> *"It is estimated that at least 30% of the world's population live in houses constructed of raw earth."*

Keefe, 'Earth Building Methods & Materials, Repair & Conservation'
London, Taylor & Francis, 2005, p. 7

Our living environments are under constatnt scrutiny and adjustment. The creation of semi-permenent living is essential.

Fig 1. The Great Mosque of Djenné

Fig 2. Shibam in Yemen

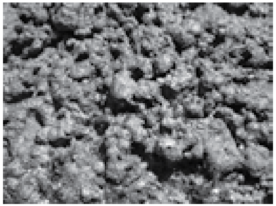


Fig 3.

Fig 4.

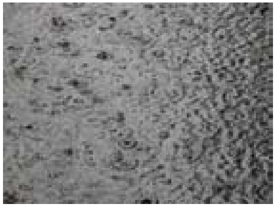


Fig 5.

Fig 6.

43. Keefe, 'Earth Building Methods & Materials, Repair & Conservation' London, Taylor & Francis, 2005, p. 7

44. Minke, op.cit p. 9

Notable historical precedents: The Great Wall of China, originally a rammed earth wall, later clad in stone and brick.[44]

Fig 1. The Great Mosque of Djenné, the world's largest mud-brick building, dates from the early 1900's.

Fig 2. The historical city centre of Shibam in Yemen dates back to the 15th Century and covers an area of 20,000m2, with buildings reaching up to 8 storey's high.

Fig 3-6.

Clay. Binder to hold the mixture together.

Sand (aggregate). Stabilizes the clay and minimizes cracking.

Water. Enables the ingredients to mix and become workable.

Straw (fibrous material). Provides added strength.

"It is estimated that at least 30 percent of the world's population, some 1.5 billion people, live in houses constructed of raw earth."[43]

In most hot and arid regions of the globe unfired earth is the principal building material, especially so in developing countries where there may be shortages of timber or other materials suitable for construction.

The earliest examples of earth construction can found in the Middle East and North Africa and have been dated to over 9000 years ago.

Although types of earth construction can differ in their manufacture and applications, they generally consist of varying proportions of the same 3 or 4 raw ingredients (see figures 3-6).

Benefits of working with earth:
Soil is often locally sourced, 100 percent biodegradable and recyclable.

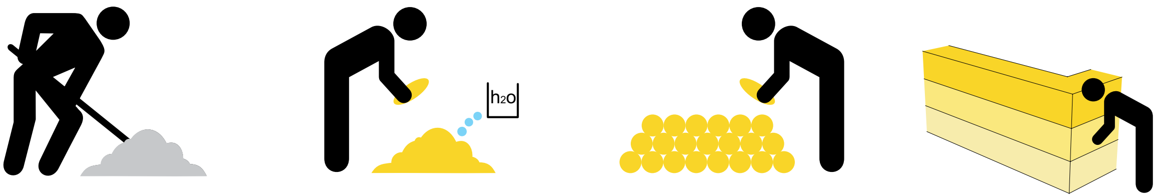
It can be quick and easy to construct with.

It has a high thermal mass that can provide passive heating / cooling and can be extremely durable.

Limitations of working with earth:
The amounts, and types, of sand, silt and clay differ from site to site, each with varying properties. The proportions needed to achieve a suitable mix will therefore also vary.

Earth construction can shrink and crack when it dries out due to the evaporation of the water used in its preparation.

Once fully dried out it must be sheltered from rain and frost as water causes dried earth to swell and return to a plastic state.



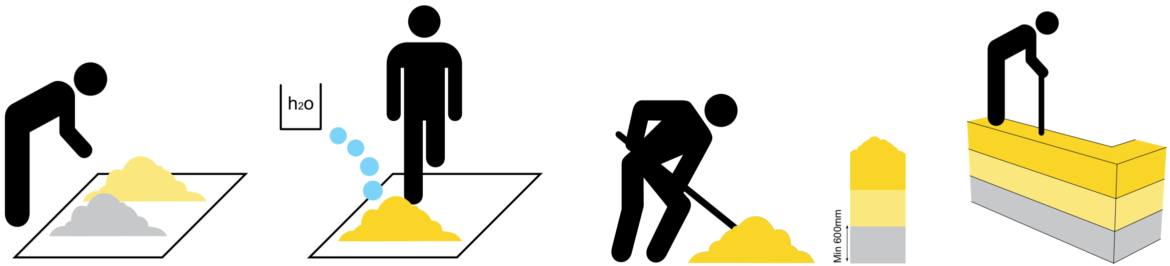
Fork soil mix from ground

Form stiff mix, with a little water, into an elliptical brick

Lay bricks in depressions of previous row

The gaps and cracks are filled and the wall is trimmed

Fig 7.



Mix clay and sand

Stamp in water to create cob mix, then add straw

Fork cob mix in 'lifts' on to a stone plinth

Pack down each lift and trim the cob wall

Fig 8.

45. Baker, Mud, 2nd ed, Trichur, India, Centre of Science and Technology for Rural Development, 1993

46. Wiseman, Bryce, The Green Building Bible, Vol 1, 3rd Edition, Carmarthenshire, Wales, Green Building Press, 2006 , p. 222

Cob wall construction, England

Cob

Cob is the simplest and most low-tech method of earth wall construction, it is best suited to single storey buildings and producing curved walls.

Standard Cob (fig7)

A small amount of water is used to hand mould an elliptically shaped brick, “approximately 30-40cm in length and 15cm diameter”[45], of very stiff mud. These cobs are then laid or thrown into rows; subsequent rows are then laid in the depressions. Once two to three courses have been laid, the cracks and gaps are filled and smoothed, then given time to harden before laying the next.

British Cob (fig8)

Similar to standard cob by its low-tech nature and lack of formwork, but British cob is more suited to temperate climates. The cob is made on a flat tarpaulin sheet where proportions of dry clay and sand are mixed. Water is added and stamped in then rolled from side to side to create a wet mixture.

Straw is then added in small measures until a “homogenous cob mix is created”[46]. Cob requires a stone or brick plinth (minimum 600mm) to prevent moisture seeping in from beneath. Fork-fulls of cob are packed onto the plinth, trodden and trimmed to create a wall.

The wall is constructed in layers, or lifts (of between 300-500mm high). these are given time to dry before the next layer is added. Standard wall thickness can be from 600mm to 900mm and it can be left un-rendered as long as it is not exposed to direct rain or prolonged freezing.

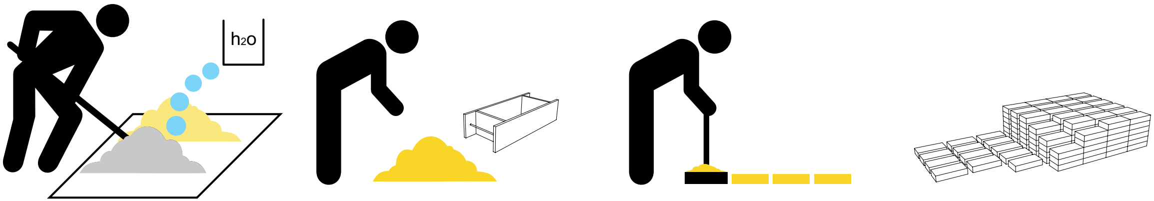
Benefits of this method:

The process is easy to learn and teach, is often sourced directly from site, requires no formwork and is suitable for a wide range of soil types.

Limitations:

Construction of cob walls can be slow and labour intensive, the consistency of the cob has to be correct as too much water could cause the wall to bulge and collapse. It also requires skill to keep the walls straight and vertical, which presents limitations on the achievable height and strength of the wall.

"Adobe is a natural building material mixed from sand, clay, and straw, dung or other fibrous materials, which is shaped into bricks using frames and dried in the sun."[47]



Mix clay, sand and water, (straw can be added)

Throw and compact mud into mould

Slice off excess mud and repeat

The finished bricks are stacked and left to cure

Fig 9.

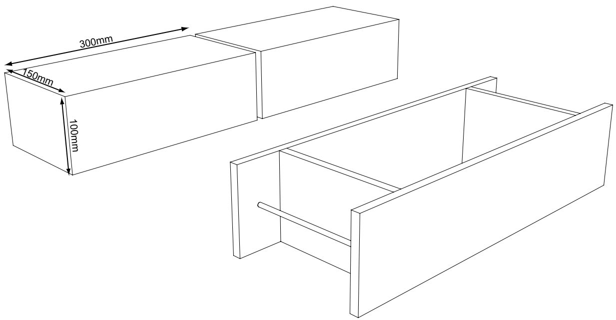


Fig 10.

Making mud bricks

"I was experimenting all the time to find the best and worst methods of mudbrick laying. All methods proved suitable and all walls are still standing.

There was no water or electricity on the block, so I used only rainfall moisture to wet the clay and a driftwood pole to ram the bricks. It was a hard, slow method, but it made very strong bricks.

Later, with the advent of water, mudbrick making became progressively more easy until, finally, a good day's work amounted to 200 bricks."[51]

47.Wikipedia.

48. Keefe, op.cit. p. 63

49. Minke, op.cit. p. 69

50.ibid. p. 73.

51. Peter Kurz, 'The Mudbrick Flats.' in, Earth Garden Magazine, December 1977

Fig 10. UN Standard mud brick dimensions & mould

Fig 11. Mud brick making, India

Adobe, mud bricks (fig9)

Adobe or mud brick is the oldest method of mass producing building materials. It differs from cob in that it is generally a wetter and more even mix that is then thrown into a formwork, usually timber, then stacked and left to dry. The bricks must be turned during the curing process and protected from direct sunlight and wind to reduce cracking. The formwork can be of any size and varies according to the vernacular though the UN standard is 300x150x100mm[48] (fig10). An average worker using single moulds can expect to produce up to 300 blocks a day[49]. Once dried (a process that often takes weeks) the bricks can be laid in an earth mortar and rendered.

Adobe in our research:

There is a tradition for using adobe in arid areas, it is simple to learn and teach, it provides a greater degree of standardisation (for testing), improved workability and overall wall strength. In addition a surplus of bricks can also be made in advance and stored until required.

The main disadvantages of adobe:

It is heavily labour intensive, the bricks require a lengthly drying period, it requires both formwork and more water than other methods

Preparation of the mix:

The mixture of adobe bricks should have enough clay to create a binding force but have enough sand to allow porosity and reduce shrinkage. Experiments have shown an appropriate mix for reduced shrinkage cracks upon drying to be 14% clay, 22% silt, 62% sand and 2% gravel[50]. A series of effective field tests can be used to determine the consistency and cohesion of the mix:

1. Drop test

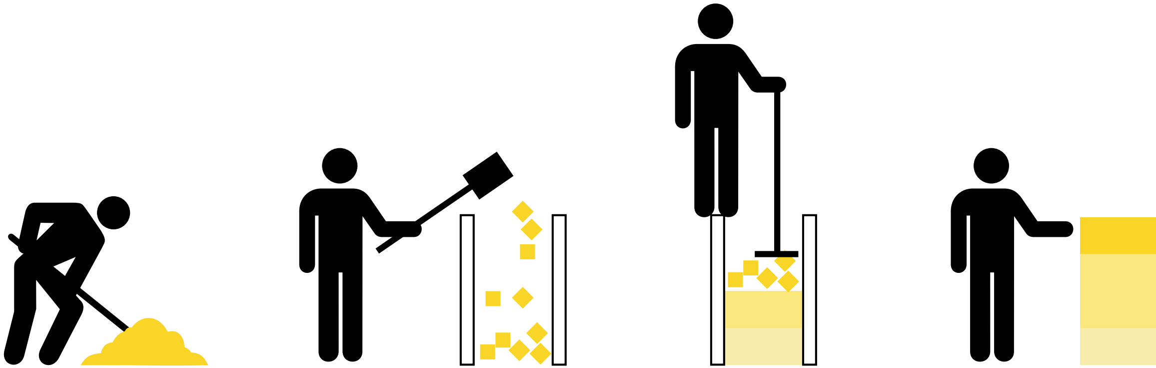
Form a ball of 4cm diameter and drop it from 1.5m. If it flattens and shows little or no cracks then it has too high a clay content and should be thinned with sand. If it fully dissipates then the sand content is too high. The correct mixture should slightly flatten and crack.

2. Cohesion test

A moist ball of around 2-3cm diameter is rolled into a thin sausage until it breaks. If it can reach a thickness of 3mm and is malleable the mixture has a high proportion of clay, if it breaks apart the sand content is high.

3. Strength test

A thread of material is flattened to roughly 2cm wide and 6mm thick. The ribbon is held and allowed to increasingly overhang until it breaks. If it reaches over 20cm before breaking then the clay content is too high for building with, if the ribbon breaks after a less than 10cm then the clay content is too low.



Fork moist sub-soil

Compact soil mix inside temporary formwork

Wall is composed in a series of layers

The formwork is removed, then the wall finished and left to dry.

Fig 12.

Fig 13.

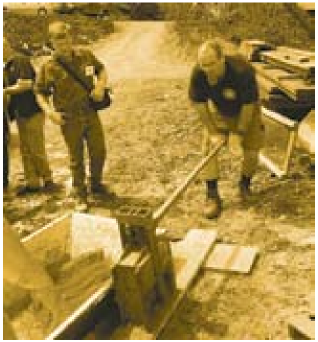


Fig 14.

Fig 15.

52. United Nations Development Programme (UNDP).

53. Khalili, 'Design Like You Give a Damn', London, Thames & Hudson, 2006, p. 110

Rammed Earth (fig12):

Similar to earlier wet methods, but here the moist sub-soil is compacted into a temporary formwork (often timber) in layers which is then removed leaving the wall to dry.

Advantages:

It produces a higher strength and higher stiffness wall to cob and Adobe. There is reduced shrinkage and cracking during the drying process as there is a lower moisture content.

Limitations:

It is a skilled technology and highly labour intensive. It can only be formed in-situ and requires more earth. It is susceptable to decay and the corners require protection.

Fig 16.

Super Adobe (fig16.)

Nader Khalili's work in Iran, also collaboratively with the UNDP[52], has been highly progressive in the field of earth construction.

Firstly, dealing with the problem of mud brick being succeptable to erosion due to rain, Khalili's solution was to seal and set fire to the buildings, effectively turning them into kilns. This resulted in the bricks becoming water resistant and harder.

Secondly, he runs Cal Earth, who manufacture, sell and continue to develop his 'Super Adobe' system that consists of long tubes of burlap or polypropylene filled with earth, laid in courses with barbed wire between to form a dome.The dome can then be rendered using an 85% earth and 15% cement plaster.

A roll of tubing, enough for one shelter, can be ordered from the Cal Earth website at a cost of US $225-$300. "The whole Philosophy was that the refugees would build their own homes. Six refugees built homes in seven to eleven days. Each structure cost $625."[53]

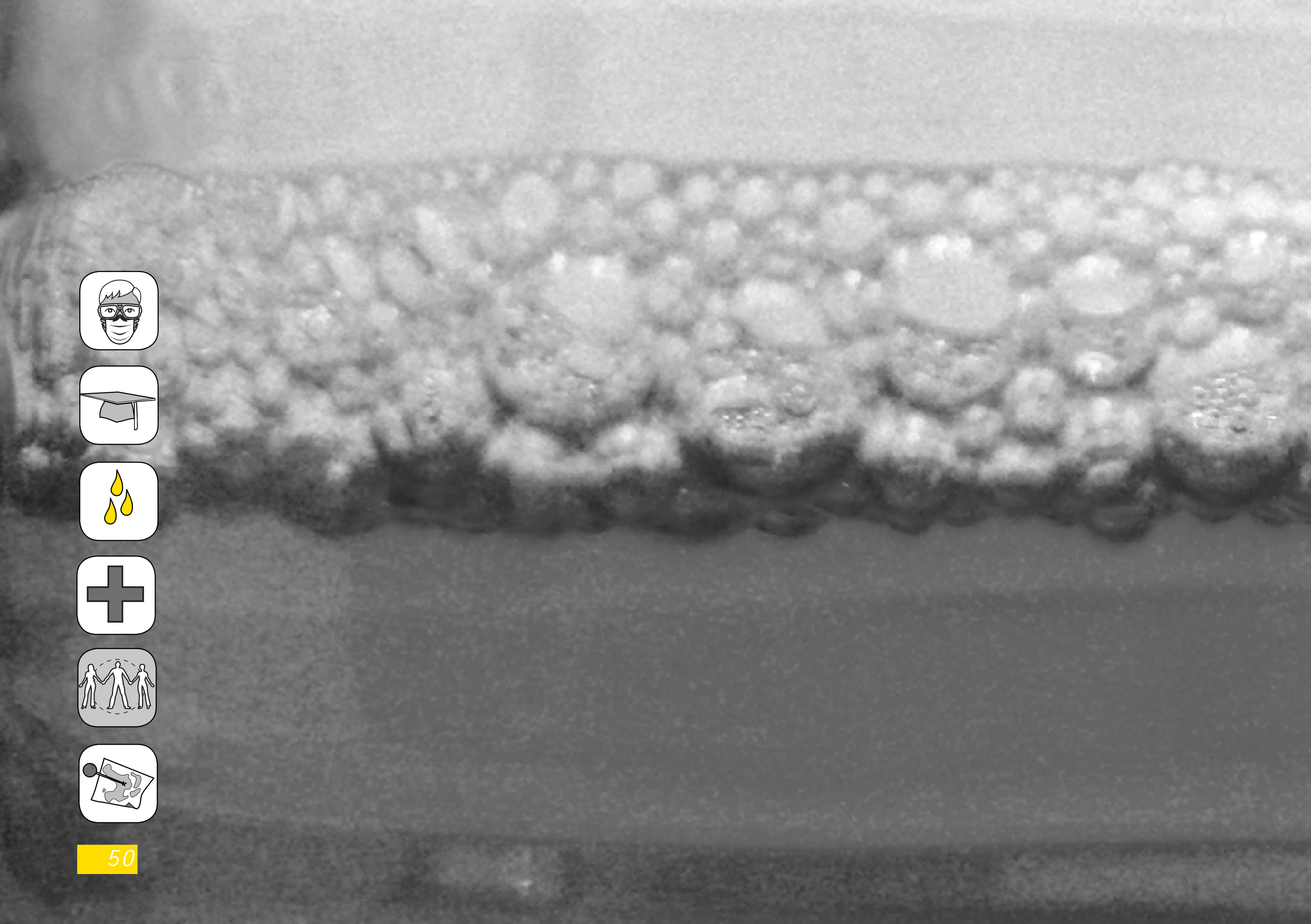
A drawback to the system is the amount of associated manual labour required which is considerably greater than other construction methods methods described.

Cinva Ram (figs13-15)

The cinva Ram, developed by Raul Ramirez for housing in Colombia, is a simple, individually and manually operated machine to produce compressed earth blocks.

A moist mixture is placed in a steel box and compressed against a fixed top plate, a sideways manoevering lever provides both compressive and ejecting forces.

It requires a great deal less water than traditional Adobe methods. The ram could be linked to waste water systems and produces more stabilised bricks at an increased rate. Research done at the University of Kansas School of Architecture shows that a variety of mixtures can produce blocks suitable for building and when used in a team of four people productivity can reach 500 blocks a day. Plans are also readily available in order to self construct the cinva ram.



"a fully nourished refuge is estimated to produce 370 litres of urine per year; equating to 1.01 litres a day."

International Sanitation Commity, Smart Sanitation Solutions, www.irc.nl , 2007

What is in urine? How much do we produce and what differences in people or lifestyle may affect the composition?

urine

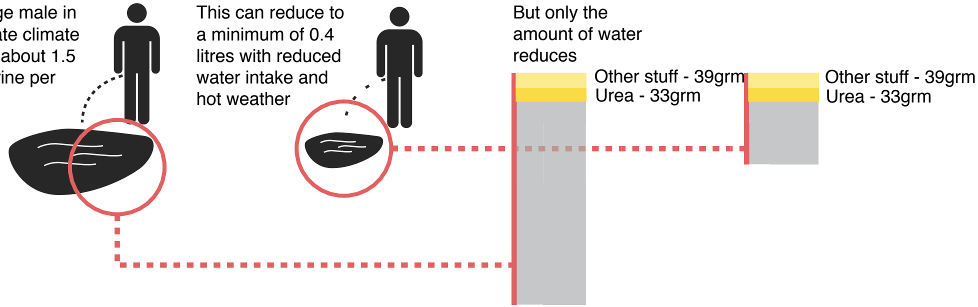
variables under field conditions

quantity

An average male in a temperate climate produces about 1.5 litres of urine per day

This can reduce to a minimum of 0.4 litres with reduced water intake and hot weather

But only the amount of water reduces



age

Urine degrades with the action of fungi and bacteria. In temperate conditions this starts within a few days, in hot conditions within a few hours

acidity

Acidity is affected by a number of factors. Those which are most relevant are shown here

54. Wikipedia, The Urinary System, http://en.wikibooks.org/wiki/human_physiology/the_urinary_system, 2007

55. Ecosan, Fact Sheet on Sanitation, http://www.econsan.nl/content/download/801/5817/file/fact+sheet+characteristics+excreta.pdf , 2007

56. International Sanitation Commity, Smart Sanitation Solutions, www.irc.nl , 2007

57. Wikipedia, Urine, www.wikipedia.org/wiki/urine , 2007

58. Mediline Plus, Urine pH, http://www.nlm.nih.gov/medlineplus/ency/article/003583.htm, 2007

59. Consultation with Dr M Wainwright, Microbiologist, University of Sheffield, 10.10.07

Table: Heitzmann, Urinary Analysis 4th Ed. London, William and Company, 1921

Diagram opposite: Ibid.

How and why is urine produced?

Urine is a waste product of the body secreted through the kidneys, collected in the urinary bladder and excreted through the urethra.[54]

Urine formation helps to maintain the balance of minerals, water and other substances in the body.

What is urine?

An average healthy male passes 1500ml urine per day. Generally this contains:

		IN GRAMS
Water	-	1500
Total Solids	-	72.00
Urea	-	33.20
Sodium	-	11.09
Pigments and other organic substance		10.00
Chlorin	-	7-8.00
Phosphoric Acid	-	3.16
Potassium	-	2.50
Sulphuric Acid	-	2.01
Creatinin	-	0.91
Ammonia	-	0.77
Uric Acid	-	0.55
Hippuric Acid	-	0.40
Calcium	-	0.26
Magnesium	-	0.21

What are the variables?

Quantity

The volume of faeces and urine varies from region to region and depends on climate, the age of a person, their water consumption, diet and occupation. The amount of urine also depends on temperature and humidity.[55]

A fully nourished refugee is estimated to produce 370 litres per year, equating to 1.01 litres a day.[56]

Age of urine

The chemical nature of urine changes with time and this process occurs faster in hot conditions. A major change is the breakdown of urea into carbon dioxide, which is catalyzed by urease (an enzyme found in bacteria, yeast and plants):

urea + water = carbon dioxide + ammonia[57]

Acidity

When urine leaves the body it is approximately pH 6, though it may be as low as 4.5 or as high as 8.2. Diet affects pH, as does health - pH of urine is decreased by starvation and diarrhoea.[58]

As urea begins to decay, hydroxide ions form, raising the pH as high as 9.3. Over time, while stored in a sealed container urine converts from an acidic to alkaline fluid.[59]

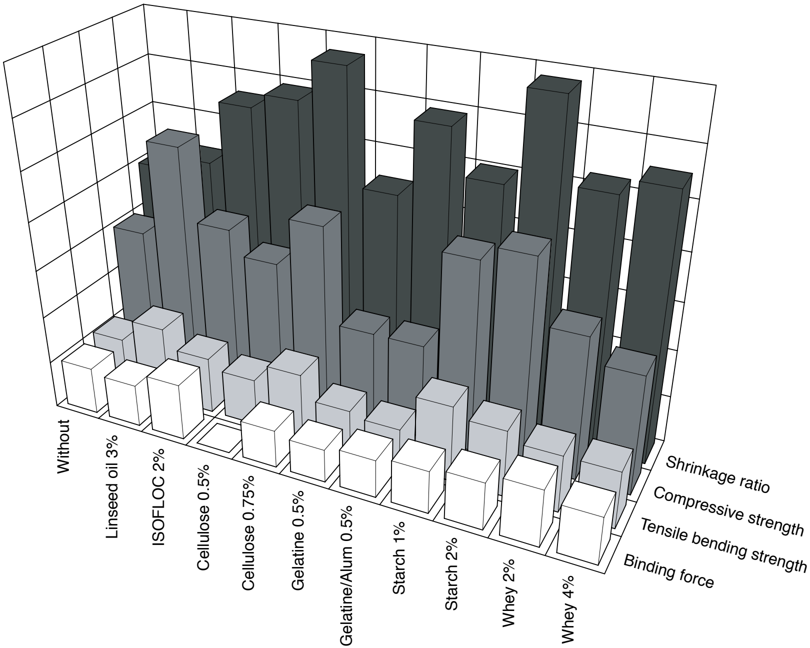


Fig 1.

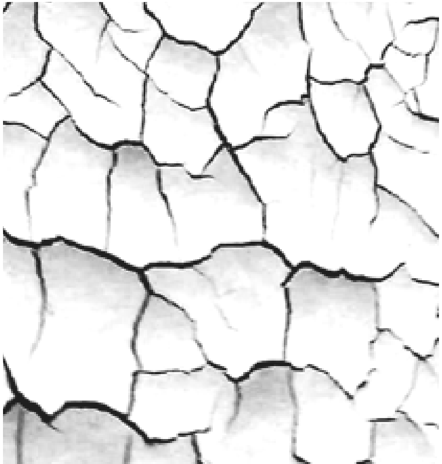


Fig 2.

Fig 3.

60. Minke, op.cit. p. 45

61.ibid. p. 52

Fig 1. ibid. p. 43

Fig 2. Andy Goldsworthy exhibition 2007, human hair used in clay wall installation

Fig 3. Yak Dung Wall, Tibet: Woods,Beau.http://www.flickr.com/photos/beauwoods/393877105/, 2007

"In Germany, the surfaces of rammed earth floors were treated with oxblood rendering them abrasion and wipe resistant. Whey and urine are most commonly used stabilisers for loam surfaces in many countries."60

"Weiss suggests that the high strength of porcelain comes from kaolinite that is soaked in putrid urine (containing urea and ammonium acetate). The tensile bending force can be increased approximately 10 to 20 times in this way."61

The graph on the opposing page shows results from experiments carried out by Gernot Minke that outline how certain additives may alter the characteristics of earth.

What is apparent from the graph is that additives can both improve and worsen the differing properties of the earth mix. Starch, for instance, will increase the compressive and tensile strength but also increase the shrinkage ratio. Also notable is that a strong binding force does not necessarily mean a higher compressive strength (relevant for load bearing walls). Improving the compressive and tensile strength of earth blocks can be necessary as it relates to the resistance of the corners to breaking. This becomes important when stacking, moving and laying the bricks.

There is a rich history of using various biological excreta such as urine, blood, dung, casein, as an additive to building materials to improve the structural properties, water resistance and workability of earth.

Lime, bitumen and cement can be added to soils, of varying clay content, for stabilisation against water. They coat the clay minerals and prevent swelling.

The characteristics of earth can also be altered by the proportions of clay, sand and water as well as by the process of mixing, making and curing.

There is a rich history of using various biological excreta as an additive to building materials as a way of strengthening structural properties or making materials more workable.

Blood

In Germany in the late Medieval period Oxblood was used to render surfaces of rammed earth floors to make them abrasion and wipe resistant.

Urine

A traditional plaster recipe includes sandy loam and horse urine.

Hair

Andy Goldsworthy used human hair in clay wall installation.

Faeces

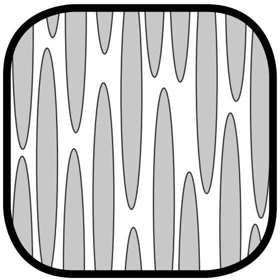
In India, Cow dung is traditionally used in loam plaster.

alternatives

The affect of a wetting agent / water on clay particles

with water

with wetting agent



wetting agent and water

washing in the Sudan image: http://flickr.com/photo_zoom.gne?id=232093046&size=o

62. Dr Neil B Milestone, Senior Lecturer, Department of Engineering Materials, the University of Sheffield

'Grey water' refers to the waste water that is generated from general domestic uses such as washing, laundry and cooking. Grey water generates between 50% and 80% of residential waste water, highlighting the level of potential there is in reusing this resource.

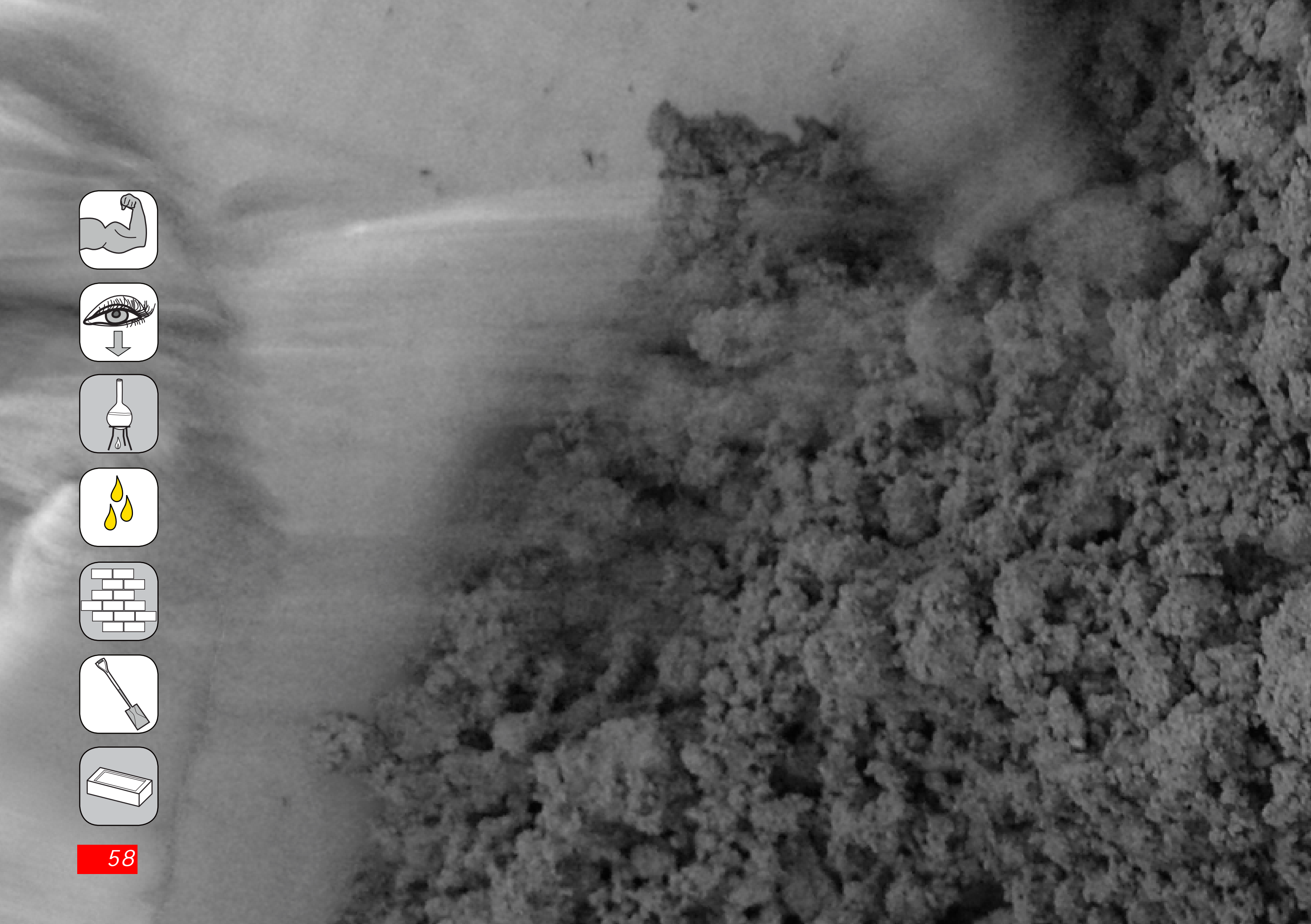
Washing water

Washing water could contain a large number of different substrates, but it is likely that washing water would include a number of soapy agents. According to Doctor Milestone[62] the soapy nature of the wetting agent decreases friction between the particles, allowing them to slide closer together. This means that the clay mixture would have tighter gaps between particles, allowing the drying process to produce a denser and therefore more watertight brick.

Cooking Water

In waste water generated by cooking there is also likely to be further potentially positive additions to a mud brick mixture. If the water was used to boil rice or some cereal products, the grey water is likely to contain high starch levels which also have potentially positive binding effects.

However, in using grey water as a binder it would be more difficult to monitor the contents of the mixture. There is the potential of chemicals that could be harmful to the strength of the brick.



26 litres of human urine were used during the experiments

introduction
hypothesis
list of materials
list of equipment
eliminating variables
how to make a urine mud brick
results
conclusion

Mud brick manufacture in arid environments brings with it the inherent problem of the supply of water.

When water is in especially short supply, such as in a refugee camp scenario, the water that is available is obviously prioritised for human consumption. Water for construction is a secondary concern. However, in many areas mud brick is seen to be the only viable form of construction for the medium to long term supply of shelter due to a simple lack of any other suitable building materials.

Much research already exists on the manufacture of mud-bricks. There is however, little that looks specifically at the use of urine in mud brick making, so there is currently very little concrete evidence for the notion that urea or urine is a beneficial additive.

Laurie Baker makes a passing reference to the use of pig's urine in an area of India where the soil would usually be unsuitable for the manufacture of mud-bricks[63]. Testing the pig's urine to try to find what it might be that made it a good additive for mud bricks he found that it had a very high concentration of urea. A further reference is made in Minke[64] concerning the addition of urea and ammonium acetate to a sand and kaolinite mix which significantly increases the compressive strength[65] though what the different effects are of the urea and ammonium acetate is not mentioned.

Minke also mentions the use of putrefied urine mixed with lime or cow-dung as a stabilising agent in mud plaster. He states that the cellulose fibres within the cow-dung act to provide tensile reinforcement, while ammoniac compounds in the aged urine act as a disinfectant against microorganisms that would presumably degrade the cellulose[66].

Urea constitutes roughly 50% of the dissolved compounds of urine, the remainder being a complex mixture of acids and trace aromatic compounds[67]. It is a relatively small molecule, whose binding effect on the massive and inert clay particles is therefore likely to be minimal and it is notable that the research quoted in Minke always uses urine in combination with something else
.

As some of the instances of urine use with mud, such as render, mention that the urine is putrified it could be that the binding effect witnessed is due to some of the products of putrefaction.

The putrefaction of urine through the action of micro-organisms produces more complex molecules than the relatively simple urea, including ammonium carbonate[68]. which forms a white crystalline solid so may form a physical binder when coming out of solution as the mud dries out.

Only the instance mentioned by Baker suggests the use of urine on its own as an additive in mud-brick making, but as this is only a passing reference it is impossible to ascertain whether this was actually the case. Baker's observation also does not mention whether or not the urine was putrefied[69].

63. Hochschild, op.cit.

64. Minke, op.cit.

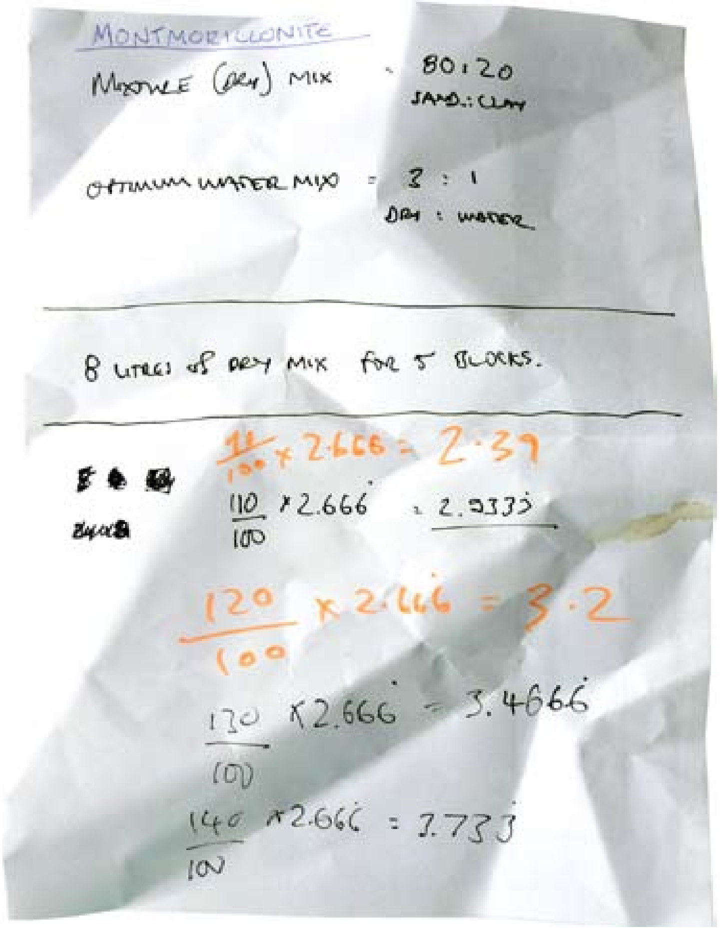
65. Weiss. A, Angewandte Chemie, Vol. 75, pp.755-762, 1963

66. Minke , op.cit.

67. Heitzmann, Urinary Analysis, 4th Ed. London: William Wood and Company, 1921,

68. Moore, 'The Ammoniacal Fermentation of Urine', Proceedings of the American Society of Microscopists, Vol 12, 13th Annual Meeting, pp.97-112, 1890

69. Hochschild op.cit.


MONTMORILLONITE
MIXTURE (DRY) MIX : 80:20
SAND : CLAY
OPTIMUM WATER MIX = 3 : 1
DRY : WATER
8 LITRES OF DRY MIX FOR 5 BLOCKS.
110/100 x 2.666 = 2.9333
120/100 x 2.666 = 3.2
130/100 x 2.666 = 3.4666
140/100 x 2.666 = 3.733

Mud bricks made substituting water with human urine will match or exceed the crushing strength of those made with water after a 3 week drying period in a 37°C low humidity environment.

list of materials

materials used during experiment

1. Montmorillonite clay x 2.5 bags (62.5 kg)
2. Kaolinite clay x 1.5 bags (57.5kg)
3. Kiln dried sand x 13 bags (260kg)
4. Urine (25.97 litres)
5. Tap Water (25.97 litres)

list of equipment

1. Rubber gloves
2. Hardware gloves
3. Protective paper suits
4. Dust masks
5. Waste disposal bags
6. Plastic dustsheets
7. Weighing scales
8. Drop test diameter check
9. Drop test height measure
10. Tape measure
11. Digital camera
12. 2 litre Measuring jug
13. 1 litre Measuring jug
14. 42 litre gorilla tub
15. 75 litre gorilla tub
16. Mixing stick
17. Blue plastic lining strips
18. Moulds x 4
19. Ejection stick
20. Layout boards
21. Drying racks
22. Portable radiators
23. Portable dehumidifier
24. Crush tester

The manufacture of mud-bricks in the field is not an exacting process. Many of the variables involved such as mixing time, drying time, clay content, water content and stabilizers have been tested in previous studies into mud-brick manufacture[70].

70. See Houben & Guillaud, Earth construction: a comprehensive guide. London, Intermediate Technology Publications, 1994

&

Minke, Earth Construction Handbook, Southampton, WIT Press, 2000

71. Hochschild, op.cit

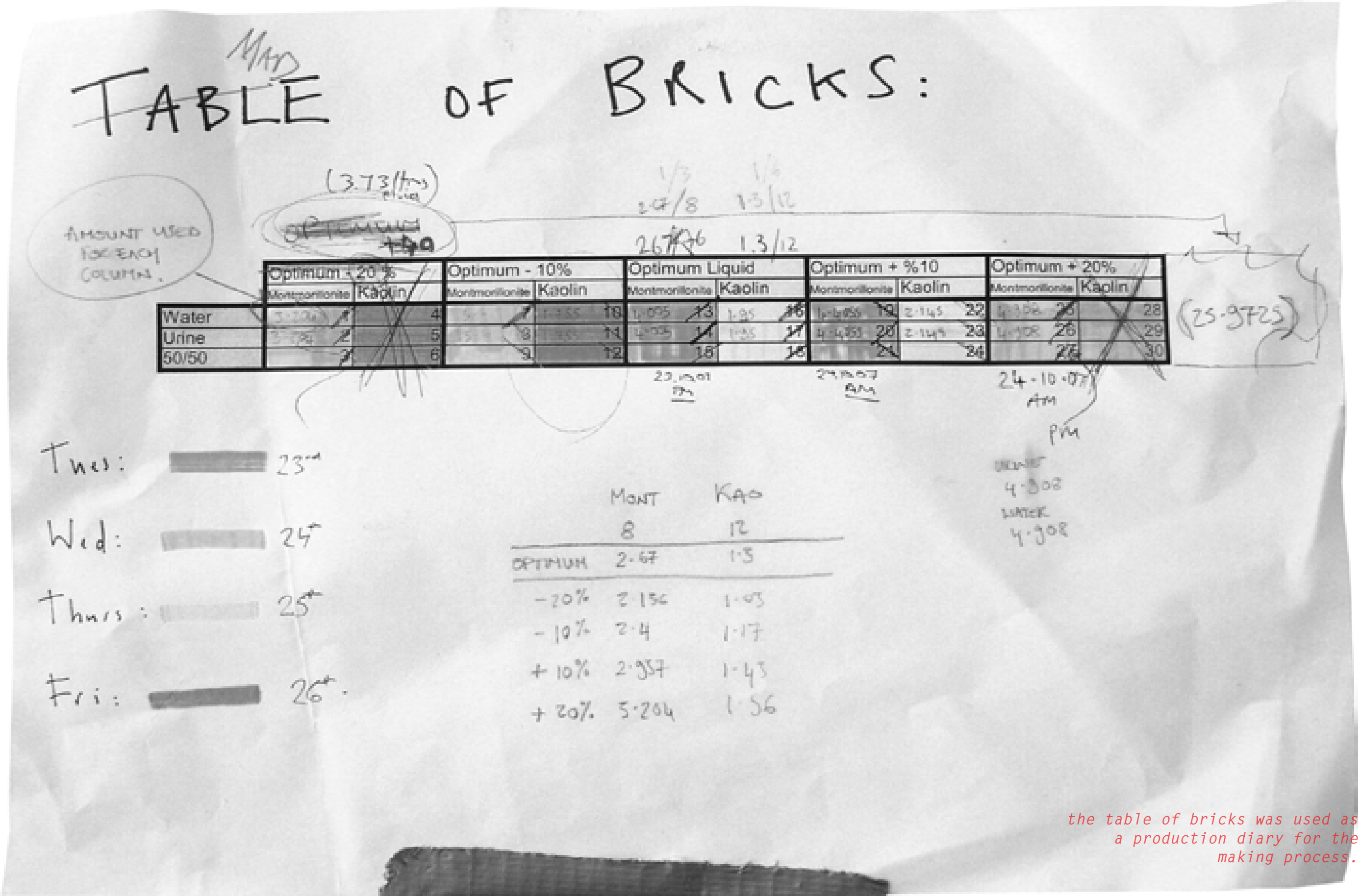
In devising the method for the experiment the key was to eliminate all possible variables, with the exception of the liquid content of the mixture.

We tested three different liquid types, water, urine and urine diluted to 50% with water, using test batches of 5 blocks each. In combination with the five different moisture contents of mix and two different types of clay this gave an experiment with 150 results under 30 conditions as described below.

Our study is concerned solely with the relative performances of water and human urine as binding agents so many of these variables have been controlled or eliminated. We used two different clay types to represent expansive and non-expansive clays, these represent the two main characteristic clay types. Though they are seldom found in isolation, for the interests of this experiment their separation enables us to test whether urine reacts differently to each. If the urine does have an effect testing on the two different clay types may give clues as to the way in which a component of the urine is interacting with the clay particles. We used bentonite with an 80% sodium montmorillonite 20% illite composition as the expansive clay sample, and standard Grade 2 kaolinite as the non-expansive clay type. Both are readily available as 25kg sacks dry-weight.

Sand aggregate was used as filler with a each clay sample. Clean silica sand was used that had been kiln-dried to eliminate uncontrolled liquid input to the brick mixes. Human urine for the test bricks was collected before and during the batch mixing period. All urine was mixed prior to being added to reduce differences between individual samples and was between 1 day and 1 week old. The urine was stored at room temperature out of direct sunlight in sealed plastic containers. Though most mention of urine in earth construction techniques is of putrefied urine this is always added alongside something else, such as dung. The only instance where urine was mentioned on its own does not state whether or not this urine is putrefied[71]. As human urine is roughly the same composition (though not concentration) when fresh, but is dependent on the species mix of micro-organisms to determine the putrefied composition, we tested relatively fresh urine up to a week old as we felt that the results of putrefied urine in Sheffield may not be representative of that obtained from putrefied urine in the arid area conditions that this research stemmed from.

The ratio of sand to clay to liquid was obtained by hand-mixing a small amount and testing using drop and cohesion tests as described by Minke.



the table of bricks was used as a production diary for the making process.

The sand to clay ratio was then kept constant for both clay types throughout all the tests, this being 1:4 clay powder to sand dry weight.

The liquid volumes added to the test batches were varied in case optimum dry brick strength is achieved with a different liquid for urine than for water. However, our starting point was the optimum ratio for water which was 1:6 by volume of water to sand/clay powder mix for kaolinite and 1:3 for montmorillonite.

To test for variation in strength for different dampness' of mix we made mixes with a 10 and 20% liquid volume above and below optimum creating five dampness conditions.

The clay and sand was dry mixed in bulk using a clean cement-mixer to eliminate variation in ratio across the test batches. These mixes, sand and kaolinite and sand and monmorillonite, were then stored indoors at room temperature.

The sand and clay mixes had the liquids added and mixed by hand as we found that the cement mixer did not adequately homogenise the mix as it was much drier than standard cement mixes. The ingredients were both mixed and kneaded for a minimum of 5 minutes per batch.

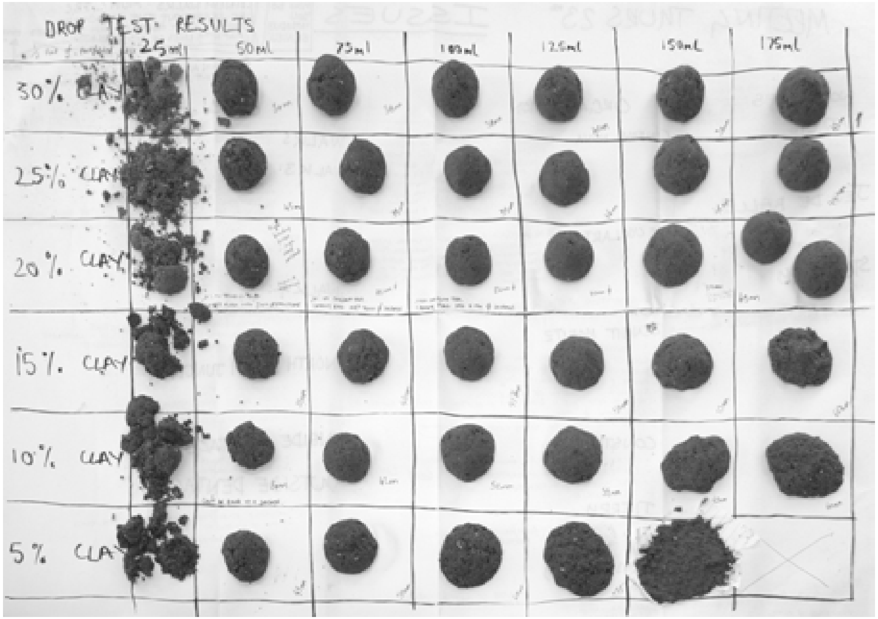
Once finished the mud was transferred to the five MDF moulds which were lined with polyethylene sheet to prevent the mud from sticking and enable them to be easily removed from the mould once finished. The mud was added a double handful at a time pressed down firmly using fingers with particular attention being paid to the corners.

To allow for the expected shrinkage in the bricks when drying we used a mould size of 110 x 110 x 110mm to ensure that the eventual cut down block sizes for crush test purposes could conform to the standard 100x100x100 test dimension.

Excess mud was scraped from the moulds using a flat piece of wood and then the brick pushed out of the mould with a stick sized to be slightly smaller than the internal dimension of the mould.

A drying room was set up using 5 electric heaters, a standard radiator and a domestic dehumidifier keeping the room at 30°C and 20-30% humidity. The bricks were placed on racks in this room to allow airflow round them and turned once a day to try to ensure the bricks dried evenly. The bricks were dried for two weeks before they were removed for testing.

eliminating variables



Drop test results (above) and cohesion testing (right): The drop tests were a means of determining appropriate ratios of sand to clay and water to mixture. Roughly golf ball sized pieces of mud were made with clay contents of 5 to 30% and with between 25 and 175ml of water per 500ml of clay / sand mixture. The balls were then dropped from a height of 1.5m. A good sample was expected to crack slightly but largely retain its shape.

The cohesion tests were designed to test the consistency of the mix by making long worm shapes and pressing them against the top of the hand until they snap. A good sample should get to between 10 and 20cm long before breaking We found samples containing a 20 to 25% clay content and using around 100ml of water performed best on the drop and cohesion tests; it was these ratios that formed the basis for the experiments.

Clay / sand content

We imitated common soil conditions using dry clay powder (montmorillonite and Kaolinite) and kiln dried sand measured to a pre-determined ratio. This ratio was determined using drop and cohesion tests. From these simple tests we found that a ratio of one part clay to four parts sand would be appropriate.

Water content

If there is too little water in the mixture the clay cannot form enough molecular bonds to bind the soil; if there is too much water the bricks will collapse on removal of mould.

From the drop tests we determined that a variable water content of around one third was appropriate.

Mixing

Longer periods of mixing allow for the clay molecules to create more bonds within the soil resulting in a stronger brick. Although there is an optimum mixing time, after this there is little gained strength. Standardising the mixing process was initially attempted using a cement mixer, but this method was found to be unsuitable and a qualitative hand mixing process was discovered to be a more accurate and effective means of mixing. This allowed a reasonable level of standardisation whilst ensuring that each mix could be properly controlled to ensure that the liquid and clay / sand mixture was properly combined.

Moulding technique

Throwing the mud mixture into the mould allows for better bonding of subsequent layers of mud as the impact helps integrate the newer layer. If compressing mix into the mould, repeated impact rather than pressure results in better bonding. We intended to cast and compress the mixture into moulds using a fixed method. A device was created to standardise the compaction process but it was soon discovered that this method was inappropriate as the compaction was insufficient and created layering in the blocks. Instead a qualitative method was adopted using our hands to compact the mixture, which helped to evenly distribute it in the moulds and created smoother, more solid blocks. The blocks were therefore less standardised but more were of a sufficient quality for testing purposes. The decision to opt for a hands on method meant that we could control the quality of each individual brick, and we found this to be a superior method of compaction to the use of a compaction device.

Drying time

A longer drying time allows for even setting of the brick, too fast and the brick can crack. This can be affected by size of mould as thin bricks dry faster. We created a drying room in which the bricks were kept at a constant 30^{0}C for two weeks. They were raised above the ground by use of a rack system and rotated 90 degrees roughly every twenty-four hours.

Additives

Additives such as straw or other fibres are known to have been mixed with mud to improve their binding strength, particularly when the clay content is high. It was decided that in order to create a fair experiment that, other than water and urine, no additional binding materials should be used. This also applied to the size of particles in the sand and clay, along with straw and other fibrous materials that may be commonly used in the field.

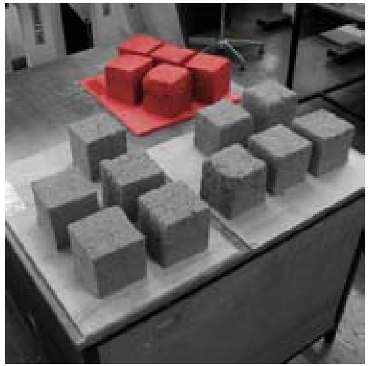
weighing out clay /sand mixture

measuring out urine

mixing

packing the moulds

removing the bricks from the moulds



keeping finished batches seperate


mixing and preparing the moulds


the drying racks

Serves five montmorillonite urine bricks

Step 1.
First take your clean, dry, 75 litre gorilla tub. Into the tub place your dry clay / sand mixture (one part clay to four parts sand), about eight litres measured using the large measuring jug would be sufficient. Be sure that you have mixed the clay and sand together well.

Step 2.
Next measure the correct amount of urine using a measuring jug and pour into the clay/sand mixture. Stir in the urine using your hands to knead the mixture into a dough, or biscuit base consistency. This should take between two and three minutes of vigorous mixing, provided there are two people participating. Before attempting this step, make sure you are wearing your rubber gloves and mask; you could also wear the boiler suit to avoid dirtying your clothes.

Step 3.
When the urine is completely mixed in, it is time to compress it into the moulds. Prepare your moulds by placing them on MDF boards and lining them using the blue plastic lining strips.

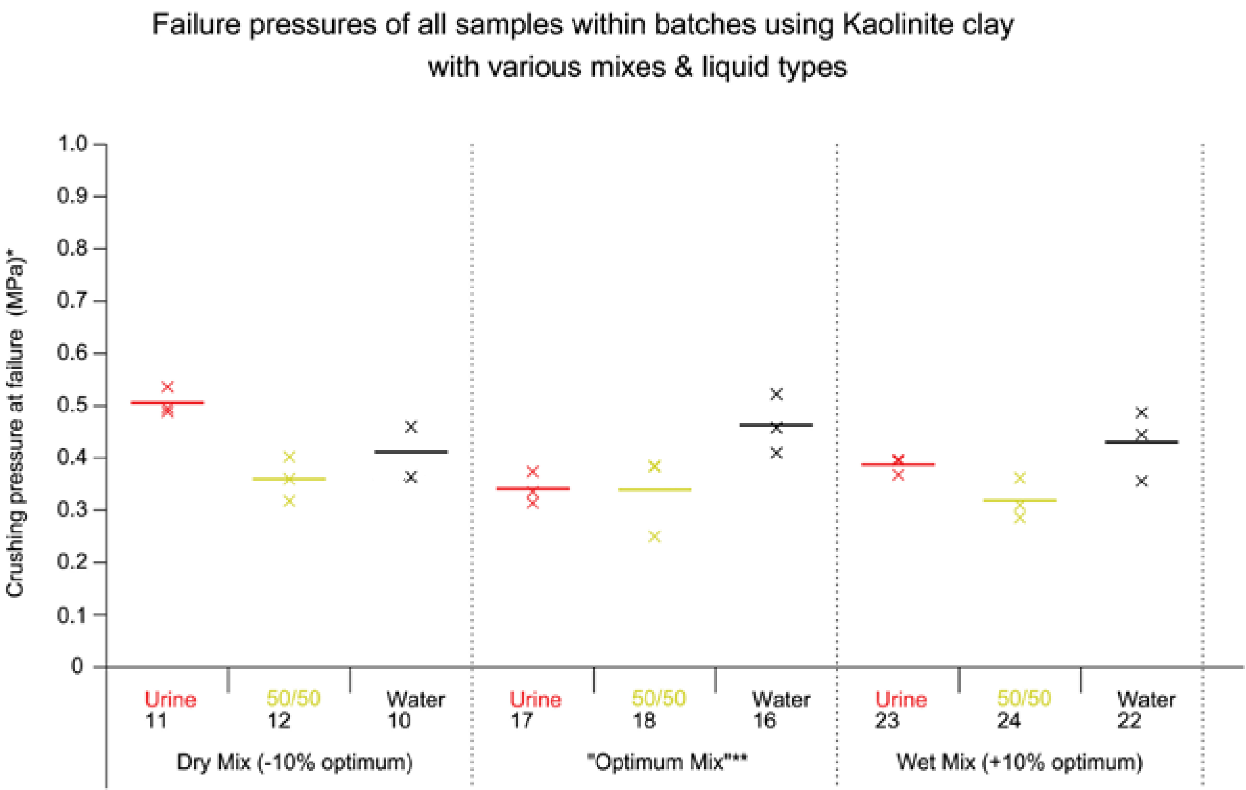
When the moulds are prepared, begin to compress the mud into them using your fingers to force the mud into the corners. It is important to really press the mud into the moulds as thoroughly as possible to avoid air gaps, as these will expand when drying, causing your brick to crack. Continue to add more mixture into the moulds, pressing firmly as you go, until the mould is full. Repeat this for the remaining four sections of the mould. Then take a flat piece of wood and press down onto the top of the mould, compacting the contents whilst flattening the top and removing any excess mixture from above the top of the mould.

Step 4.
Once this is done, turn the mould upside down and, getting a friend to help you, hold the mould above the floor and push the blocks out using the ejecting stick. Now simply remove the blue plastic lining strips and place your finished bricks on a layout board, remembering to write the correct batch number on the board to avoid confusion later.

Step 5.
Now your bricks are ready to go to the drying room, where they will slowly bake at 30ºC for two weeks, before they can be removed and tested.

crushing, sniffing, scratching, dipping, weighing, spraying

The following section illustrates the findings of our experiments. The crush test results are represented graphically to compare the failure pressures of the different brick types then photographic images are presented to analyse qualitatively the behaviour of the bricks against a spectrum of additional tests including, scratch, sniff, spray and dip.



* values of pressure have been converted from crushing force values, assuming there was an identical area of contact of 100mm x 100mm for each sample (crosses show values, bars show mean average).

** "optimum mix" was the ideal workable mix when water was used, determined by drop tests.

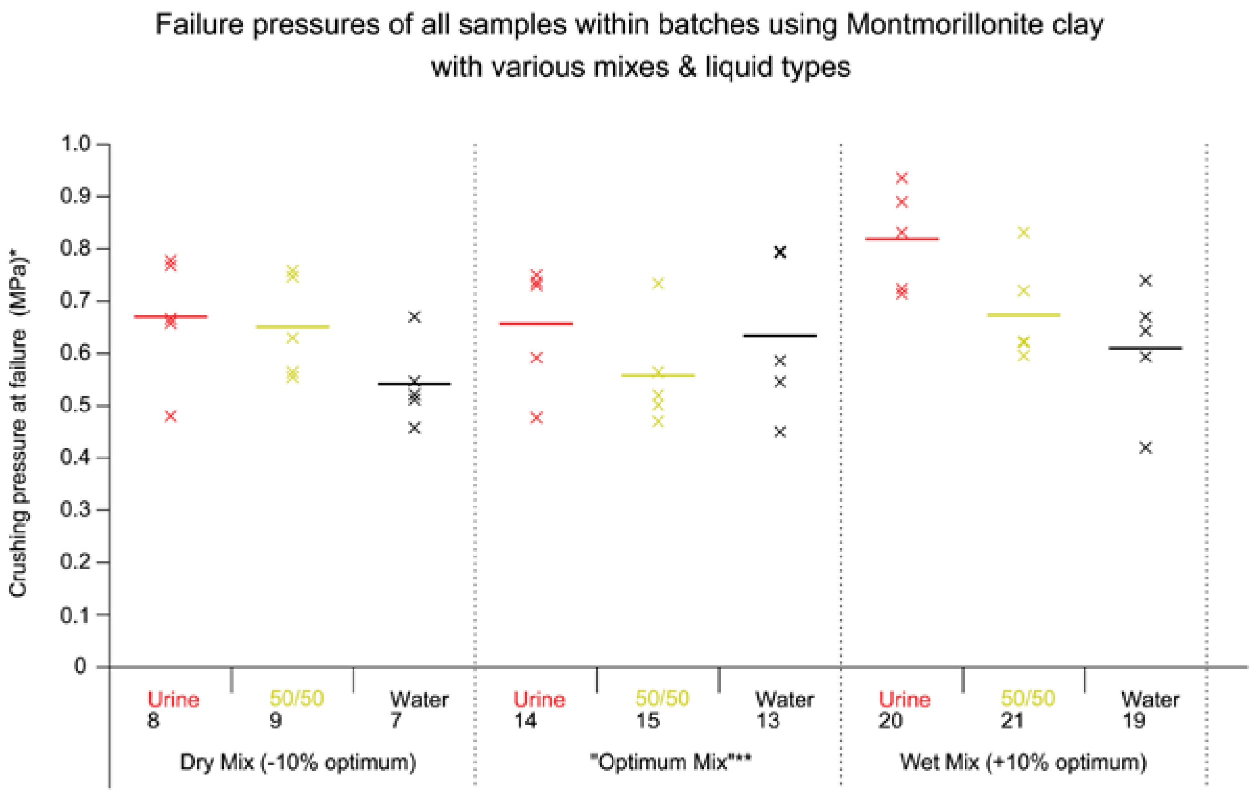
kaolinite crush test results

Urine						
		Failure Force kN				
		a	b	c	av. Force kN	av. Pressure MPa
Batch	Liquid Percentage%					
11	Dry Mix -10%	4.95	4.88	5.36	5.06	0.506
17	Optimum Consistancy	3.14	3.35	3.74	3.41	0.341
23	Wet Mix +10%	3.68	3.96	3.96	3.87	0.387

50/50						
		Failure Force kN				
		a	b	c	av. Force kN	av. Pressure MPa
Batch	Liquid Percentage%					
12	Dry Mix -10%	4.02	3.60	3.18	3.60	0.360
18	Optimum Consistancy	3.83	3.85	2.50	3.39	0.339
24	Wet Mix +10%	3.10	3.62	2.86	3.19	0.319

Water						
		Failure Force kN				
		a	b	c	av. Force kN	av. Pressure MPa
Batch	Liquid Percentage%					
10	Dry Mix -10%	2.60	4.60	3.64	4.12	0.412
16	Optimum Consistancy	4.10	4.58	5.22	4.63	0.463
22	Wet Mix +10%	4.87	3.56	4.45	4.29	0.429

The failure pressures for the kaolinite blocks all come between 0.30 and 0.51MPa, a relatively low figure, even for mud-bricks. The results show no visible or statistically significant differences between any of the test conditions.



* values of pressure have been converted from crushing force values, assuming there was an identical area of contact of 100mm x 100mm for each sample (crosses show values, bars show mean average).

** "optimum mix" was the ideal workable mix when water was used, determined by drop tests.

montmorillonite crush test results

Urine								
		Failure Force kN						
		1	2	3	4	5	av. Force kN	av. Pressure MPa
Batch	Liquid Percentage%							
8	Dry Mix -10%	7.68	6.66	7.78	4.80	6.58	6.70	0.670
14	Optimum Consistancy	4.77	7.37	5.92	7.30	7.50	6.57	0.657
20	Wet Mix +10%	8.90	7.14	8.32	9.36	7.24	8.19	0.819

50/50								
		Failure Force kN						
		1	2	3	4	5	av. Force kN	av. Pressure MPa
Batch	Liquid Percentage%							
9	Dry Mix -10%	5.55	6.30	7.47	5.64	7.58	6.51	0.651
15	Optimum Consistancy	5.20	7.34	5.64	4.70	5.02	5.58	0.558
21	Wet Mix +10%	5.96	6.22	5.96	7.20	8.32	6.73	0.673

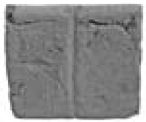
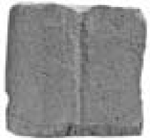
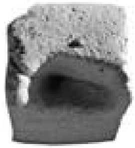
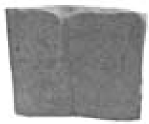
Water								
		Failure Force kN						
		1	2	3	4	5	av. Force kN	av. Pressure MPa
Batch	Liquid Percentage%							
7	Dry Mix -10%	5.12	6.70	4.58	5.47	5.21	5.42	0.460
13	Optimum Consistancy	7.94	4.50	5.46	7.94	5.86	6.34	0.532
19	Wet Mix +10%	7.40	6.44	4.20	5.94	6.70	6.14	0.614

The average failure pressures for the montmorillonite blocks come between 0.46 and 0.82MPa. The results show no statistically significant differences between any of the test conditions though there is a noticable trend in the graphs suggesting that there is a strengthing interaction.

kaolinite erosion test results

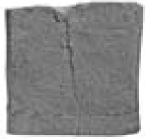
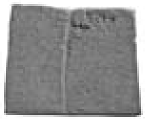
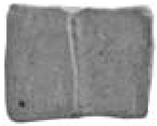
[observations]

water

batch	mix	sniff	scratch	spray	dip
10	Dry mix -10%	0/5			
16	Optimum 0%	0/5			
22	Wet mix +10%	0/5			

kaolinite erosion test results

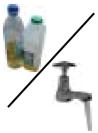
urine 

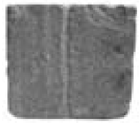
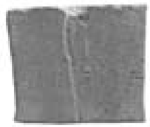
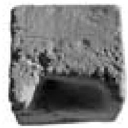
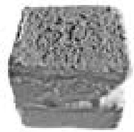
batch	mix	sniff	scratch	spray	dip
11	Dry mix -10%	2/5			
17	Optimum 0%	2/5			N/A*
23	Wet mix +10%	3/5			

* Brick damaged during drying

kaolinite erosion test results

[observations]

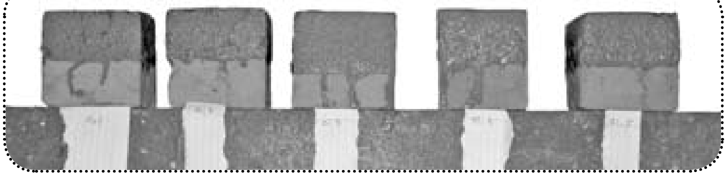
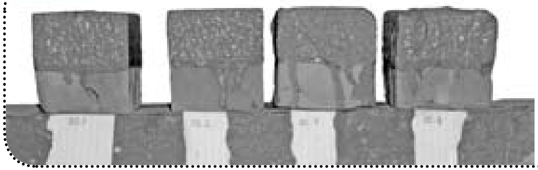
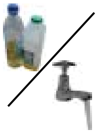
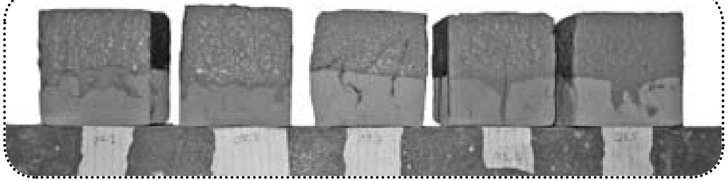
50/50 

batch	mix	sniff	scratch	spray	dip
12	Dry mix -10%	0/5			
18	Optimum 0%	0/5			
24	Wet mix +10%	1/5			

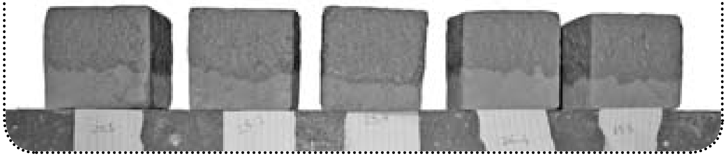
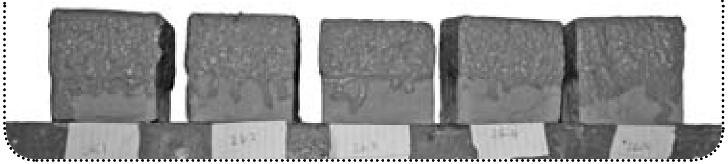
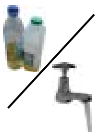
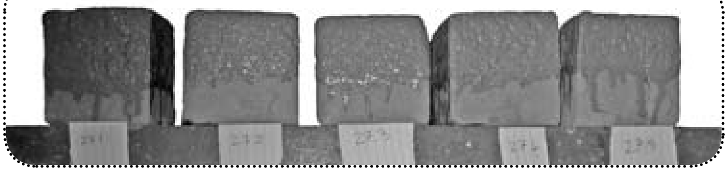
The observational tests conducted on the kaolinite batches show a noticeable resistance to water damage in the urine blocks both from soaking and spraying, but it is the soak test that shows this difference most clearly with much reduced loss of material from the urine block.

montmorillonite immersion test results

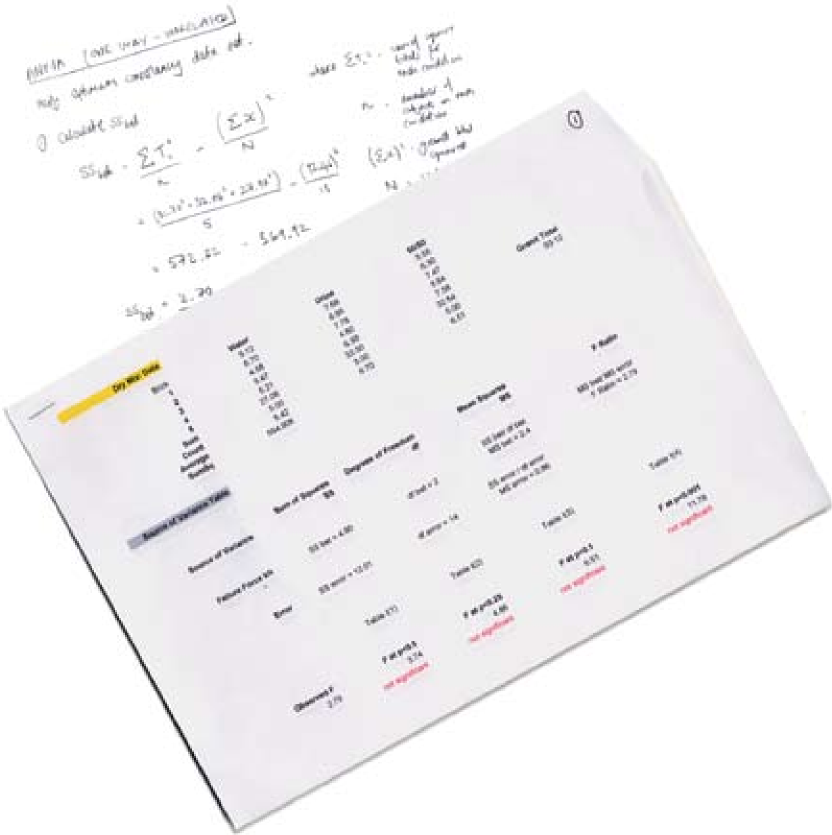
[observations]

	batch	mix	dip
water 	1	Dry mix -20%	
urine 	2	Dry mix -20%	 N/A*
50/50 	3	Dry mix -20%	

* Brick damaged during drying

		batch	mix	dip
water		25	Wet mix +20%	
urine		26	Wet mix +20%	
50/50		27	Wet mix +20%	

The soak tests conducted on the montmorillonite blocks did not show any visible difference of effect between test conditions. The montmorillonite blocks were far superior in soak resistance than the kaolinite blocks as none of them showed any noticeable material loss.



Statistical analysis (using ANOVA) of the crush test results indicates that our experimental data does not describe a ‘significant’ variance between urine, water and the 50/50 mix in the strength of montmorillolite mud bricks.

Therefore we cannot catagorically state that urine makes mud bricks stronger based on our crush tests results alone.

We suspect the main reason for this outcome is due to the insufficient quantity of test samples we crushed. 5 samples for each catagory is significantly less than the recommended 10 - 30 that would be used in a longer study.

However this result does enable us to state that the urine does not make the bricks significantly weaker. Therefore ‘material strength’ can be dismissed as a limiting factor in the implementation of a urine brick strategy.

Perhaps more interesting are the less quantifiable observations that resulted from the erosion testing. The potential that urine could increase the resistance of mud bricks to water, and the possibility that urine might increase the range of soils suitable for mud brick construction is very interesting and certainly warrants further research.