The potential role of cattail-reinforced clay plaster in sustainable building

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SUMMARY

Sustainable development is a key goal in town and country planning, as well as in the building industry. The main aims are to avoid inefficient land use, to improve the energy efficiency of buildings and, thus, to move towards meeting the challenges of climate change. In this article we consider how the use of a traditional low-energy building material, namely clay, might contribute. Recent research has identified a promising connection between the reinforcement of clay for internal wall plastering with fibres from the wetland plant *Typha latifolia* (cattail) and the positive environmental effects of cultivating this species. If large quantities of *Typha* fibres were to be used in building, the need for cultivation of the plant would increase and create new possibilities for the renaturalisation of polluted or/and degraded peatlands. We explore the topic first on the basis of literature, considering the suitability of *Typha* for this application and possibilities for its sustainable cultivation, as well as implications for the life cycle analyses of buildings in which it is used. We then report (qualitatively) the results of testing different combinations of clay with natural plant (straw and cattail) fibres for their suitability as a universal plaster, which demonstrate clearly the superior properties of *Typha* fibres as a reinforcement material for clay plaster mortars.

KEY WORDS: clay mortar; life cycle analysis; paludiculture; peatland; *Typha latifolia*; wetland

INTRODUCTION

Clay usually forms by secondary sedimentation in low-energy depositional environments such as large lakes and marine basins, and can easily be found on building sites. It is a versatile building material that requires no special preparation, and consequently has a long (*ca*. 8000 years) history of use in various construction techniques (half-timbered, rammed clay, wattle and daub *etc*.). There are currently around 2.2 million clay buildings in Germany (Lehmschwalbe 2013), some of which are several centuries old.

The Industrial Revolution of the 19th century brought new manufacturing and processing technologies that enabled the development of a new generation of building materials including bricks, which largely replaced clay in construction until the debate on sustainability was opened. Nowadays, the use of unlimited energy by industry is no longer acceptable or affordable against the backdrop of global energy and oil crisis. Sustainability is a primary focus in building, and research is seeking out new materials with lower manufacturing costs, higher energy efficiency and life-cycle sustainability (Schroeder 2010). Usually, the life cycle of the whole building is considered and analysed, then concepts are developed for energy optimisation.

Although frequently neglected in this context, clay has already been proved as a sustainable building material. If it is extracted and used directly from the construction pit, there are hardly any manufacturing or transport costs, and it can be re-used many times without losing functionality (Schroeder 2010).

There are clear needs and demands (and, therefore, markets) for continuation of the traditional construction techniques in which clay has been a prominent material. According to Manfred Gerner, member of the executive board of Arbeitsgemeinschaft Historische Fachwerkstädte (Working Committee of Historic Half-timbered Building Cities), approximately one-quarter of the 2.4 million half-timbered buildings in Germany are listed as historic buildings. After being unoccupied for long periods, they are in such poor condition that demolition is frequently the only viable course of action (Göres 2010). In other words, the number of traditional buildings in need of affordable rehabilitation in Germany is very high. Figgemeier & Knoffel (1993) point out that, since clay was superseded by bricks, it has been increasingly noticed that the thermal, sound and impact sound insulation of traditional buildings cannot be achieved by a normal one-layer truss façade. Therefore, the goals of a restoration project should include the preservation of the original structure of the building and the integration of traditional materials into modern materials systems. Some relaxation of the restrictions imposed by energy-efficiency regulations may be required. The cost, effort and time required to renovate traditional buildings could be reduced by devising standardised maintenance measures, based on a thorough understanding of the fundamentals of traditional construction, that tradesmen and craftsmen could apply to achieve total solutions in the future.

Independently of the historical use of various infill materials (including clay) in half-timbered buildings, clay mortars were (and still are) very frequently used as interior plaster. It has long been understood that clay plasters create a pleasant design and haptic (tactile) effect and, at the same time, efficiently solve indoor climate problems on account of their capacity to absorb humidity (Eckermann & Ziegert 2006). Moreover, they are generally recognised by building owners as ‘ecological’ and healthy, capable of introducing a desired element of ‘naturalness’ into modern constructed environments. Because clay plasters are now applied in new buildings as well as in old ones, demand has increased (Claytec 2013) but, despite their great popularity, they are still too expensive. If the manufacture of clay products could become more cost-efficient, they would be used more frequently in the future. To achieve this goal, both researchers and the industry are investigating the properties of clay and various clay material compositions, with a view to improving their practical application in building and developing sustainable industrial production methods.

The beneficial properties of clay are maintained only if no synthetic materials or stabilising substances are added. However, depending on the composition of the material originally excavated, various natural fibres and sands can be added to create a clay mortar with the desired physical properties. The next challenge is to discover how to achieve clay plasters with perfect properties for universal application.

A current focus of our research group is to inconspicuously reinforce clay plasters by adding natural plant fibres. We aim to develop a solid and strong ‘universal’ humidity-regulating clay plaster. It would be a great step forward for sustainable building to develop a plaster composition that would be suitable for use in the preservation and/or restoration of ancient monuments and historic buildings as well as in new buildings. Our research has identified a promising connection between the reinforcement of clay plasters with fibres from the wetland plant *Typha latifolia* (cattail) and the positive environmental effects of cultivating this species. If large quantities of *Typha* fibres were to be used in building, the need for cultivation of the plant would increase and create new possibilities for the renaturalisation of polluted or/and over-used peatland areas. In this article we explore the potential contribution of *Typha* to this new avenue for sustainable building, and outline the results of some preliminary tests of its performance as a reinforcement material for clay plasters.

POTENTIAL OF THE CATTAIL PLANT

Suitability for use in building materials

Typha or cattail (*Typha latifolia*) is a rhizome-forming grass-like plant that grows naturally in swamps and marshes, as well as on the banks of slow-flowing rivers. It typically reaches a maximum height of two metres, or up to three metres under optimal water level conditions (Figure 1A). It reproduces vegetatively from spreading rhizomes as well as from seeds, which are borne on a distinctive spadix (Figure 1B,C). As an adaptation to its aquatic habitat, the plant has a high polyphenol content, which makes all of its parts highly resistant to mildew and bacterial infections (Heinz 2010).

Typha has many potential uses (Access Washington 2013), and very high potential for the building industry, due to its physical structure. Because approximately 85 % of the plant mass consists of aerenchyma tissue, the leaf mass has high porosity (Figure 1D), a (low) density of approximately 30 kg m^{-3}, and lower thermal conductivity ($\lambda = 0.032$ W m^{-1} K^{-1}) than polystyrene ($\lambda = 0.04$ W m^{-1} K^{-1}). Highly efficient insulation boards can be produced by combining the leaves with a simple mineral binder (magnesite). A significant advantage of using cattail biomass as thermal insulation is the very low production of dust. Cattail leaves can also be used as reinforcing fibre for various building materials.

The seeds account for approximately one-quarter of the total dry mass. The so-called “seed parachutes” are very light and their structure (Figure 1E) is such that they create a strong network when mixed into clay mortar. When they are added as reinforcing fibres to lean clay plaster (with a low clay fraction), the strength of the plaster is improved (Müller-Sämann *et al*. 2003).

Prospects for cultivation

The high polyphenol content of the *Typha* plant makes it not only a durable component of building materials, but also an agricultural crop that is resistant to adverse weather conditions, moulds and insect infestations. A nutrient-rich soil is sufficient to provide all of the necessary minerals. Therefore,

(A)

Figure 1. Relevant characteristics of broad-leaf cattail (*Typha latifolia*): (A) a stand of cattail in nutrient-rich water; (B) and (C) the distinctive spikes ripen to release the seeds, which are dispersed by wind; (D) sections of leaves showing their porous structure; (E) the seeds, whose structure makes them ideal reinforcing material for clay plasters. Sources: (A)–(C) from Wikipedia; (D) and (E) from Fritsch & Theuerkorn (2010).

Typha can be cultivated successfully without pesticides or fertilisers, and harvests of more than 10 t ha^{-1} can be achieved. Optimal growth is attained on ground that is constantly submerged to a depth of at least 30–50 cm, and raising the water level by further tens of centimetres results in higher harvests (Müller-Sämann *et al*. 2003).

The cattail plant can be propagated for cultivation by establishing new sprouts from rhizomes in vegetable planters and subsequently bedding-out onto the cultivation area (Figure 2). Bedding-out at three plants per square metre and subsequent controlled flooding of the cultivation area can generate a stand of similar density to natural stands (47–70 sprouts m^{-2}) after one vegetation cycle, and high cropping rates can be expected after two years. Propagation from seed is also possible, but there is currently little experience of using this technique in the context of cultivation. The best time for sowing is in June and July, under conditions of small temperature difference between day (25 °C) and night (10 °C). Achieving favourable sowing conditions is likely to be a key requirement for establishing cattail as an agricultural crop in the future (Müller-Sämann *et al*. 2003).

Typha and sustainable agriculture

The cultivation of *Typha* offers good possibilities for stabilising bare soil, as well as for establishing fens and newly developed water retention areas as fertile agricultural land. A high density of biomass is produced with little further effort after bedding-out. Cattail also has potential for filtering and cleaning chemically and/or biologically polluted water; according to investigations by TU München, *Typha* cultures can remove 22–66 % of the nitrates, 59–74 % of the contained ammonium and 50–85 % of the phosphates from water percolating through them (Müller-Sämann *et al*. 2003). When growing around the shores of lakes, it is effective in filtering out organic pollutants, as well as copper and nickel, from the influent water. Various insect and other species could be introduced to planted *Typha* stands to increase their biodiversity. Therefore, the outlook for the sustainable utilisation of this species is highly promising (Müller-Sämann *et al*. 2003).

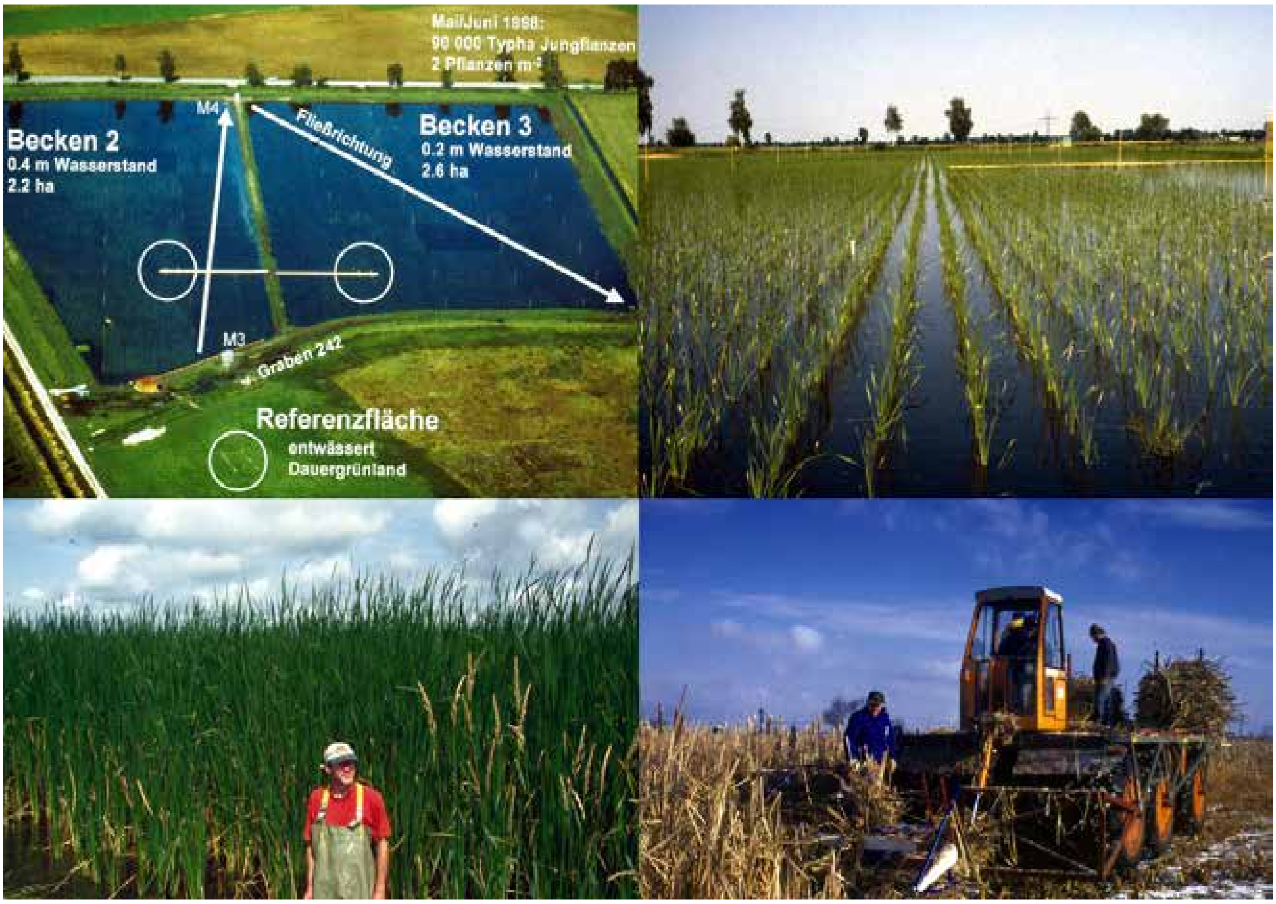

Figure 2. Cattail cultivation in Danube marshland, carried out within a DBU (Deutsche Bundesstiftung Umwelt / German Federal Environmental Foundation) project (from Fritsch & Theuerkorn 2010).

Environmental impacts of cattail cultivation

The global temperature has been rising continuously since the beginning of the Industrial Revolution in the 19th century (NASA Science 2013), causing frequent weather anomalies worldwide. One reason for these changes is the increasing greenhouse gas concentrations in the atmosphere (Pfadenhauer 2002). As shown in Figure 3, wetlands in their natural condition are able to sequester and retain carbon dioxide and nitrous oxide, but emit methane (which is also a greenhouse gas) to the atmosphere. When they are drained, the methane flux declines and may even reverse, but the fluxes of both carbon dioxide and nitrous oxide also reverse so that the net effect is an enhancement of greenhouse gas emissions. Re-wetting and planting with *Typha* can contribute to reducing global warming by reducing the rates of emission of these gases.

POTENTIAL ADVANTAGES OF *TYPHA*-REINFORCED CLAY PLASTER

Clay plaster: the basics

Clay plaster shows excellent adhesion to various natural surfaces, but is much more suitable for indoor than for outdoor application. If used outside, it should be protected from rainfall, which can cause serious mechanical damage to the finished surface (Volhard & Röhlen 2009).

The pleasant look and feel of clay plaster makes it a favoured material for coating the interiors of building façades. The pastel colour tones of the natural clay provide a calming link to nature (EDC 2008), and there are numerous design options for clay surfaces involving:

- colour effects - an almost unlimited range of natural colourants can be used to give clay plaster different atmospheres and shades;
- textural effects - clay plaster can be treated using various methods and/or tools to give a wide range of different surface textures (Volhard & Röhlen 2009); and
- layered arrangement effects, which offer very strong architectural potential (for example, the stratification of soil was recently simulated in clay plaster).

Clay serves not only as an architectural element, but also has very important physical functions for the interior of the building. The most significant of these for clay plaster is its humidity-buffering capacity, which tends to stabilise the indoor climate. When the air in the room has high humiditity, water is absorbed rapidly into the clay plaster, and when the humidity level later decreases, the water is released back into the air mass in the room (Eckermann & Ziegert 2006).

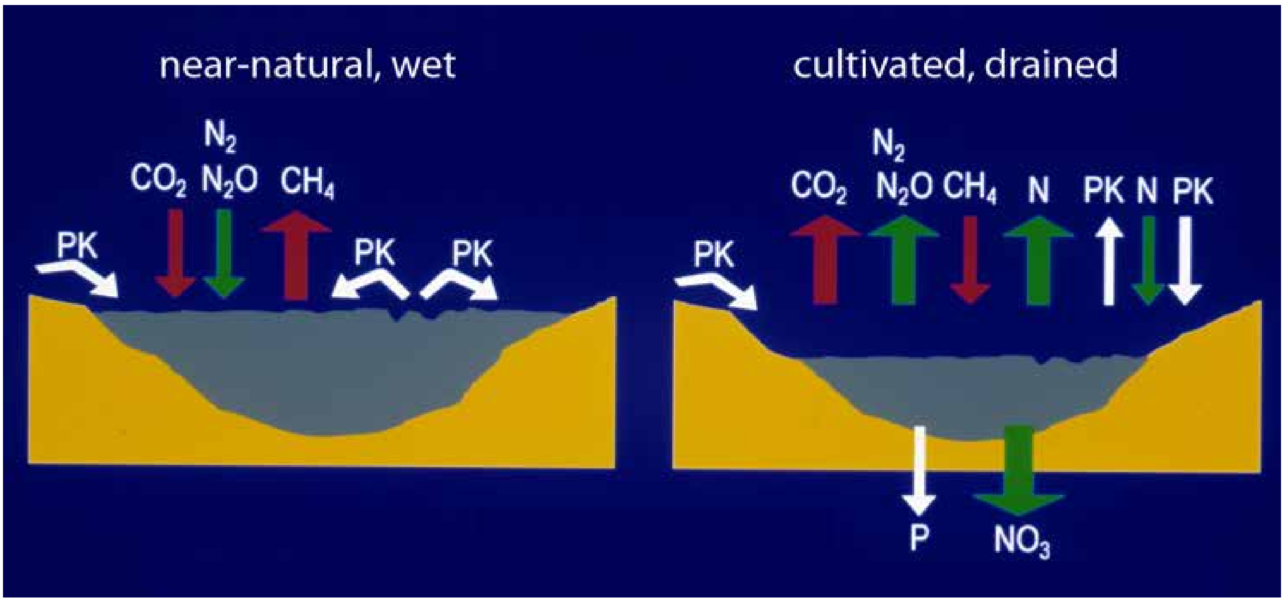

Figure 3. A schematic comparison of greenhouse gas (and other) emissions from wet and dry swamp lands, from Fritsch & Theuerkorn (2010). The important greenhouse gas fluxes discussed in the text are those of carbon dioxide (CO_2), nitrous oxide (N_2O) and methane (CH_4).

Life cycle considerations

In order to place *Typha*-reinforced clay mortars within the global list of sustainability values for building materials, their life cycle should be described. The plant is cultivated in swamp areas. It filters river water and restores polluted land. New swamp fields could be created by diverting parts of rivers, and the *Typha* plant could be cultivated at high productivity levels in these zones. The harvesting process is very simple and could be completed using standard techniques. The next step is processing of the raw material and the final product, which should ideally take place in decentralised factories close to the *Typha* fields. The seed mass could easily be separated from the spadix in a controlled-humidity environment, then mixed into different kinds of clay mortars. These would be transported to urban building sites for use in new buildings or in the restoration/retrofitting of old ones, and thus contribute to the preservation of existing sustainable urban systems.

Clay plaster layers have finite lifespans whose lengths depend on the building systems and the quality of application. At the end of this time, cattail-reinforced clay mortar could be re-used, recycled or composted. The clay retains its mineral structure indefinitely and new *Typha* fibres could be added. This step completes the 100 % sustainable life cycle of the family of *Typha* materials (Figure 4). Thus, through the use of cattail as a reinforcement for clay plasters, combined with its cultivation (Fritsch & Theuerkorn 2010), sustainable spatial planning could be ensured at all levels (Figure 5). This is a national goal not only for Germany, but also for other countries within the European Union.

Energy considerations

Typha-reinforced clay mortars improve on common mineral mortars because they are 100 % recyclable and their production costs (financial and in terms of energy) are low. The primary energy content (PEC) of a building usually describes the manufacturing process and transport of materials, up to the point of installation (WTA 2013). To achieve a realistic comparison of the energy consumption per unit of building mass, all costs must be integrated into the total life-cycle calculation (Schroeder 2010). If durability of the building is also to be taken into account, maintenance costs must be added. The cumulative energy use is the energy demand of the building in question during the whole of its life cycle (Schroeder 2010). Table 1 shows that the energy content of clay is lower than that of any of the other materials considered. This would increase minimally after mixing in *Typha* seed fibres, so that

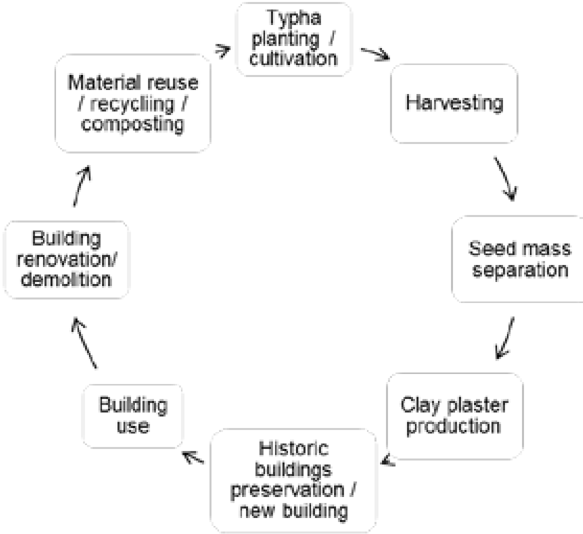

Figure 4. The life cycle of *Typha*-reinforced building materials.

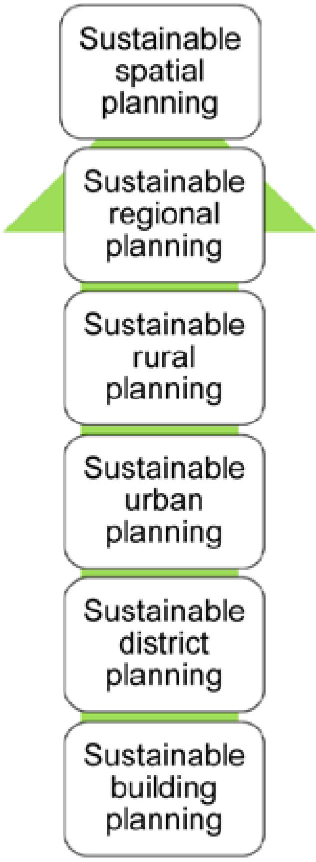

Figure 5. The hierarchy of sustainable spatial planning.

Typha reinforced clay mortars and plasters may be classified as highly sustainable and nature-friendly building materials.

Table 1. Primary energy contents (PECs) of selected building materials (Schroeder 2010).

Building material	**PEC [kWh m^{-3}]**
clay	0–30
straw slabs	5
wood, local	300
wooden building materials	800–1,500
bricks	500–900
cement	1,700
concrete	450–500
sand lime brick	350
flat glass	15,000
steel	63,000
aluminum	195,000
polyethylene-PE	7,600
PVC	13,000

TESTING THE PROPERTIES OF *TYPHA*-REINFORCED CLAY PLASTER

Objective

Finished buildings often deviate from their plans due to inaccurate workmanship or deformation of components or materials. This is particularly important for historical timber buildings because the infill frequently shows significant irregularities. Wall surfaces that are uneven due to stacking often have irregularities 2–3 cm deep which can be flattened by applying clay plaster in layers until it is up to 4 cm thick. An additional advantage is that plastering secures the permanent protection of wooden building components. However, the plaster can be applied only by very experienced craftsmen who are able to use it both efficiently and with artistry (achieving aesthetically pleasing designs), whose skills are required in perpetuity because clay-plastered surfaces need regular maintenance. To improve efficiency and sustainability, we aimed to optimise the application method so that a four-centimetre layer could be applied in one step without cracking during drying, to give a visually pleasing result that did not require an additional finishing layer. We compared the performance of plasters without and with reinforcement by natural fibres (straw or *Typha*). We also conducted strength tests, for which correct preparation and composition (according to standards) is essential.

Procedure

We used two kinds of substrate. For the first 30 samples, small clay building boards were laid horizontally, each board was dampened with a brush to enable better adhesion, and the plaster was applied with a trowel. For another 12 samples we used larger fibre cement boards to which reed mats were attached with wires. Reed matting has high surface roughness, which makes for excellent adhesion of plasters. These boards were always plastered in one work step, but usually in two layers. The first layer was thrown onto the board for better adhesion to the reed mat, and the second (thicker) layer was applied and finished by trowel. The constant movement of the craftsman's hands in all directions is crucial to successful adhesion of the thick clay layer to the board.

In total, 42 samples were prepared, with the following dimensions:

36 cm × 27 cm (21 samples);
60 cm × 60 cm (4 samples);
70.6 cm × 2.5 cm (1 sample);
80 cm × 60 cm (9 samples); and
125 cm × 125 cm (7 samples).

In the first phase of testing, we aimed to gain familiarity with the basics of clay plasters and the principles of their application. We compared different plaster compositions on small horizontal boards, then selected for further investigation on larger vertical boards those with high resistance to cracking, low density, favourable optical and haptic attributes, and low visibility of reinforcing fibres (if present).

Because the production of larger quantities of clay plaster was more complicated, small samples were mixed with a planetary paddle mixer and larger ones with a whisk. The processing of the boards was labour-intensive and physically challenging; for example, the plaster that was applied to a 125 cm × 125cm board weighed more than 120 kg.

As described in Technical Norms DVL (2011), DIN (1999), DIN (2009a,b) and the Fraunhofer IBP guidelines, clay mortars are mixed according to defined specifications. Longer mixing of the plaster mortar with the planetary paddle mixer gives a better distribution of particles and, thus, better mortar texture. The optimal distribution of particles is achieved if the mixture is left overnight and mixed again with a planetary paddle mixer the following day.

Drying of the clay plasters, applied to a thickness of 3–4 cm, took approximately one month. Room ventilation was necessary to prevent mould from growing on the damp plaster. Regulation of the temperature of the room was decisive because the tests were done during the transition from summer to autumn. Both room temperature and air humidity were recorded and analysed over the whole period of the study.

After drying, any cracking, peeling away of pieces of plaster from the substrate *etc*. was recorded, and the eight best samples were selected. Further specimens of these materials were then prepared for mechanical strength tests, which were carried out according to DIN 1015-11 (DIN 1999). Three test prisms (16 cm × 4 cm × 4 cm) were made from each mix and allowed to dry for at least 28 days before testing (Figures 6 and 7).

Figure 6. Test specimens after 28 days of dehydration in the climate chamber.

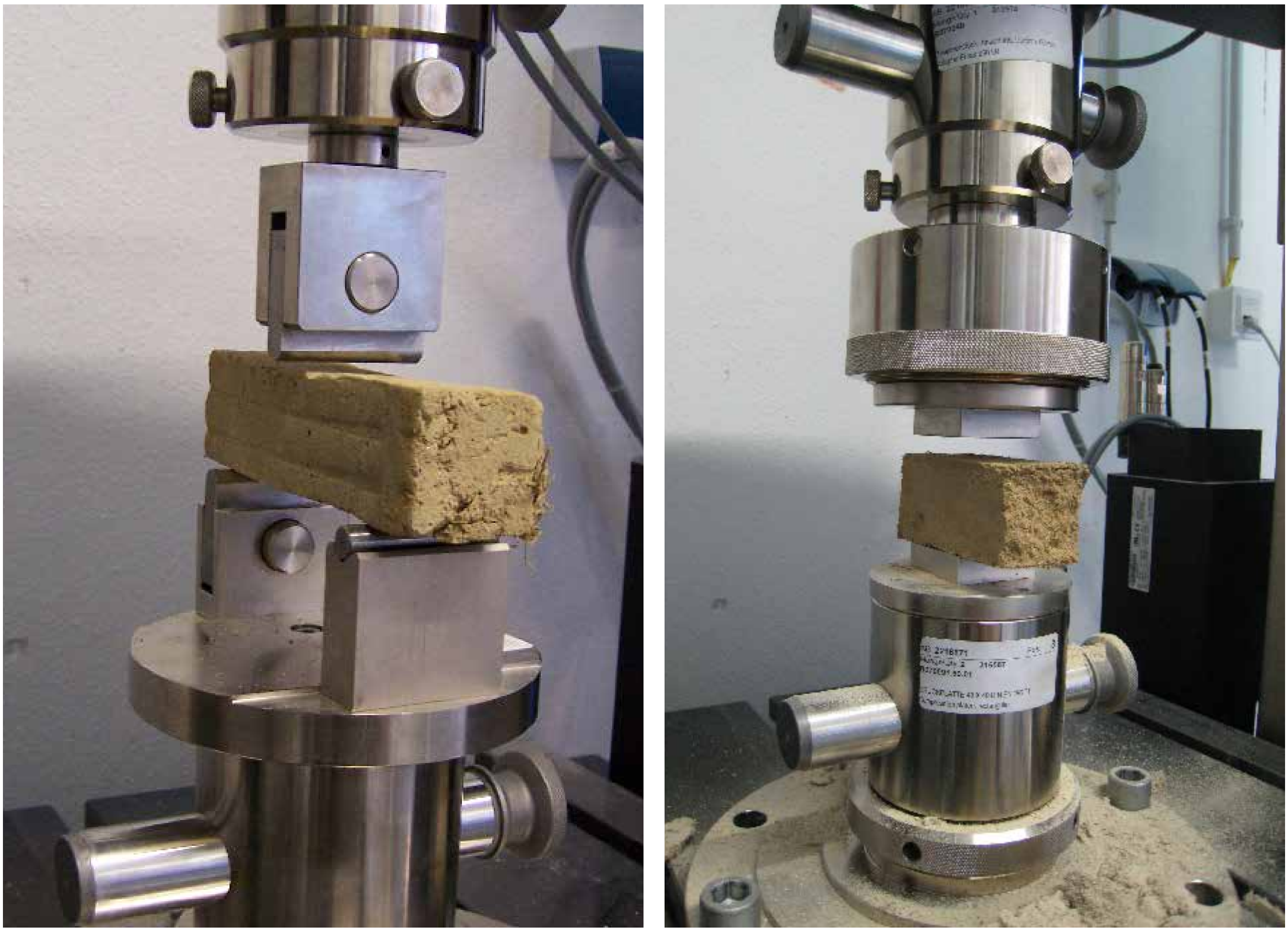

Figure 7. The bending tensile strength test (left) and the pressure strength test (right).

Performance
The following samples gave the most distinctive results:

Sample 1 consisted of completely unreinforced clay plaster, thickness ~50 cm, on a large (80 × 60 cm) clay board. The results were obviously negative, as deep structural cracks developed during the drying process (Figure 8). Therefore, clay plasters should always be reinforced in some way.

Sample 2 was basic plaster with straw as the reinforcement fibre, applied to a thickness of ~2.5 cm. It was easy to prepare and apply, no cracks appeared during drying, and strength tests produced satisfactory results (Figure 9).

Sample 3 was prepared and applied as for Sample 2, but the thickness of the plaster layer was ~3.5 cm. Despite its thickness, this sample proved to be strong and showed no signs of structural damage after drying (Figure 10).

Sample 4 was a 1.5 cm layer of undercoat plaster with straw as reinforcement. No cracks occurred during drying and strength tests produced good results (Figure 11).

Sample 5 was similar to Sample 4, except that the thickness of the plaster layer was doubled (3 cm) (Figure 12).

Sample 6 was a mixture reinforced with *Typha* fibres that was tested in the second phase of the investigation, working on the 125 cm × 125 cm fibre cement boards. The plaster was easy to work with and was applied as a thin (~1.5 cm) layer (Figures 13 and 14). This sample had excellent material strength.

Sample 7 was similar to Sample 6 except that the total thickness of the plaster application was 2–2.5 cm, consisting of a thin undercoat with a second layer applied and finished by trowel, all in one work step (Figures 15 and 16). The application procedure took two hours in total.

Samples 8 and 9 (Figures 17–20) were proprietary mineral clay plaster from a well-known manufacturer, which we reinforced with *Typha* fibres and applied to fibre cement boards covered with reed matting. They differed in the mass of cattail reinforcement fibre added; in Sample 8 it was 1.6 kg, and in Sample 9 it was 1.3 kg. These samples were heavy (100–120 kg) and the plaster had to be repeatedly applied and finished. However, it was possible to achieve a plaster layer 3–4 cm thick, without any visible structural cracks or other defects, in only one work step. Both of these samples performed well in the strength tests.

Although we are reporting the results in a largely qualitative manner here, it is important to mention sufficient ‘hard data’ from strength testing to enable a first comparison of the strength of clay plaster mortars with and without the added *Typha* fibres. For Sample 3, the bending pressure strength was 242 N and the pressure strength was 1375 N. Sample 9 had higher bending pressure strength (276 N), and its pressure strength was substantially higher (2353 N). Both samples were prepared using the same plaster mortar combined with the same amount of water (one-fifth of the total mortar mass). However, they differed in that the reinforcement fibre used for Sample 3 was straw, and for Sample 9 it was *Typha* fibres. In other words, this test clearly demonstrated a positive advantage of *Typha* fibres as a reinforcement material for clay plaster mortars.

Figure 8. Sample 1 (not reinforced) developed deep and spreading structural cracks during drying.

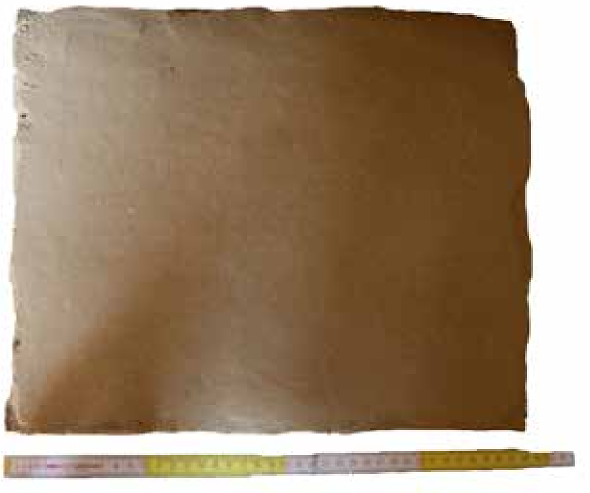

Figure 9. Sample 2.

Figure 10. Sample 3.

Figure 11. Sample 4.

Figure 12. Sample 5.

Figure 13. Sample 6: plastering in progress.

Figure 14. Sample 6: dry finished clay plaster.

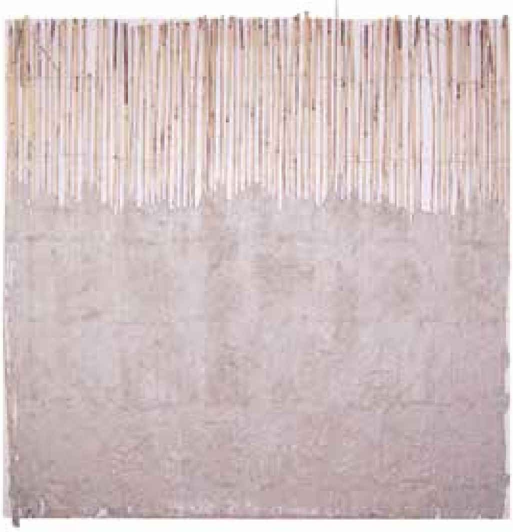

Figure 15. Sample 7: plastering in progress.

Figure 16. Sample 7: finished clay plaster.

Figure 17. Sample 8: plastering in progress.

Figure 18. Sample 8: finished plaster still drying.

Figure 19. Sample 9: plastering in progress.

Figure 20. Sample 9: finished, plaster almost dry.

DISCUSSION AND CONCLUSIONS

In order to meet requirements for a half-timbered building, which moves constantly, plasters should be simultaneously strong and elastic. They should also bind well to wooden components. The cattail-reinforced clay plasters that we tested fulfil these requirements. The natural fibres reinforce the clay and increase its tensile (bending) strength as well as its compressive strength. Increasing the mass of natural fibre in the clay plaster mixture provides further improvements in strength. Both the integration of fibre particles into the mix and the crack resistance of the plaster are improved by including natural fibres with a large range of lengths. By interlacing themselves, the cattail seed fibres build a strong network which remains stable over a long period of time.

Other positive qualities of *Typha* for this application are its near-invisibility when mixed into clay mortars, its high content of polyphenols (natural tanning agents in the cattail plant) which assure long-term natural microbiological protection of the plant and make the plaster resistant to mildew, and the pleasing interior design effects that can be achieved.

The positive effect of *Typha* on the whole of the life-cycle energy analysis for the building material must be emphasised. The potential for cultivating *Typha* sustainably in rural areas under schemes such as *Green Communities and Regions* is as promising as that for establishing a prominent place for *Typha* building materials in the construction of new buildings and the rehabilitation of old ones. Moreover, because the application of clay plasters requires a high level of skill, the mass production and application of cattail-reinforced clay mortars and plasters would create many new jobs for qualified craftsmen.

In other words, *Typha* seed fibre is a 100 % natural unprocessed product that offers respectable reinforcement qualities and other advantages for this application which are unparalleled by any other currently known material. On this basis, *Typha* appears set to attain a top position in world commodity markets in the future. However, much further research in this field will be necessary to place it there.

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REFERENCES

Access Washington (2013) Native freshwater plants: cattail; a common and useful native plant. Department of Ecology, State of Washington. Online at: http://www.ecy.wa.gov/programs/wq/plants/native/cattail.html, accessed 29.05.2013.

Claytec (2013) Lehmputz (Clay plaster) (in German). Online at: http://www.claytec.de/produkte/bautechniken/lehmputz/61-lehmputz.html, accessed 30.01.2013.

DIN (1999) *DIN EN 1015-11: Bestimmung der Biegezug- und Druckfestigkeit von Festmörtel* (*Determination of Bending and Compressive Strength of Hardened Mortar*). Deutsches Institut für Normung, Berlin (in German).

DIN (2009a) *DIN EN 196-1: Biegezugfestigkeit Mörtel* (*Bending Strength of Mortar*). Deutsches Institut für Normung, Berlin (in German).

DIN (2009b) *DIN EN 196-1: Druckfestigkeit Mörtel* (*Compressive Strength of Mortar*). Deutsches Institut für Normung Berlin (in German).

DVL (2011) *Technische Merkblätter Lehmbau - Blatt 04. Lehm-Putzmörtel: Begriffe, Baustoffe, Anforderungen, Prüfverfahren* (*Technical Data Sheets on Clay Construction - Sheet 04. Clay Plaster: Concepts, Materials, Requirements, Test Methods*). Dachverband Lehm e.V., Weimar (in German).

Eckermann, W. & Ziegert, C. (2006) Auswirkung von Lehmbaustoffen auf die Raumluftfeuchte (Effect of clay building materials on indoor air humidity). Claytec, Potsdam, 10pp. (in German). Online at: http://www.claytec.de/fileadmin/user_upload/pdf_download/lehmputz_raumklima.pdf, accessed 07.11.2013.

EDC (2008) American clay earth plaster users claim energy savings, company announces at Greenbuild. *EDC Magazine*, November 11, 2008. Online at: http://www.edcmag.com/articles/american-clay-earth-plaster-users-claim-energy-savings-company-announces-at-greenbuild, accessed 30.01.2013.

Figgemeier, M. & Knoffel, D., WTA (1993) Lehm - ein historischer Baustoff im Fachwerkbau (Clay - a historical material in timber-framed buildings).

In: Wittmann, F.H. (ed.) *Werkstoffwissenschaften und Bausanierung Tagungs 3* (*Materials Science and Restoration 3*), Kontakt und Studium 420, Grafenbau-Expert Verlag, Renningen, 248–270 (in German).

Fritsch, A. & Theuerkorn, W. (2010) DBU (2010) *Typha*– ein neuer Baustoff am Beispiel des Fachwerkhauses Pfeifergasse 9 in Nürnberg (*Typha*– a new building material; example of the half-timbered house Pfeifergasse 9, Nuremberg). Fachkolloquium 14–15 September 2010, Osnabrück, Deutsche Bundesstiftung Umwelt (DBU), Nürnberg (in German). Online at: http://www.dbu.de/media/071010104726i7lk.PDF, accessed 31.01.2013

Göres, J. (2010) Fachwerkhäuser: Einkaufsbummel in historischen Höfen (Half-timbered houses: shopping spree in the historic courtyards). *Süddeutsche Zeitung*, 17 May 2010 (in German). Online at: http://www.sueddeutsche.de/geld/fachwerkhaeuser-einkaufsbummel-in-historischen-hoefen-1.45720, accessed 30.01.2013.

Heinz, S. (2010) *Population Biology of* Typha latifolia *L. and* Typha angustifolia *L.: Establishment, Growth and Reproduction in a Constructed Wetland*. Shaker Verlag Gmbh, München, 108 pp.

Lehmschwalbe (2013) Online at: http://www.lehmschwalbe.de/lehm.html, accessed 30.01.2013 (in German).

Müller-Sämann, K.M., Reinhardt, G., Vetter, R. & Gärtner, S. (2003) *Anhang zu Nachwachsende Rohstoffe in Baden-Württemberg: Identifizierung vorteilhafter Produktlinien zur stofflichen Nutzung unter besonderer Berücksichtigung umweltgerechter Anbauverfahren* (*Agricultural Raw Material in the State of Baden-Württemberg. Identifying Promising Product Lines for Industrial Uses, with Special Reference to Sustainable Cropping Technology*). FZKA-BWPLUS Research Report, Müllheim, 70–74 (in German). Available for download at: http://www.ifeu.de/index.php?bereich=lan&seite=nawa_bawue, accessed 25.01.2014.

NASA Science (2013) How is the global earth system changing? Online at: http://science.nasa.gov/earth-science/big-questions/is-the-global-earth-system-changing-and-what-are-the-consequences/, accessed 30.01.2013.

Pfadenhauer, J. (2002) *Multitalent Rohrkolben: Ökologie, Forschung, Verwertung; der nachwachsende Rohstoff, Pilotprojekt Donaumoos* (*Multi-talented Cattail: Ecology, Research, Recovery; Renewable Resource Pilot Project Donaumoos*). Technische Universität München, Freising, 20 pp. (in German).

Schroeder, H. (2010) *Lehmbau: mit Lehm ökologisch planen und bauen* (*Wattle and Daub: Ecological Design and Building With Clay*). Springer, Wiesbaden, 494 pp. (in German).

Volhard, F. & Röhlen, U. (2009) *Lehmbau Regeln : Begriffe, Baustoffe, Bauteile* (*Wattle and Daub Rules: Components, Building Materials, Vocabulary*). Springer, Wiesbaden, 120 pp. (in German).

WTA (2013) Thema 5: Energie – Beispiel für Primärenergie (Topic 5: Energy – example of primary energy. Wissenschaftlich-Technische Arbeitsgemeinschaft für Bauwerkserhaltung und Denkmalpflege (WTA) (in German). Online at: http://www.wta.de/de/%C3%B6koglossar/prim%C3%A4renergie, accessed 31.01.2013.

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