silica (SiO_2)		54.70
Titania (TiO_2)		0.97
Alumina (Al_2O_3)		19.70
Ferric oxide (Fe_2O_3)		8.63
Lime (CaO)		0.93
Magnesia (MgO)		3.55
Potash (K_2O)		3.90
Soda (Na_2O)		1.78
Phosphorus pentoxide(Pe_2O_5)		0.17
Chromium sesquioxide (Cr_2O_3)		0.02
Manganic oxide (Mn_3O_4)		0.12
Zirconia (ZrO_2)		0.03
Zinc oxide (ZnO)		0.03
Barium oxide		0.08
Loss on ignition at 1025 °C		5.04
Sand content	22.50%	Bouyoucos Densimeter
Silt content	45.00%	Bouyoucos Densimeter
Clay content	32.00%	Bouyoucos Densimeter
Classification	Clay	International Society of Soil Science (ISSS)
Atterberg limits		
Liquid limit	34.8%	EN 103103 and EN 103104
Plastic limit	19.1%	EN 103103 and EN 103104
Plasticity	15.7%	EN 103103 and EN 103104
Chemical analysis		
Organic material content	0%	UNE 103-204 + Err
Soluble salt content	0.43%	NLT 114
Soluble sulphate content (SO_3)	0%	UNE 103-201 + Err
Lime content ($CaSO_4 \cdot 2H_2O$)	0%	NLT 115
Hydrogen's potential (pH)	8.0	pHmeter, electrometry
Carbonate content ($CaCO_3$)	12.4%	UNE 103-200
Soluble chloride content (Cl^-)	0.027%	UNE-EN 1744-1
Electric conductivity	554.00 μS/cm	Conductimeter 25 °C, saturated plaster
Total dissolved solids	355.00 mg/l	Arithmetic calculus

Tests done by Bouhicha et al. [30] proved the positive effects of adding straw in decreasing shrinkage, reducing the curing time and enhancing compressive strength if an optimal reinforcement ratio is used. Flexural and shear strengths were also increased and a more ductile failure was obtained with the reinforced specimen. Straw in the mixture acts not only as reinforcement but also catalyzes homogenous drying. The large amount of clay required in the binding process causes an increase in shrinkage. Straw in the mixture minimizes the shrinkage and prevents cracks in the earthen blocks.

A review on the existing literature shows that most studies of natural fibres are focused on cellulose-based/vegetal fibres obtained from renewable plant resources. This is due to the fact that natural protein fibres have poor resistance to alkalis and cement is present nowadays is many building construction material. There are very few studies detailing composites made from protein fibres (animal hairs). Barone and Schmidt [31] reported on the use of keratin feather fibre as a short-fibre reinforcement in LDPE composites and showed that protein fibres have good resiliency and elastic recovery. Besides protein fibres have higher moisture regain and warmthness than natural cellulosic fibres properties all related to its possible use in earth material. The keratin feather fibre for these tests was obtained from chicken feather waste generated by the US poultry industry.

Wool fibres exist in abundance in Scotland without widespread use in textile industry any more. The feasibility of using these fibres in conjunction with a soil matrix to produce composite soil has been investigated experimentally.

In our research, specimens have been prepared with an addition of a small amount (0.5–0.25%) of animal fibre – in this case raw, unprocessed wool. It was supplied directly from Scottish sheep and was used, untreated and straight from the animal's skin. This meant that there were no additives to the wool such as detergents.

Table 2
Proportions used (by weight).

Proportion	Soil	Alginate (%)	Lignum (%)	Wool (%)	Water (%)
01ERROL	80.0% ERROL	–	0.5	–	19.5
02ERROL	79.5% ERROL	19.75	0.5	–	0.25
03ERROL	79.5% ERROL	–	0.5	0.25	19.75
04ERROL	79.0% ERROL	19.5	0.5	0.50	0.50
05ERROL	79.5% ERROL	19.5	0.5	0.25	0.25

Fig. 1. Specimen under compression test.

Table 3
Results for density and mechanical tests of the five different mixes prepared.

	Density (g/cm^3)	Compressive strength (MPa)	Flexural strength (MPa)
01ERROL	1.82	2.23	1.12
02ERROL	1.84	3.77	1.06
03ERROL	1.80	3.05	1.10
04ERROL	1.79	4.37	1.05
05ERROL	1.79	4.44	1.45

Lignum, a resin, oil-like substance extracted from tree bark of the genus Guaiacum, also called guayacan was added to improve the workability of the soil, recommended and supplied by the brick manufacturer.

3.3. Alginate

Sodium alginate, with molecular formula: $C_5H_7O_4COONa$ and molecular weight: 216 is a biological polymer, natural polysaccharide consisting of a linear chain of (1–4)-linked residues of b-D-mannuronic acid (M) and α-L-guluronic acid (G) in different proportions and sequential arrangements [32]. Alginates are isolated from the cell walls of various species of brown algae. The biological functions of alginates in the plant include preventing desiccation, maintaining the integrity of the cells and providing mechanical strength. Ion-exchange functions are also important.

Alginates are used in a wide range of applications, particularly in the food, industrial and pharmaceutical fields, because of their capacity to hold water, form gels, and form and stabilize emulsions [33].

For example in food industry is used as a stabilizer of ice cream replacing starch and carrageenan, sodium alginate can avoid of ice crystal and make the product tasty. It also applies to the mixed drinks, such as ice lolly, iced fruit juice and iced milk. Also as thickener and emulsion, in jam, tomato ketchup and canned products to improve the hydration, because sodium alginate also can equal the products' internal form and hold water so that it can be kept for a long time and also as preserving agent [34].

Alginate is a hydrophilic gelling material (such as gelatine, carrageen, pectin and starch), containing 98 wt.% of water. Alginate is utilized in calcium phosphate cements for implanting of prostheses (bones, tooth), where they improve the setting behaviour, the consistency and the mechanical properties of these biocements. In medical industry is also used as a dental impression material and preventing and exclusion from radioactive harmful metals [35]. Sodium alginate is also used as printing agent in textile and printing industry.

In engineering and construction it has been reported and patents have been approved to use alginate for in situ stabilization of contaminated and not contaminated soils [36,37].

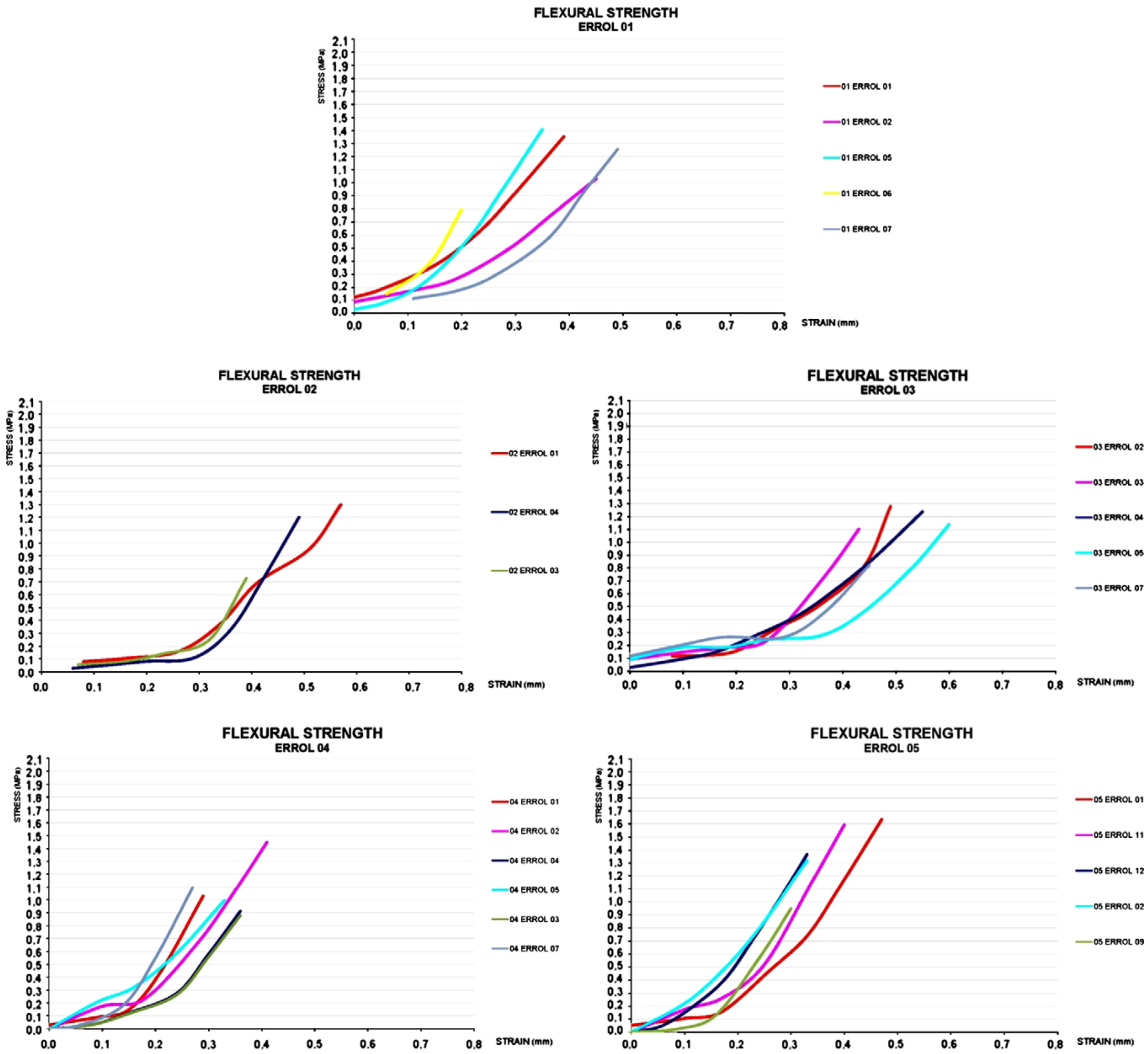

Fig. 2. Stress–strain curves for three points bending flexural tests of the five different mixes prepared with ERROL soil.

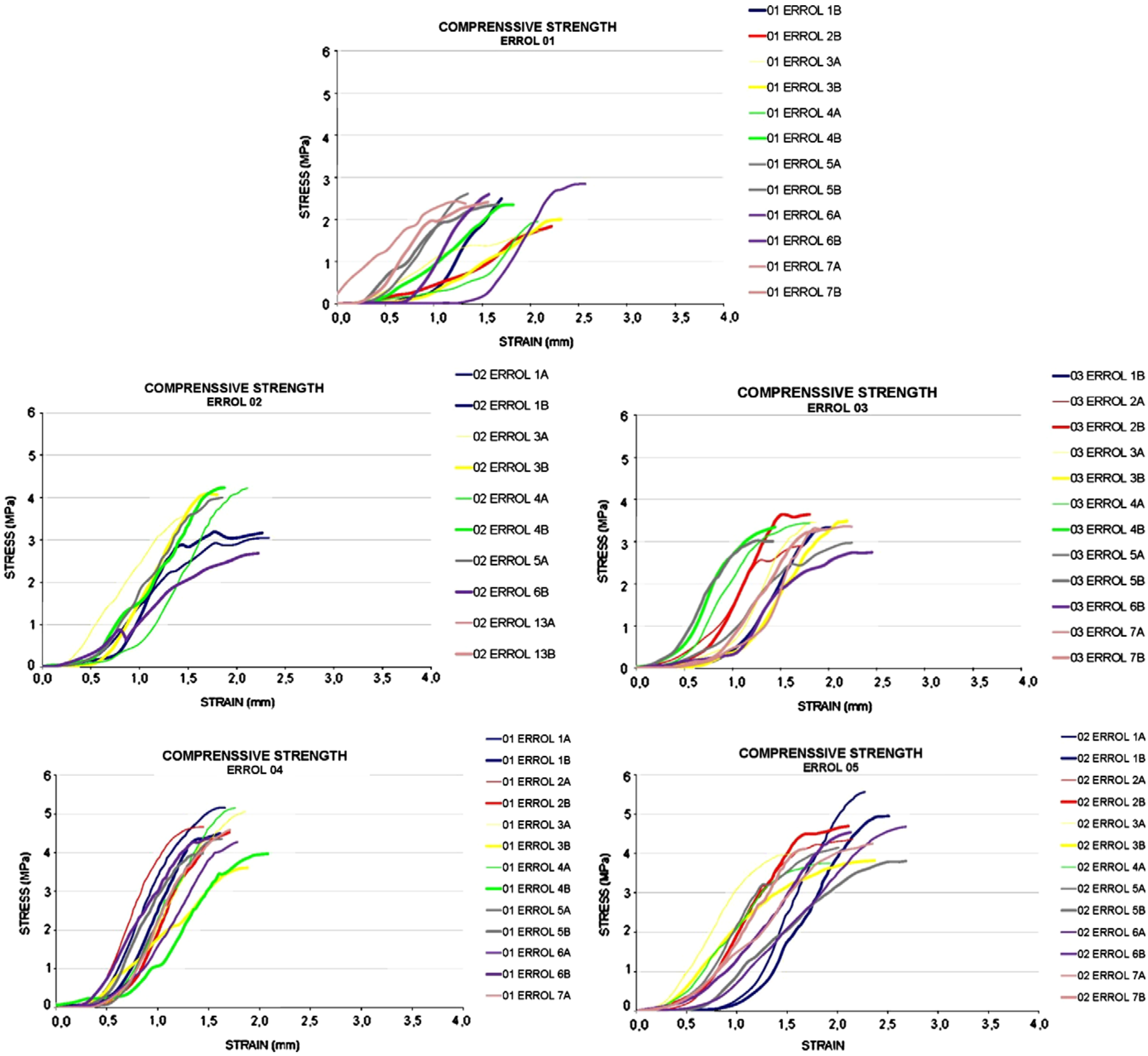

Fig. 3. Stress–strain curves for compressive tests of the five different mixes prepared with ERROL soil.

Few previous tests such as Friedemann et al. [38] have been done to use alginate in building materials. They obtained excellent results to improve the cement hydration using the alginate for internal post-curing with respect to compressive strength and to its frost de-icing salt resistance on high performance concretes. Conclusions on water retention of the alginate additive for internal post-curing and on temporal moisture requirement of the cement during hydration reaction were done.

Alginate for our test, was supplied by FMC BioPolymer, Girvan, UK, as a product named seaweed extract, containing sodium alginate, sodium carbonate, and inorganic salt.

4. Preparation of specimens and testing procedures

Specimens preparation was done following the Spanish-European standards UNE-EN 196-1 2005 [39], UNE-EN 1015-2, [40] and UNE-EN 12190 1998 [41]. According to these standards a 5 l mechanical mixer was used to prepare the material. The optimum moisture content was experimentally determined for the soil using the Proctor test; standard compaction. Further details of this methodology and associated test results have been published by Hall and Djerbib [7].

Soil mixes presented a very dry consistence and difficult workability, related to the very high ERROL soil plasticity index (Table 1) especially in the liquid limit value.

Standard steel moulds for prismatic 40 mm × 40 mm × 160 mm specimens were used. The pouring and placement of the mix was done according to the standards and mechanical compaction was done. All specimens were placed in an oven at 50 °C to dry for 24 h before unmolding. According to the standards no curing time in wet chamber was necessary due to the absence of cement in the mixes.

To test the influence of the addition of the different elements, the five different proportions used were named and listed. The number of specimens manufactured for each ratio was seven. Previous tests were carried out on natural soil without addition (just water and lignum), plus fibre and/alginate and with two different proportions of fibre, as shown in Table 2.

The cast and hardened mixes were tested for their mechanical properties. Tests developed were density, bending strength and compressive strength. The bending strength was determined using the three-point test on the specimens, according to the specifications of EN 83-821-925 [42] Spanish standards for the determination of bending strength of mortars used for rough castings and mortar linings, in the absence of EN standards for this type of mortars.

The apparatus used was a Codein S.L., MCO-30/139 tester (Fig. 1). According to standard procedures, applies a load up to 10 MPa ± 1.0%. In agreement with the specifications, the charge velocity used has been 0.5 MPa/s.

Compressive strength was determined in both halves of each prismatic specimen, after breaking them in a three-point bending test strength test. This test complies with the EN 83-821-925 Spanish standards for the determination of compressive strengths in mortars used for rough castings and mortar linings, being made with lime or hydraulic conglomerate, in the absence of specific UNE standards for this type of mortars.

5. Results and discussion

Table 3 shows average values of results for the compressive and three-point bending test. Each value represents the average of a total of 7–14 specimens. The number and series of specimens was according to these standards and depending on the number of different mixes (proportions) tested, with a minimum of five specimens per batch.

One of the significant effects of the inclusion of natural fibres in the soil matrix was the prevention of visible shrinkage cracks due to the drying process. The failure mode of the specimen made of natural soil was very quick and almost without warning. In contrast, in the case of the composite material, after the ultimate load was reached the specimens still deformed and fine cracks could be seen on the surface of the specimens. This was the same for all the composite soil material.

The compression stress–strain curves for flexural and compression tests done on prismatic specimens of 4×4 cm are given in Figs. 2 and 3. Each graph represents the results of all the specimens and shows the homogeneity of the results. It can be seen in Fig. 2 that the addition of wool plus alginate stabilization increases the slope of the curve and hence the Young's modulus of the material.

The stress–strain relationship is linear for all the test series up to maximum load. For the natural soil the final failure occurs immediately after the ultimate load. However, in tests on soil with natural fibres work softening can be seen. This may be explained by considering the redistribution of internal forces from the soil matrix to the reinforcing fibres. After final failure the soil–fibre composite was not disintegrated completely in contrast to natural soil specimens. Also it must be mentioned that the fibres hold soil matrix and together no rupture of fibres occurred although a loss of fibre bond was observed. The bonding between the soil and the wood fibres will be examined at the microstructure level to establish the factors that influence soil–fibre bonds.

Density remains very similar in all the tests. Bare soil has the highest density. When adding alginate or wool, density decreases but not significantly, always between 1.79 and 1.82 g/cm^3.

Tests showed that adding alginate increases compression strength from 2.23 to 3.77 MPa a 69%. The addition of wool without alginate (maybe due to its hard workability) does not improve performance so much: adding only wool also increases compression strength a 37%, from 2.23 to 3.05. But the addition of both, wool and alginate improves quite significantly (doubles) ERROL soil resistance up to 4.44 MPa. Better results were obtained with a lower quantity of wool. Test results have shown that for the ERROL soil, the optimum wool/soil ratio needed to produce a high-strength soil matrix is just 0.25%.

As expected, adding alginate or wood alone does not improve flexural resistance at all. Mixing wool + alginate increases a 30% its flexural resistance only in case of 25% of wool but not so significantly as with compression strength.

6. Conclusions

This study presents the characteristics of clayey soils stabilized with alginate and reinforced with sheep wool fibre. On the basis of the test results obtained from five different stabilized soil mixtures, the following conclusions can be drawn:

- The potential benefit of stabilization was found to depend on the combinations of both stabilizer and wool fibre. Alginate stabilized soils showed better mechanical characteristics than unstabilized ones and similar to those stabilized with cement and lime. However, a low percentage of wool fibre 0.25%, can be more effective than a higher content of wool. The influence of adding just the stabilizer or the fibre alone has been studied and also produce acceptable mechanical characteristics.
- The addition of wool and alginate increases the compressive strength of stabilized soil specimens. The compression strength values obtained (4.44 MPa) are similar to the values mentioned in Spanish standards [23] for Portland cement stabilization with medium dosage (10% cement content) and better than the values mentioned for high dosage of lime (3.6 MPa).
- The potentials of alginate in the soil stabilization are considerable compared to lime and cement. Since seaweed as well as clayey soils are abundant in many parts of the world, alginate stabilized soils can be potentially utilized as a substitute of cement-stabilized soil. The proposed use of natural stabilizers should help promote sustainable development in the construction industry.
- In this paper the 10 mm long fibres, introduced randomly, were used in the production of the soil composite. It will be necessary to investigate other dimensions in order to establish the optimum length for maximum strength. The effect of fibre orientation inside the matrix should also be studied. Furthermore, in order to understand better the bond between soil matrix and fibre, a study of the microstructure is needed.
- This paper has focused on mechanical properties of stabilized earth. Further tests such as thermal conductivity, air permeability, moisture absorption and desorption and resistance to water are being developed at the moment to investigate their resistance to detrimental effects of water, in order to asses sustainability and practicality of extending its use to temperate climates such as UK.

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