"Trees and Livestock"

Farm Woodland Forum
Annual Meeting at GWCT Allerton Project, Loddington, Leicestershire

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Game & Wildlife CONSERVATION TRUST
The Allerton Project

Farm Woodland Forum
Farming with trees

"After thirty years UK agroforestry, are we barking up the wrong trees?"

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Abstract:

UK agroforestry has focussed on growing specimen trees for timber planted across arable fields or pastures. However, this has several disadvantages such as long growth periods (30 - 100 years), low short term economic returns, long term threats from fungal diseases and pests - as well as major reduction in crop yields or pasture productivity (unless species with edible leaves are planted); in addition, it appears that for some species timber quality from comparatively fast grown widely paced trees is poor compared to well managed forest grown trees. Should we not look to alternative markets - while biofuel is well catered for, there may be major potential to address the burgeoning eco-house market. In Sweden quality timber is shredded to produce wood wool, which is then bound with cement to form both wood wool cement insulation panels as well as large wall elements. These elements are non-load bearing, but a system using poured reinforced concrete frames has been developed. In the UK wood wool cement insulation can replace baled straw in eco-house construction (such as "Mod-Cell") and give six hour fire resistance compared to only two hours for straw bales. Standard stud walls or I-joist stud wall construction to UK standards can be used for 40 cm wide wood wool cement insulated walls, and systems for local off-site production in "Pop-Up" factories developed. The key aspect for developing wood wool cement systems is that the wood wool can be produced by direct harvesting of short to long rotational coppice with a biomass harvester, or by mechanical pollarding of "windbreaks" with shredding of this growth on a four - six year rotation. This will result in early returns to the forestry component, while eliminating depression of crop and pasture yields currently experienced with mature trees. Small scale samples of wood wool / binder using various binders including PVA alone, cement + lime, lime + burnt gypsum, burnt gypsum alone, and clay/PVA are shown, and Demo stud and I-stud frame walls are presented. The paper concludes with proposals for future studies / activities and funding sources.

1. Introduction

1.1 Where are we now?

Several sylvoarable and sylvopastoral trials established in the late 1980s in both UK and the rest of EU focussed on growing timber trees on high value agricultural land. Instead of high density tree planting as in forestry at 2500 to 4000 stems/ha where trees are thinned or allowed to self-thin to a final population of 100 – 400 stems/ha, in these agroforestry systems high value timber species are planted at near final spacing and the trees treated as individuals with high pruning. Besides production of high value timber, objectives of the timber agroforestry systems include continued agricultural production to cover the costs of timber establishment in the early years, reduced time to timber harvest due to use of high quality land, and environmental benefits to crops and to pasture/livestock systems. Examples include high value timber / crops near Montpellier, France (Fig. 1a) and sheep under Ash trees (*Fraxinus excelsior* L.) at Loughgall, Northern Ireland (McAdam 2018) (Fig. 1b).

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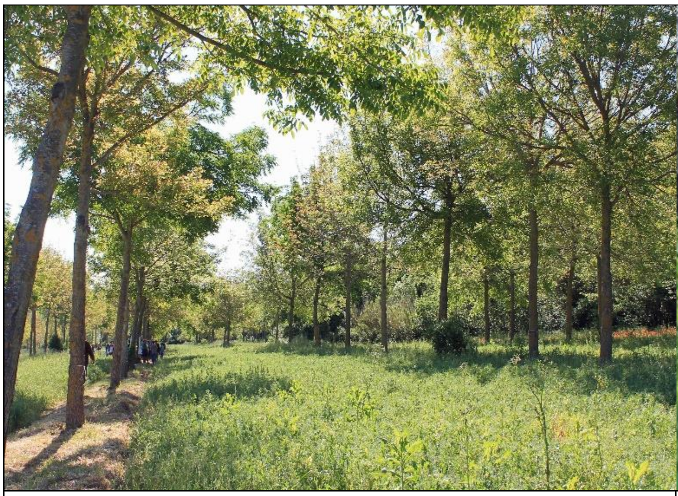


Fig. 1a. Sylvoarable system near Montpellier, France

Photo: J.H. McAdam

Fig 1b. Sylvopastoral system, Loughgall, NI

However, these timber agroforestry systems have problems that include:

Trees: Both arable and pastoral systems tend not to meet expectations for high value timber due to:

- A time frame for timber production that far exceeds that of agricultural systems - especially slow growing high value species such as oak
- Poor growth form of widely spaced trees which affects trees in both sylvoarable and sylvopastoral systems – although this depends on tree species and plant breeding
- Inferior timber quality due to both the growth form and to more rapid growth of the trees within fertile agricultural systems – as noted by timber specialists at EURAF 2016.

So, although timber can be produced from any tree (Mike Strachan, *pers. comm.*), it is likely that the high expectation for agroforestry systems may not be met.

Crops: In planning AF systems it is anticipated that once the tree canopy closes most crop production will become uneconomic. The time at which this occurs depends on the distance between tree rows / alleys, the geographical situation and the tree species. Competition was expected to be primarily for light, but experience shows that in the main arable areas competition for moisture can be more important – unless crops are irrigated. In Bedfordshire UK it became uneconomic to grow wheat under Poplar grown with 12 m alleys by about year 12 due to moisture competition, even though the tree roots primarily ran along the tree rows. This competition effect is shown in Fig. 1a for trees in similar alleys in Montpellier, where studies on moisture flows in the trees are being undertaken (Fig. 2). Such competition impacts on the short and long term economics of the AF system. Commercial systems with 24 – 48 m alleys would allow extended contributions from the crop component. Alternatively, trees planted with narrow

Fig. 2. Scientific measurements on individual trees, Montpellier, 2016

alleys can be thinned within rows or entire rows can be harvested to maintain crop growth – as for the closely spaced Paulownia rows that were grown in the NE Plains of China. Shade loving crops can also be cultivated to extend the duration of the agricultural component.

Pastures / Livestock: In general, similar competition effects were anticipated for the pasture component of sylvopastoral systems. However, in NW Europe where grassland production is concentrated in wetter coastal zones, McAdam (2018) has shown the benefit over thirty years of timber trees grown in an orchard configuration. This arises both from the trees sucking moisture from the soil which results in greater trafficability of the soil and extended grazing season; and from use of a tree species (Ash) which has edible leaves so that fallen leaves in autumn compensate for any reduction in pasture yield. In this case Ash trees were thinned to one quarter of their original population which allows continued pasture growth – while providing an excellent environment for the animals. This benefit would be lost with tree species that have inedible leaves at the time of leaf fall.

1.2 Invasion of Mesquite (Prosopis juliflora) in the Afar Region of the NE lowlands of Ethiopia

A year ago, the author was requested to act as interim rangeland restoration / dryland specialist for a German funded project to improve the resilience of the pastoral and agro-pastoral peoples of Afar Region to drought. Among the Terms of Reference was: "*large scale mechanized debushing as in Namibia*". The main subject for debushing is the invasive woody species *Prosopis juliflora* or Mesquite which was introduced 30-40 years ago from the southern US / Mexico by FAO[2] for sand dune stabilisation and by cotton and sugar cane managers for stabilisation of irrigation bunds. Mesquite is an incredible plant – it has a tap root down to 40 m, which is twice that of most Acacia species, so it can tap ground water; it also has a surface rooting system of fine roots that extend 1 metre beyond the tree canopy cover. While being most effective at stabilising sand dunes, it is a prolific seeder – the seeds are carried down irrigation channels and river systems, so that it has now invaded the seasonally flooded grasslands that make up the dry season and drought reserves of the pastoralists. In 4 - 6 years it reaches 4 - 6 m in height, has numerous thorns 5-7 cm long, and forms dense monospecific stands that are impenetrable to livestock (Fig. 3). At this stage multiple stems are up to 5-7 cm thick (Fig. 4a).

3a. 4 y old stand in Teru district

3b. 6 y old stand in Yalo district

Fig. 3. Invasion of dry season grazing by Mesquite in Afar Region of NE lowlands of Ethiopia (1)

It can be cleared by hand, but even when stumps are dug out regrowth is rapid. The regrowth shown in Fig. 4b is only one year old. Full control is only possible with integrated mechanical and chemical control, as Integrated *Prosopis juliflora* Management (IPjM) as proposed by the author at the Inception Workshop of the Project. Biological control is being introduced in RSA but is slow and long term. 1.5 million ha have been invaded by Mesquite in Ethiopia alone, and it is the major invasive species from

[2] FAO: Food and Agricultural Organization of the United Nations

Sudan to Kenya in the Horn of Africa, Republic of South Africa, and into desert regions of south Asia such as Pakistan and NE India.

4a. Multiple stems of 6 y old Mesquite in Yalo district | *4b. One year old regrowth of Mesquite in Yalo district*

Fig. 4. Invasion of dry season grazing by Mesquite in Afar Region of NE lowlands of Ethiopia (2)

1.3 Large scale Mechanical Debushing

While in Ethiopia in May / June 2017 the author was informed of the actual situation in Namibia. Local rangelands had been invaded by various Acacia species in a similar way to Mesquite in Ethiopia. A local cement factory installed equipment to co-fire Acacia biomass at up to 50% with coal. Two companies were set up to supply the biomass from local ranches, each with four self-propelled biomass harvesters model BMH-480 from AHWI Prinoth in southern Germany (Fig. 5a). These have an H-600 biomass

Photo: AHWI Maschinenbau GmbH

5a. BMH-480 biomass harvester in Namibia harvesting invasive Acacia species

Photo: AHWI Maschinenbau GmbH

5b. H-600 biomass harvester on RT-400 crawler platform harvesting Mesquite in Rajasthan

Fig. 5. Biomass harvesters from AHWI Prinoth of Germany

harvester mounted on an RT400 crawler platform with a hydraulic high-reach side-unloading biomass container mounted behind[3]. Unfortunately, these machines proved too sophisticated for Africa. A more durable and robust system is the H-600 biomass harvester mounted by 3-point linkage on the basic RT-400 crawler platform[4], and this is being used successfully to harvest Mesquite in Rajasthan, India (Fig. 5b). The H-600 harvester costs around EUR 200,000 and can also be mounted on reverse drive wheeled tractors of 300 – 500 HP. Compared to use of forage harvesters that chip biomass, the H-600 harvester uses knives to shred woody biomass, with a final set of chopping knives mounted on the output fan. With 4-12 knives fitted, chop length can be varied. The output resembles "Wood Wool"

[3] https://www.prinoth.com/en/vegetation-management/products/biomass-harvesting/bmh-480-130/
https://www.youtube.com/watch?time_continue=50&v=l7EdOjuB8Hw [Copy & Paste all Links]

[4] https://www.prinoth.com/en/vegetation-management/products/biomass-harvesting/h-600-129/
https://www.youtube.com/watch?time_continue=22&v=sbJveZC4sJs [Videos may start at end – go to start!]

Photo: Eden Products Ltd	Photo: AHWI Maschinenbau GmbH	Photo: AHWI Maschinenbau GmbH
6a. "Wood Wool"	*6b. Mesquite biomass being tipped*	*6c. Mesquite biomass*

Fig. 6. "Wood Wool"; and Shredded biomass from the AHWI H-600 Harvester in Rajasthan, India

(Fig. 6a). In Rajasthan this is piled into heaps and dries down to 15% moisture within two weeks – given temperatures of 40-50 C and 10-20% humidity (Fig. 6b, c). The same should apply in Afar Region, ET.

Arrangements had been provisionally made for the biomass harvested in Afar Region to be baled and wrapped (to prevent loss of seeds) and transported from the lowlands to one of two cement factories on the Ethiopian plateau that had already been equipped for co-firing. Unfortunately, these arrangements unravelled when it became apparent that firstly this could be part of a land-grab by non-Afar agencies; and secondly that the cement factories did not see the need to pay for the biomass as harvesting was part of an externally funded project for debushing Mesquite.

For debushing to be sustainable beyond the life of the project, it is essential that economic uses can be found for the harvested biomass. If carried out by large scale mechanical means, this would amount to up to 100 tons per day (air dry) at 10 ton per hour, and 200,000 tons per year with a 200 day harvesting season. Depending on the age of the Mesquite stand, yields would be 40 – 80 t air dry biomass/ha. Possible uses for the mesquite biomass are given in Table 1, although these are not exclusive.

Table 1. Economic utilisation of harvested shredded biomass in Afar Region of Ethiopia

LOCAL USES	NATIONAL AND INTERNATIONAL USES
• Biochar • Compost • Toxic mulch • Biofuel pellets • Combined Heat & Power (CHP) • Fibrous binder in cob wall construction	• Bale and wrap biomass • Transport bales to cement factories for co-firing (50%) • Export biofuel pellets • Make Wood Wool Cement (WWC) building products

Production and trial application of biochar for soil amelioration was in the original TOR, as was evaluation of making compost and use as a mulch. Manufacture of biofuel pellets for either local or international use for CHP[5] has been evaluated; although it allows an international value to be placed on the biomass, costs of both production and export are high – although a possible turnkey role for a Chinese company should not be ruled out. Wood wool, besides packaging, has multiple uses in the construction industry – with possible application both in Ethiopia and in the UK / EU.

Initial trials at a building materials institute in USA showed that OSB panels made with shredded mesquite, even including leaves, passed standard tests for equivalent panels made from high grade timber. Mesquite is a hardwood, and as a timber is far stronger than tropical softwoods grown in the same environments.

[5] CHP: Combined Heat and Power

2 Wood Wool Cement Construction Products

Several Wood Wool Cement (WWC) building boards are produced commercially on a large industrial scale, such as those in Fig. 7. Typically, these use Wood Wool 33-50% and a cement based

Photo: Skanda Savolit

Examples:

- Skanda Savolit (*see image on left*)
- Celenit
    - 35% Portland cement
    - 15% calcium carbonate (marble dust)
    - 50% long strong fir fibres
- Eltomation
    - High density 1000-1400 kg/m^3
    - Medium density 600-1000 kg/m^3
    - Low density insulation boards 280 – 400 kg/m^3

Fig. 7. Examples of Wood Wool Cement Building Boards

Binder 50-67%. Dimensions of the wood wool strands depend on the purpose the cement board is to be used for; fine and long strands are best for boards to be used for heat insulation, while wide thin strands are used for structural boards. Fine fibre and sawdust are used for high density flooring boards. The Binder comprises either straight Ordinary Portland Cement (OPC) or approximately 2/3 OPC and 1/3 calcium carbonate, although other compounds may be included. During the maturation process the binder reabsorbs half of the carbon dioxide displaced during the production of the cement. The density of the boards to a large extent determines their strength – low density boards are non-structural insulation boards, while medium and high density boards have increasing structural properties.

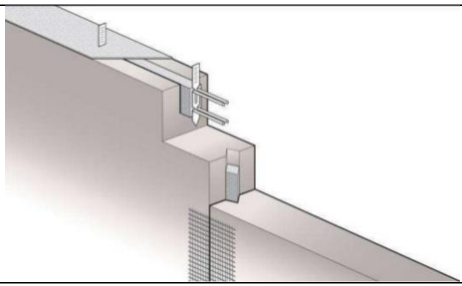
Given the large quantities of Wood Wool that can be produced by a single biomass harvester, and the current low state of house construction in UK, the Large Wood Wool Cement Wall Element Building System developed by Eltomation in the Netherlands with Traullit in Sweden (Fig. 8) is of interest[6].

Photos: Eltomation (NL)

Fig. 8. Large Wood Wool Cement Wall Element Building System (Eltomation)

Whole wall elements 400 mm thick are formed of wood wool cement off site. Spaces for vertical columns and ring beam are moulded in. After setting, elements are transported to prepared sites, and load bearing columns and beams poured over steel reinforcement (Fig. 9). Elements then receive

[6] https://www.eltomation.com/application/files/6714/5768/9051/1_Traullit_LE_folder_ENG.pdf
https://www.eltomation.com/eng/our-products/large-wwc-wall-element-plant
https://www.eltomation.com/eng/our-products/wood-wool-cement-board-plant
https://www.youtube.com/watch?time_continue=116&v=0-J0LSuvmmM



Photos: Eltomation (NL)

Fig. 9. Wood Wool Cement Wall Element Building System: Principles, and Pouring of Concrete

30 mm plaster on the inside, and 30 mm cement render on the exterior. With a density of 330-350 kg m^3, the elements have high insulation as well as high heat storage capacity.

Photo: Eltomation (NL)

Fig. 10. Production line for Wood Wool Cement Boards and Wall Elements (Eltomation)

Eltomation (NL) market large scale plants for producing WWC boards and WWC wall elements (Fig. 10). These can output elements for the construction of 1000 houses per year, using small diameter soft wood and thinnings from Pine / Spruce and Poplar / Aspen. Such plants, and new production lines specifically designed for WWC wall elements, each cost around EUR 10 million. When the author put the above information to the Project in Afar, the concept was rejected as too large a scale and taking more time than available. However, the author thought the concepts could be applied and tested on a small scale, for use in Afar with Mesquite, and in UK with local woody resources and equipment. Hawkes and Cox (1992) had in fact described a medium scale system developed at NRI (Natural Resources Institute) for developing countries based on a scaled down version of the Eltomation process.

3 Backyard production of Wood Wool Elements

3.1 Biomass sources

Starting in March 2018 the author sourced biomass as "water wood" from both crab apple and traditional apple trees growing in his garden (Fig. 11). These were pruned in March and April respectively, and 1 – 2 year old shoots selected (Fig. 12). Prunings of Leylandii were also shredded in June after removal of leaves. With heavy duty shredders, pollards could potentially be selected from Poplar, Plane and other suitable species (Fig.13).

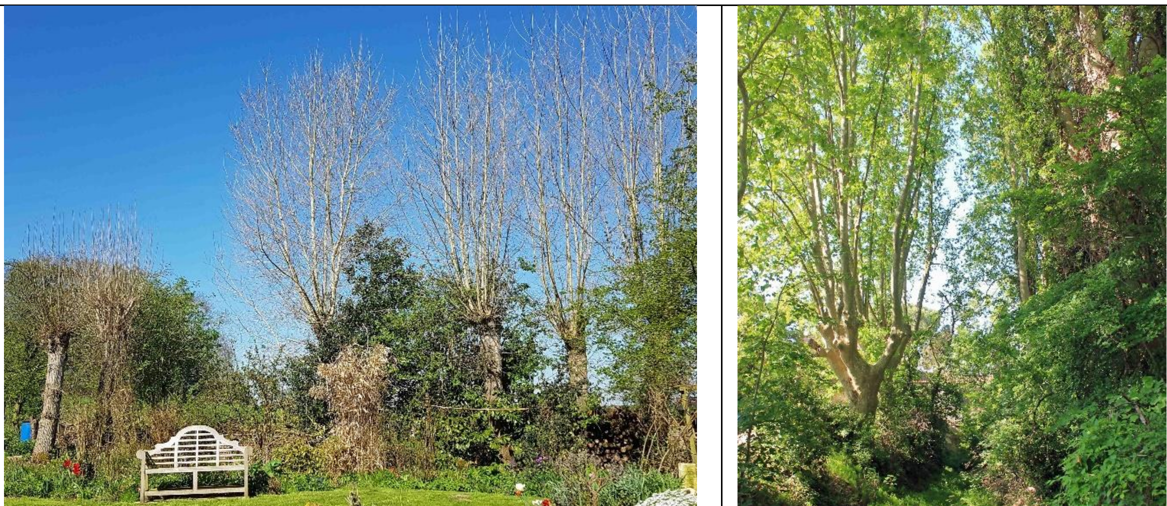
3.2 Biomass preparation – Shredding, Sieving and Drying

A Ryobi 2HP Model RGS 1500 "Trisecta Mulch Maker" 3 cycle garden shredder was used (Fig. 14a). This has a "V" blade for shredding (Fig. 14b) in addition to horizontal knives for chipping. The 1-2 year old green crab apple and apple shoots were forced through the shredder to obtain as long pieces as possible – around 75 mm long. Much of the bark was shredded finely. The whole shredded biomass was passed over a 10 mm screen or a 10 mm garden sieve (Fig.15), and the fractions were air / sun dried and stored separately (Fig. 16). For this demo we shall designate the coarse fraction as "Wood Wool".

11a. Crab Apple | *11b. Traditional Apple*

Fig. 11. Sources of biomass (1) Water wood from top fruit trees

Fig. 12. Sources of biomass (2) Selected 1-2 year old water wood from a traditional Apple tree



13a. 50 year old Poplar windbreak – Kenfield, UK | *13b. Pollarded Plane tree, Montpellier, France*

Fig. 13. Sources of biomass (3) 2 - 8 year pollard growth

14a. The shredder set up | *14b. Shredding V blade and chipping knives*

Fig. 14. Shredding of apple water wood biomass with a Ryobi "Trisecta Mulch Maker"

15a. Whole biomass | *15b. Fine fraction <10 mm* | *15c. Coarse fraction > 10 mm*

Fig. 15. Sieving of shredded biomass from Crab Apple over 10 mm screen

16a. Drying fine fraction | *16b. Drying coarse fraction*

Fig. 16. Air / sun drying shredded biomass from Crab Apple (beneath a pergola)

This exercise was to demonstrate possibilities of local WWC production. Genuine wood wool is available in UK from www.edenproductsltd.co.uk made in EU from sustainable wood sources.

3.3 Run #1. Application of dry binders to soaked wood wool

The objective was to compare different binders to produce wood wool / binder insulation for use in large element building systems. While the standard method uses cement, this has a high carbon footprint, requires imported coal and is relatively expensive. Lime requires less energy for production and reabsorbs the CO_2 released in its production. Gypsum (Burnt gypsum or Plaster of Paris) only has to be heated to 150C and is mined in Afar Region to produce Gypsum boards.

The target density was 200 kg m^{3}. Cardboard 5-ream A4 paper boxes were used as moulds, volume 12,000 cc, lined with plastic garden sacks. Following early methods for WWC products, the binders were applied at a rate of 2/3 binder (1600 g) : 1/3 air dry wood wool (800 g) (Crab Apple > 10 mm). The wood wool was soaked in water for 24 h, drained, mixed with dry binder by hand in a bucket, and gently pressed into the moulds. For one treatment liquid PVA 25% by weight diluted x2 was added to dry wood wool. Results are presented in Fig. 17. with comments. Dry application of binders and lining of moulds with plastic was not successful. Application of PVA to dry wood wool was successful but will act as a barrier to water vapour transfer (Ingrid Chauvet, *pers. comm*); it may also have a higher fire risk. Sugars in the sap may have "poisoned" the cement binder, so that 3-5% calcium chloride needs to be added to the soaking water to form a mineralising solution for "detoxification" (Hawkes & Cox 1992).

	**Cement (OPC**[7]**)**: due to denser binder only filled 80% of mould. Dry but not set – crumbly throughout although the approved method had been followed		**Lime**[8]: additional water needed to get good distribution of binder. Set at top but still moist at base
Gypsum: additional water needed to get good distribution of binder. Only set on surface but not bonded throughout; oven dried at 80C, lower part bonded as single block.		**PVA**: wood straw compacted when wet – needed extra 50% WW / PVA to fill mould. Good bonding but flexible, final drying in oven at 60C.	

Fig. 17. Results of Run #1 – soaked wood wool with dry application of binders (except PVA)

3.4 Run #2. Application of clay as binder with dry wood wool

Town buildings in Afar are stick framed with cob infill comprised of mud / straw / animal dung. The same mould was used as for Run #1, with the same ratio of dry binder (2/3) to air dry wood wool (1/3) by weight. The cardboard mould was not lined to allow moisture to move through. Wood wool was air dry apple wood. The single treatment was:

1) Clay (modelling clay at ± 50% moisture) (3200g) + PVA solution (200g) + wood straw (800 g). This was mixed with water to a "cow pat" / plasterers consistency to hang off a trowel but the mix was too dense so that an additional 600 g of wood wool was added (total 1400 g WW). After setting the mould was air / sun dried until solid.

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[7] OPC: Ordinary Portland Cement
[8] Lime: The lime used was powdered hydrated lime, which may have lost its main activity (Ty Mawr) https://www.lime.org.uk/products/lime.html

The Wood Wool / Clay block set well but had little strength and tended to fall apart when fully dry (Fig. 18). However longer / finer particles of wood wool would provide a better matrix, while internal plastering and external rendering would stabilise a wall. Wood wool from Mesquite could easily replace most cereal straw and animal dung in local construction in Afar.

3.5 Run #3. Application of binders as slurries to dry wood wool

Following further study of commercial systems, it was noted that "Celenit[9]" WWC insulation boards are made with approximately:

15%	$CaCO_3$ (marble dust)
35%	Mainly OPC cement
50%	Wood fibres

In addition, for non-structural insulation products a density of 280 – 380 kg/m^3 is normal. The Eltomation 400 mm thick Large Wall Elements have a density of 350 kg/m^3.

The same 12,000 cc cardboard moulds were used as before but without a plastic liner, with a target density of 300 kg/m^3, and a ratio of wood wool 50% binder 50%. The following binders were tested applied as slurries to air dry wood wool[10] without prior soaking:

1) <u>Cement / Lime</u>: Rapid set cement[11] (OPC) 67%: Hydrated Lime 33%
   (to speed up setting – also a finer cement while the lime improves plasticity)
2) Lime / Gypsum: Hydrated lime 67%: Burnt gypsum (Plaster of Paris) 33%
   (the gypsum speeds up setting of the lime)
3) Gypsum: Burnt gypsum 100%

With the higher proportion of wood wool, the volume of the moulds was exceeded. Weights in the form of 4 x 0.7 kg bricks were used to press the mix to fit the mould for 2 h, then removed. For each treatment four batches each of ¼ of the mix were prepared by hand mixing in a bucket to fill a single mould. The quantity of water was critical: for #1 Cement / Lime, one mix made up as follows was best:

50% Binder		
	2/3 Quick Drying Cement	300g
	1/3 Hydrated Lime	150g
50% Wood Wool (air dry apple >10mm)		450g
Water		500g

The resulting blocks are shown in Fig. #18 after two weeks setting. Target densities were almost achieved, and excellent block properties were obtained with cement / lime and lime / gypsum binders. These blocks can be freely handled without disintegration. Cement / lime was the hardest binder and was used for further studies on plasters and renders (see below). Drying time with the quick setting cement was half that for lime / gypsum. Gypsum alone produced a hard surface, but improved setting / drying conditions are required for it to be used for thick large wall elements. It can be used for thin medium density boards, especially in hot dry climates such as Afar; however, it lacks the protective properties against mould and insects provided by the extreme alkaline conditions of cement binders.

4 Development of timber based structural building systems to use with WWC large wall elements

The Eltomation / Traullit off-site building system using Large Wood Wool Cement Wall Elements uses poured reinforced concrete for vertical and horizontal structural components. While houses in Fiji used load bearing 75 mm medium density WWC slabs dowelled together with 12.5 mm mild steel rods, those in Zambia used more standard reinforced concrete post and beam construction with wood wool / cement slab infill (Hawkes and Cox, 1992). While these designs can be used in both Afar and UK,

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[9] https://www.celenit.com/Public/Downloads.php?celenit_depliant_building-construction_201706_ed01rev01_eng.pdf&Open

[10] Hawkes and Cox (1992) (p.15) soaked wood wool for 3 minutes in 3-5% $CaCl_2$ solution before it was centrifuged. OPC cement mixed with water 2:1 was applied as a slurry to the moist wood wool in a cement mixer until it was well coated. Total curing time for 50mm WWC boards was 14 days.

[11] Rapid set OPC contains hydrates (possibly gypsum)

	**Cement / Lime**: rapid setting and natural drying. Solid well compacted block with excellent adhesion and hard binder. Some structural strength. Density 320 kg/m^3.		**Lime / Gypsum**: slow to dry and still some moisture. Solid block with good adhesion and structure. Binder not as hard as cement/lime but may develop with time, present density 335 kg/m^3
Gypsum: solid, compact & hard upper and lower surfaces with excellent binding / adhesion; but centre remained moist and friable with mould. Density 320 kg/m^3.		**Clay + PVA**: solid block but soft binder so block is falling apart. Wood wool proportion may be too high, while drying was finished in oven. Density 290 kg/m^3	

Fig. 17. Results of Runs #2 & 3 – Application of binders as slurries to dry wood wool

integration of WWC elements with current developments of off-site timber frame construction is appropriate. Straw bale construction systems are now certified for UK, while modification of systems for traditional stick built timber houses and new eco-house systems are possible.

4.1 ModCell®[12] Straw based Large Wall Elements

Tightly compacted small rectangular straw bales have been used in "unconventional" construction tied together with hazel rods; to insulate buildings with conventional construction (including the new Allerton Trust Centre – Chris Stoate, *pers. comm*); and now with a specially designed off-site construction system known as ModCell® that combines the insulation and eco properties of 400 mm wide straw bale panels with the strength of glulam structural components. The principles of construction, finishing with external cement render and plaster interior, and completed housing and institutional structures for ModCell® are shown in Fig. 18 – 20. Key features include rapid on-site construction, good insulation properties, 2 hour fire resistance of panels with 30 mm render and plaster finishes, and ability to provide any external finishes required. However, the glulams do require high quality timber and precision engineering.

Photos: ModCell®

Fig. 18. ModCell® large wall elements – principles: stuffing 400 mm straw bales into glulam frames

[12] http://www.modcell.com/

Photos: ModCell®

Fig. 19. ModCell® large wall elements – finishing: 30 mm external render & internal plaster

Photos: ModCell®

Fig. 20. ModCell® large wall elements – buildings: terraced houses and institutions

4.2 Stud-frame houses

Timber frame houses are traditional through many parts of the UK and form the main construction method for non-institutional buildings in rural Africa. Typically, frames were erected by hand on-site, that is "stick-built". The upper storey of the author's cottage (Fig. 21), built in 1858, is constructed of

Fig. 21. The author's cottage in Kent with timber stud wall upper elevation and rear extension

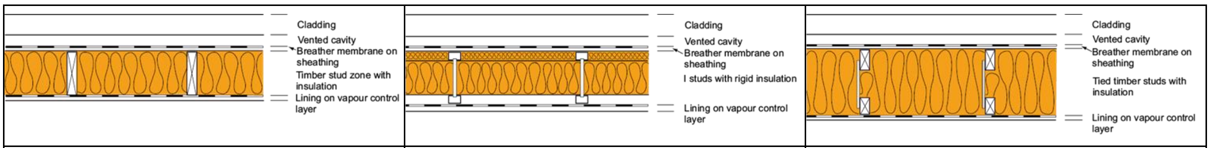
50 x 100 mm sawn softwood studs at 400 mm spacing. The exterior has fancy Kent peg tiles held by hand cut poplar pegs plus weak lime mortar on hand split poplar laths; the interior is lime plastered

(with horse hair) over close spaced hand split poplar laths. There is no insulation! The 60 year old wooden rear extension has similar stud frame with new 200 mm weatherboard to the exterior and 12 mm plasterboard to the interior – with 100 mm fibreglass insulation. Regional variations include brick infill; rendered OSB[13] or plywood cladding with or without pargeting, and any local facing material.

Modern timber frame systems retain the basic studs with lower and upper plates for load bearing but mounted on OSB or plywood sheets to form platform frames. This allows entire wall, floor and roof elements to be precision cut and assembled off-site for rapid on-site construction[14]. The amount of insulation that can be included within stud walls relates to their depth and construction (Table 2, Fig. 22). A benefit of WWC as insulation is that it is permeable to water vapour so that eco-houses can be designed to allow the house to breathe passively through its walls – provided they are not sealed from the inside with plasticised paints and vapour control layers, and plasticizers such as PVA are left out of renders, plasters or the WWC insulation itself (Ingrid Chauvet, architectural engineer, *pers. comm.*)

Table 2. Stud types and depth ranges[15]

Stud type	Depth range mm
Softwood studs at least 38 mm wide	140 - 245
Engineered timber I-joist studs with flanges at least 38 mm wide	145 - 450
Tied double studs of softwood at least 38 mm wide	200 - 500



22a. Softwood studs | *22b. I-joist studs* | *22c. Tied double softwood studs*

Fig.22. Stud systems for external timber frame walls[15]

4.3 Stud wall systems for 400 mm Wood Wool Cement insulation

At an Eco-house demonstration at Inverness, Scotland, thirty house were recently constructed by different companies according to their own designs. Half of these employed I-joist studs of 400 mm depth, mainly stuffed with flexible fibreglass insulation. In keeping with the 400 mm thick WWC whole wall elements produced by Eltomation / Traullit two possible systems are proposed (Fig. 23):

1) Softwood stud wall with studs 50 x 100 mm at 40 or 60 cm spacing, with 400 mm deep base and top plates: with temporary form work 400 mm internal depth to take WWC insulation for final density of 300 – 350 kg/m^3 (Fig. 23a)

2) Timber I-joist studs – two softwood studs 50 x 50 mm joined by 12 – 18 mm OSB or plywood, at 40 or 60 cm spacing, to give total internal depth of 400 mm. Temporary OSB sheets as formwork would be fixed to the internal and external wall surfaces. After the WWC insulation has set, these would be replaced by plaster / render mesh (Fig. 23b).

[13] OSB: Oriented Strand Board
[14] TRADA: Timber Research and Development Association: https://www.trada.co.uk/
https://www.trada.co.uk/media/1375/introduction-to-timber-frame-construction.pdf
https://www.trada.co.uk/books-online/timber-frame-construction-designing-for-high-performance-5th-edition/
[15] https://www.trada.co.uk/books-online/low-energy-timber-frame-buildings/

23a. Softwood studs with base plate & formwork

23b. Timber I-joist studs ± end formwork and plaster/render mesh

Fig. 23. Demonstration Stud wall systems for 400 mm deep wood wool insulation

Both systems can be used in "Pop-Up" factories for production of whole wall elements according to good timber frame construction practices and building regulations. Formwork would be filled and allowed to set in a horizontal position but would be transported and erected in the vertical position. Given the solid nature of WWC insulation studs at 600 mm should be sufficient, especially for low rise buildings, thus saving on high value timber.

I-joist stud walls provide semi-permanent formwork and aid fixing of metal plaster / render mesh and cladding, and is suited to rectilinear architecture. It is also more suited to small scale local production, as the I-joist studs split the whole wall element into small compartments each of which can take a single batch of WWC. However, use of flexible plastic formwork with WWC insulation supported on softwood studs allows construction of curvilinear architectural structures. Whether or not further cladding is used, both types of stud wall need to be rendered externally with 30 mm cement / lime mortar in three layers and plastered internally with 30 mm bonding and top coat plaster to seal the WWC insulation. Fire resistance of WWC whole wall elements with render and plaster finishes is six hours – against a requirement of one hour – as individual WW particles are encased and bonded to the cement.

4.4 Render and Plaster for Wood Wool Cement Insulation

A set of 8 moulds were made by the author from 12 mm OSB and 72 x 18 mm softwood to demonstrate render and plaster coatings on WWC insulation. Internal dimensions for WWC insulation was L 300 x W 200 x D 72 mm = 4320 cc. Moulds were made with extended sides to allow for 30 mm render or plaster, and movable ends to be raised as each layer of render or plaster was added (Fig. 24a). Five 700g bricks were used as press (Fig. 24b). After WWC insulation had set (Fig. 24.c) 7 x 10 mm diagonal plaster mesh was stapled to each mould[16] (Fig. 24d). The first bonding coat of render or plaster was forced through the mesh[17], then levelled off 10 mm above the sides of the moulds. The second coat of 15 mm was applied after setting and drying of the first coat. 5 mm was left for finishing coats of render or plaster, but this has not been applied to date.

WWC insulation was prepared as before with 50% Wood Wool : 50% binder; and the binder was 2/3 quick setting cement : 1/3 hydrated lime. WW was air dry apple wood, and the binder was applied as a

[16] Wickes galvanised steel plastering lath (although specified for internal use it was also used for the render moulds)
[17] The latest Eltomation video (footnote #8 p.6) shows 25 mm square galvanised steel mesh being nailed to walls

24a. Mould | *2b. Brick Press* | *24c. Five prepared moulds with WWC insulation* | *24d. Mould + Mesh*

Fig. 24. Preparation of moulds for demos on render and plaster to WWC insulation

thin slurry to coat all surfaces of the WW. Target density was 280 kg/m^3. Sufficient apple WW was available for five moulds (Fig. 24c). One mould was left as a control. Treatments are in Table 3. It was easy to press plaster or render alone through the plaster mesh to fill voids in the surface of the WWC insulation, and this was done for all treatments. Plaster or render with WW was applied above the plaster mesh to meld with wet plaster or render below and built up to 10mm (Fig. 25).

Table 3. Treatments for render and plaster on WWC insulation

#	Treatment
1	Bonding plaster alone:
2	Bonding plaster mixed 50:50 with WW < 10 mm
3	Render alone: sharp sand 4 parts : rapid setting cement 1 part : hydrated lime 1 part[18]
4	Render with half sharp sand replaced by WW < 10 mm

25a. Bonding plaster +/- WW < 10 mm | *25b. Cement/Lime render +/- WW < 10 mm*

Fig. 25. First coat of plaster and render applied to demonstration moulds of WWC insulation

Render set hard within 7 days for 1st coat and 5 days for 2nd coat; plaster set but was slow to harden. Addition of WW had little effect on the strength and hardness of render and plaster but considerably lightened the demonstration moulds. Both render and plaster were applied to cover both the WW insulation and the wooden sides – in all treatments this would have provided a good seal between insulation and wooden studs. After the second coat all treatments provided a solid surface, suitable to take the top skim coat (Fig. 26).

The original WW / binder insulation blocks and the demonstration moulds for renders and plasters were displayed at the FWF 2018 meeting (Fig. 26). At the rear from left to right are WW insulation with binders – PVA; clay / PVA; cement / lime; lime / gypsum; and gypsum. At the front from left to right are render / plaster demo moulds – Leylandii with render + WW without plaster mesh, not further discussed here; plaster alone; plaster + WW; render alone; render + WW. Note penetration of the plaster and render to fill surface voids in the WW insulation, and application of the second coat.

[18] Traditional cement render consists of 6 parts clean sharp sand, 1 part cement (OPC) and 1 part lime. A stronger mix was used for the demo, including use of wood wool. https://en.wikipedia.org/wiki/Cement_render

Fig. 26. Display of WWC insulation blocks and Render / Plaster demo moulds at FWF 2018

5 The Future

5.1 Sources of Biomass for use in construction

Biomass resources suitable for Wood Wool Cement insulation and medium density construction boards from farm woodland and agroforestry are at present being developed throughout the EU through farm diversification and biodiversity programmes. These include sources which would normally be discarded, burnt, mulched, composted or chipped for biofuel, and include:

- Increased planting of fruit and nut trees in agricultural settings – as discussed for UK at the APPG Agroecology Agroforestry meeting in Parliament on 18th June 2018 presented by the Woodland Trust and the Soil Association:
    - Prunings from fruit and nut trees and from vineyards
    - Thinnings and end of cycle clearance
    - Pollarding of shelter strips within and around orchards
- Thinnings of high value timber trees within Agroforestry systems
    - Walnut and cherry in Spain (Rosa Mosquera, *pers. comm.)*
- Vegetation management
    - Clearance of White and Black thorn plus Hazel from The Burren, Galway, Ireland
    - Clearance of Rhododendron from forest understoreys, especially in maritime climates
    - Management of woody vegetation on hill and mountain pastures following destocking
- Pollard and coppice from Poplar and other broadleaved species specifically grown for biomass in alley systems in sylvoarable and sylvopastoral agroforestry systems
- Thinnings of conifers and broadleaves in forestry systems
- Recycled urban biomass.

5.2 Harvesting and Shredding Systems

On a small scale, and where volunteers can be mobilized, manual harvesting of biomass resources is possible. Commercial operations will require mechanized systems that depend on the scale and nature of the biomass resource to be harvested. Suitable systems[19] for the above biomass resources include:

- Small round balers and handling systems to collect prunings
    - CAEB International vineyard baler from Italy with chopper knives capable of picking up prunings to 30 mm with twine or net wrap plus built-in bale transporter[20] (Fig. 27).

[19] Mention of products from specific manufacturers is for example only and does not imply criticism of manufacturers not specified.
[20] http://fialhostore.com/images/7217/products/982_20180228155644_pdf_products.pdf

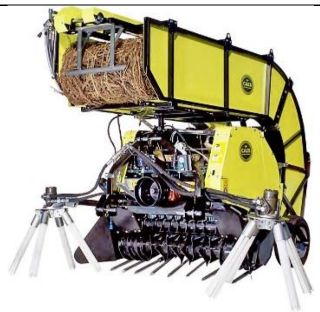


Photo: CAEB International

27a. CAEB Int Quickfire 1230 vineyard baler

Photo: CAEB International

27b. CAEB Int baler in vineyard

Fig. 27. Vineyard baler with bale transporter and swath brushes

- High reach multi-saws, heavy duty cutter-bars and tree loppers to pollard and re-pollard poplars and other broadleaved trees grown in alleys (Fig. 28):
    - McConnel[21] and Bomford-Turner multi saws
    - McConnel HD cutter-bars[22]
    - Bomford-Turner tree lopper[23] (to 450 mm diameter branches)
    - Additional tree harvesting systems from the forestry industry

Photo: McConnel

28a. McConnel multi-saw

Photo: Bomford

28b. Bomford

Photo: McConnel

28c. McConnel cutter-bar

Photo: Bomford-Turner

28d. Bomford-Turner tree lopper

Fig. 28. High-reach multi-cut saws, heavy-duty cutter-bars and tree loppers

- Biomass harvesters to direct harvest and shred standing biomass crops or to pick up and shred windrowed pollards and other pre-cut biomass. For construction purposes biomass harvesters must shred rather than chip the biomass so that it resembles as closely as possible wood wool:
    - AHWI H-600 biomass harvester from Prinoth of Germany mounted on a crawler platform or reverse drive wheeled tractor (Fig. 29).
- Mobile biomass shredders and grinders (rather than chippers) to shred piles of wood waste loaded by crawler / wheeled excavator, agricultural telehandler or tractor fore-loaders. A tractor power take-off (p.t.o.) model would suit the scale of operation envisaged; however only large scale units with their own 350 – 800 HP engines could be sourced, suitable for Green Waste composting centres (eg Arjes Shredder VZ 750, Komptech Crambo, Doppstadt Shredder AK 310 Ecopower). It might be possible to hire a unit from a nearby Green Waste centre.
- Wood wool machines vary in scale. All use round or squared logs of 250-500 mm length and up to 150-350 mm diam. (Fig. 30).
    - small scale Chines machines[24] at GBP 1000-7000 (Fig. 30a)

[21] https://www.mcconnel.com/power-arms/power-arm-attachments/multisaws/
[22] https://www.mcconnel.com/power-arms/power-arm-attachments/cutterbars/
[23] https://www.bomford-turner.com/forestry/_product/79/tree-lopper/

- medium scale heavy duty Indian machines (Fig. 30b) with hydraulic or pneumatic log manipulation and conveyors to carry the WW away at GBP 10,000-30,000
- large industrial scale: Eltomation (NL) "Eltomatic CVS-16 Rotating Wood Wool Machine" (Fig. 30c) with a 4000 kg/hour output, as part of a EUR 9 million plant.

Photo: AHWI Maschinenbau GmbH	Photo: AHWI Maschinenbau GmbH	Photo: AHWI Maschinenbau GmbH
29a. H-600 on RT-400 crawler carrier	*29b. H-600 close-up*	*29c. H-600 mounted on Fendt 350 HP wheeled tractor – reversed controls*

Fig. 29. AHWI H-600 biomass harvester from Prinoth

Photo: Zhenzhou Leabon	Photo: G.K. Sales Corporation	Photos: Eltomation (NL)
30a. Low cost WW machine – Henan China mainland[25]	*30b. Hydraulic WW machine – Nagpur, India*[26]	*30c. Eltomation, NL, CVS-16 Eltomatic Rotating WW machine*[27]*. Left: log feed; right: logs within WW machine*

Fig. 30. Medium to large scale wood wool machines

5.3 Wood Wool Cement Building Systems

5.3.1 Wood Wool Cement composition

Both Hawkes and Cox (1992) and the Eltomation system (to 2018) continue to use Ordinary Portland Cement (OPC) as the main binder at about 2 parts to 1 part wood wool for all products at a range of densities, with soaking of the WW in salt solution prior to dosing with the cement. Other companies such as Celenit vary both the proportion and the composition of the binder. From the perspective of adding value to various biomass resources making use of available equipment while minimising carbon footprints there appears scope for further studies:

- Species of woody materials
  - Broadleaves and softwoods

- Particle size of "Wood Wool" for low density insulation and medium density boards:

[24] https://www.Alibaba.com offers 4,828 wood wool machines, mainly from China mainland
[25] https://www.alibaba.com/product-detail/Crazy-Selling-Small-Capacity-6KW-Mini_60506437867.html?spm=a2700.7724857.main07.25.45b84f738WhB33&s=p (with video)
[26] https://www.indiamart.com/proddetail/hydraulic-wood-wool-making-machine-14690395791.html
[27] https://www.eltomation.com/eng/our-products/large-wwc-wall-element-plant/pictures-large-element-plant

    - Output from different shredders and chippers ranging from genuine wood wool through various shredded materials to wood chips of different sizes
    - Importance of uniform large shreds, or benefits of combining large and small shreds or of using small finer shreds (equivalent to combining sand aggregate to make concrete)
    - The relative importance of the wood itself or the air entrapped in spaces between fibres in imparting heat insulation properties

- Preservation of wood wool within the WW binder insulation
    - Effectiveness of different binders
    - Pre-treatment of WW including charring, and composition of mineralising solutions
- Composition and form of the binder:
    - Fineness and grades of OPC
    - Form of lime[28]: hydrated lime compared to use of lime putty or of hydraulic limes (with added clay content)
    - How to use gypsum effectively for different products
    - Mixtures of cement and lime, and lime with gypsum
- Proportion of binder to WW for different products:
    - For different binders
    - For different dimensions of "wood wool"
    - For wall and for ceiling insulation in relation to weight of the large elements
    - For medium to high density boards compared to low density insulation products
- Inclusion of wood fibres in bonding render and plaster layers.

5.3.2 WWC Building Systems

The main attention so far has been given to WW/binders for insulation within large wall elements, and how this might be utilised with different wooden frame building systems. There is also scope to produce WW/binder slabs of various densities and dimensions and with different uses.

- Full development of the two wooden frame systems noted above (Section #4.3)
- Medium density boards (500-700 kg/m^3, 20-50 mm depth) for external and internal lining of wooden frame buildings and for internal partitions
- Low to medium density insulation boards (400-500 kg/m3, 100-150 mm depth) to provide hung and infill insulation to traditional wooden frame buildings
- Medium to high density structural components +/- reinforcement such as posts and beams to replace:
    - High value timber components in wooden frame construction
    - Glulams as posts and beams such as in ModCell® construction
    - Reinforced concrete posts and beams in WWC large wall elements
    - OSB or plywood in I-joists stud walls.

5.4 Funding

5.4.1 Innovation Funds - biomass

Various Innovation Funds are currently available to fund development of this concept, with support through the APPG Agroecology and the new farming and environment programmes:

- Innovate UK for Agriculture and Food[29]:

[28] https://www.lime.org.uk/community/types-of-lime/types-of-lime.html
[29] https.www.innovate.gov.uk

  - Farming systems and agroforestry research to monetise biomass from fruit, nut and timber systems
- Innovate EU for Agriculture:
  - To add value to thinnings from high value timber trees – Spain, Portugal etc.
  - To control thorn bushes and hazel on species rich grasslands – The Burren, Ireland
- DiFD and development banks
  - Utilisation and valorisation of biomass harvested from invasive woody species in the Third World – Afar Region, Ethiopia; Rajasthan, India

5.4.2 Innovation Funds - building

Various Innovation Funds are available within the building industry, with support from government, academia and industry:

- To increase use of timber within building systems, especially in mixed media combining timber and concrete and timber and metal.
- Possible industry partners include TRADA[30], the Concrete Centre[31], and Ty-Mawr[32].
- Innovations to be considered include:
  - Mixed cement binders
  - Wood wool properties
    - Timber species
    - Particle size
    - Preservation
  - Building designs and structural components
  - Carbon sequestration and carbon footprints
- DfID: wood wool in traditional and modern house construction in Africa and Asia.

6 Conclusions

The following conclusions can be drawn from this experiential scoping study:

- Existing and additional biomass resources can be developed within agroforestry systems including purpose-designed pollard timber crops, vegetation management, use of byproducts such as prunings from fruit and nut trees and vineyards, and green waste
- Wood Wool Cement off-site building systems can add value to low grade timber resources, and their use needs to be evaluated and extended in UK, EU and Africa / Asia
- Present manufacture of wood wool with long fine fibre requires semi-mature timber of high alternative value. Small to large scale machinery to produce long fine fibre from low grade timber resources needs to be further developed
- Variations in the WWC system need to be evaluated to:
  - Use lower grade wood resources
  - Optimise binders and binder / WW ratios to reduce carbon footprint, maximise carbon sequestration and make use of local resources
  - Produce a range of building products to minimise the need for imports of high grade timber in construction
- Innovation funds and potential partners are currently available to take this concept forward.

30 https/www.trada.co.uk/
31 https://www.concretecentre.com/
32 https://www.lime.org.uk

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