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Unfired clay masonry has a high potential to regulate indoor humidity and therefore create healthier living environments. The measurement of such potential on various building materials has received increasing attention and has generated the Moisture Buffering Value (MBV) concept. This work experimentally explored various conditions affecting the measurement and calculation of the buffering potential. Measurements of MBV and steady state properties (water vapour permeability and sorption isotherms) were performed on 18 samples, Compressed Earth Blocks (CEB) and Stabilised Compressed Earth Blocks (SCEB). It is quantitatively shown how the variability of experimental conditions in the dynamic measurement can change the obtained MBV ($MBV_{practical}$). The calculated buffering potential (MBV_{ideal}) is equally affected by the variability of the steady state properties measurements. A good agreement between calculated and measured MBV was observed for most samples when reducing this variability which was shown by using a DVS (Dynamic Vapour System) system to obtain the sorption isotherms of the material.

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Conditions affecting the moisture buffering measurement performed on Compressed Earth Blocks

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1. Introduction

Indoor air quality (IAQ) and humidity levels in buildings have become a major concern as they can have a direct impact on the health of occupants (Jones, 1998, Arundel et al., 1986). Humidity buffering in a room is a combination of environmental variables (current and previous humidity levels, temperature, air exchange rate and air velocity) and material properties (moisture absorption properties and vapour permeability). It is the combination of environmental variables and different materials which influence the buffering capacity of an enclosure, and therefore the related benefits of humidity buffering.

The potential for microporous building materials to self-regulate indoor humidity levels has been studied by Padfield (1998) who identified unfired clay masonry as one of the materials having the highest potential and the present study is therefore focussed on these materials. The experimental measurement of humidity buffering is still in early stages, therefore to further investigate the performance of unfired clay masonry, the influence of different test methods and equipment has to be determined. In 1965 Kunzel measured the moisture sorption of indoor surfaces with a dynamic experiment by using the “step response” method (Kunzel, 1965). Such method corresponds to a high relative humidity (RH) cycle for a set time span characterising the adsorption followed by a low humidity cycle to characterise desorption, the mass change of the sample being monitored during the process. This type of experiment was then continued by several authors as reported by (Svennberg et al., 2007). A Japanese Industrial Standard (JIS) (JIS, A 1470-1, 2002) test was developed using the same principals and the outcome of the Nordtest project also proposed the same type of testing for moisture buffering evaluation (Rode et al., 2005, Roels and Janssen, 2006). This method has led to a recent international ISO standard (ISO, 24353: 2008). However, there is little information in the scientific literature on different materials tested according to these methods (Svennberg et al., 2007). It is therefore difficult to quantify the effect of the test methods on results for particular materials.

The obtained experimental result is referred to as moisture buffering or hygric inertia value which can be presented as the $MBV_{practical}$ as proposed by the Nordtest.

"*The practical Moisture Buffer Value ($MBV_{practical}$) indicates the amount of water that is transported in or out of a material per open surface area, during a certain period of time, when it is subjected to variations in relative humidity of the surrounding air. When the moisture exchange during the period is reported per open surface area and per % RH variation, the result is the $MBV_{practical}$. The unit for $MBV_{practical}$ is kg/(m2·% RH).*"(Rode et al., 2005).

Padfield (1998) used a different approach to test the moisture buffering capacity of building materials by utilizing a flux chamber. Instead of measuring the adsorption capacity of the building material, he directly measured the effect of the materials on the RH in a closed chamber when a constant amount of moisture was released in a given time. The flux chamber method of Padfield (1998) may be considered to better represent the situation in a real building where there is a sudden release of moisture (e.g. an occupant having a shower), but this method does not quantify the adsorption/desorption within the material and can be influenced by the buffering capacity/leakage of the test chamber. The methods using controlled humidity levels were therefore considered more suitable to compare the influence of material properties on the measured moisture buffering.

Along with Padfield, only a few authors have investigated the buffering potential of earth building materials. A thesis written by Lustig-Rössler (1992) investigates the hygroscopicity of earth building materials (sorption isotherms), and also the dynamic adsorption using a step response method. Materials used had varying particle size distribution and surface treatments. The results of this study remain unpublished in English or in the peer-reviewed scientific literature. Allinson and Hall (2011) have experimentally and numerically investigated the moisture buffering of Stabilised Rammed Earth (SRE), the outcome underlined the importance of surface film resistance in the results of experimental measurements and the necessity to increase the amount of tested samples for better reliability. They compared the numerically obtained results (MBV_{ideal}) with the experimental results ($MBV_{practical}$) for three different SRE samples, they observed that MBV_{ideal} >$MBV_{practical}$. However, no proportionality could be established with the small number of samples potentially a limitation to establish such a relationship. The MBV_{ideal} is based on the moisture effusivity, b_m, which is the analogy of the thermal effusivity (see equation 1). Proposed by the Nordtest (Rode et al., 2005), it is based on steady state measured parameters (equilibrium moisture content and water vapour permeability). These parameters are non-linear over the RH range, this was numerically investigated by Roels and Janssen (2006). It was concluded that a good agreement can be obtained when the steady state derived properties are obtained at the average RH of the dynamic test. They have also numerically investigated the sensitivity of the dynamic "step-response" method on wood fibreboard, plywood, aerated cellular concrete and gypsum plaster. The following

parameters were investigated: the specimen thickness, time steps and the surface film resistance.

In this paper, the sensitivity of the dynamic "step response" method is experimentally investigated and then used to characterise the moisture buffering properties of compressed earth blocks (CEB) and stabilised compressed earth blocks (SCEB). SCEB can have improved durability and strength compared to unstabilised CEBs (Morel et al., 2007) however some previous work seems to indicate that stabilisation reduces the buffering capacity (Lustig-Rössler, 1992, Eckermann and Ziegert, 2006). This may depend on the type of stabilisation, as explained by Liuzzi et al. (2012), who calculated a higher MBV_{ideal} for lime stabilised samples. Therefore to control the reliability of calculated results (MBV_{ideal}) both methods were compared and discussed.

2. Materials

The clay used for the preparation of the samples was extracted from the Wealden Clay group in West Sussex in the UK. The Wealden Clay was extensively used for making fired clay bricks and represents 6% of British brick clay resources (Reeves et al., 2006). The soil has higher clay content than what is recommended for CEBs or SCEBs. Therefore a mix ratio of 50% brick clay and 50% fine sand was used to readjust particle size distribution within the range of 10 to 20% of clay as suggested by (Barbosa, 2007). The silt content remains high, however it has been considered as acceptable. The particle size distribution of the final soil mix is given in Figure 1.

In the case of cement (Portland cement, CEM I) and lime (air lime, CL90) stabilised bricks, stabiliser contents of 4% and 8% per dry weight of sample were added. In the case of the geopolymer stabilised brick, 3% per dry weight of dissolved NaOH (Sodium Hydroxide) was added, as recommended by Davidovits (Davidovits, 2011). The geopolymer samples were left for two days at room temperature after mixing before compacting to assist dissolution. The samples used in this study were compacted using an adapted Wykeham Farrance 50kN triaxial frame and a proctor mould used with a 100mm plastic sewage pipe as a form.

3. Methods

Steady state properties

Water vapour permeability was tested following the ISO 12572:2001 standard (ISO, 12572: 2001), using the wet cup method where a RH of 94% is set inside a container using a saturated salt solution of potassium nitrate. The exterior RH was set in a climate chamber at 50%. Aluminium tape is used as sealant material, which has shown the best results in previous studies (Svennberg, 2006). From the transmission rate of water vapour through the sample, the water vapour resistance can be determined (μ). The recording was done in the same climate chambers than for the moisture buffering (air velocity between 0.41 and 0.65 m/s).

Dynamic Vapour Sorption (DVS) testing was undertaken to determine the sorption isotherms of the material only one sample was measured per material. The basic assumptions that were applied for all samples when using the DVS equipment are:

(i) for a hygroscopic material a very small sample of less than 4g is representative of the entire sample (Engelund et al., 2010) which is not considered a problem for a soil with the particle size distribution provided in Figure 1 ;

(ii) Each step in RH during the DVS measurement is incremented either when a stable mass is achieved with less than 0,0001% mass change per minute or a maximum time interval of 360min is reached for each RH step.

(iii) The adsorption at very high RH may be undervalued because total equilibrium could not be reached in the specified maximum time allocated, but this is not considered a problem as these high humidity levels are unlikely to be achieved for an extended period in a real building.

The same criteria were used for all samples to allow comparison. All the tests were carried out at 25°C, with the exception of the moisture buffering test which was undertaken at 23°C. However there should not be a major variation between 23°C and 25°C as mentioned by Künzel (1995) who explains that the effect of temperature on moisture sorption between 20°C to 70°C can be disregarded.

Dynamic properties

Moisture buffering was measured in terms of water vapour adsorption in response to cyclic humidity variations. This was according to the recently published ISO 24353 standard (ISO, 24353: 2008) and the Nordtest (Rode et al., 2005). Both of the methods use gravimetric measurements and they mainly vary in the procedure of the test, the time-steps used, the humidity levels, and the sample sizes to use. There are various sets of RH levels proposed by both methods. Therefore the soil samples were tested in different RH cycles and with varying time steps to compare the results. Table 1 summarises the different cycles used.

Table 1: Humidity buffering control environment

RH (%)	Time step (h)	Sources
85/50	8/16	based on Nordtest and McGregor (2012)
75/53	8/16	based on ISO 24353 standard and Nordtest
75/53	12/12	based on ISO 24353 standard

The methods used are variations to the test methods proposed by the Nordtest, the ISO standard or the Japanese Industrial Standard and were used to determine the effect of

sample thickness, logging method, surface film resistance, RH levels, time steps and the addition of stabiliser.

The MBV is calculated using the equation given by Rode et al. (2005) and is based on experimental results. Previous studies (Delgado et al., 2006) have shown that the maximum cyclic moisture adsorption is lower once it has reached a stable condition. Stable cycles are obtained when the samples are left to run in the step response test until the final weight (end of cycle) of the sample was equal to the initial weight (beginning of cycle). This means the sample does not adsorb more moisture than it will release. This equilibrium was usually reached after 5 to 10 days in the cycles depending on the initial conditions of the samples and was used for all testing.

Prediction of buffering capacity from steady-state properties

Previous studies have used the concept of MBV_{ideal} as proposed by the Nordtest to compare with experimental results or to determine the most suitable buffering material (Allinson and Hall, 2011, Liuzzi et al., 2012). These studies have mentioned the limits of the MBV_{ideal} calculated from steady-state measured material properties.

The MBV_{ideal} has been calculated to compare with the experimental results, as shown in Figure 9. The equation given by Rode et al. (2005) was used to determine moisture effusivity, b_m *[kg/(m².Pa.s$^{1/2}$)]* which is provided in the Table 2:

$$b_m = \sqrt{\frac{\delta_p . \rho_0 . \frac{\partial_u}{\partial_\varphi}}{p_{sat}}} \quad (1)$$

Where δp *(kg/m.s.Pa)* is the water vapour permeability, ρ_0 *(kg/m³)* is the dry density of the material, p_{sat} *(Pa)* is water vapour saturation pressure, at 23°C. The moisture capacity *(kg/kg)* is determined by the equation (2):

$$\xi = \frac{\partial_u}{\partial_\varphi} \quad (2)$$

Where *u* (kg/kg) is the moisture content by mass and φ (-) is the RH. The water vapour permeability and the moisture capacity are obtained from experimental results. The moisture capacity is the slope of the sorption isotherm which is assumed linear in this analysis in spite of the variation observed in Figure 2. Roels and Janssen (2006) explained that a difficulty appears when determining the moisture capacity because of its nonlinear character. In Hall and Allinson (2009), the moisture storage capacity is determined using the pseudo-linear section of the sorption isotherm which is in the middle range of the isotherm. This excludes the sharp increase at higher RH. So in this case, the linear relation obtained in this area (40-75% RH) was used to determine the moisture capacity based on results

obtained for each sample with saturated salt solutions according to the ISO 12571:2000 standard (ISO, 12571: 2000) and with the DVS, see Table 2. Equation (3) was used to calculate the MBV_{ideal} it was adapted from Rode et al. (2005) in order to fit a 12h/12h time frame. This was done by changing the α in the h(α) equation (equation 3 in Rode et al., 2005) from 1/3 corresponding to the 8h/16h cycle to ½ corresponding to the 12h/12h cycle, the equation for MBV_{ideal} is therefore:

$$MBV_{ideal} = 0.0061.p_{sat}.b_m.\sqrt{t_p} \quad (3)$$

4. Results

Steady state measurements

Figure 2 shows the sorption isotherms (a, c and e) and the associated hysteresis (b, d and f) for different stabilisation contents.

It visible on Figure 2a and c that stabilisation with cement and lime slightly reduces the equilibrium moisture content (EMC) over the whole range of RH, whereas the geopolymer stabilisation reduces EMC over the middle range and increases EMC at high RH levels. This indicates the geopolymer stabilisation may influence the pore size and structure more than other stabilisation methods.

The hysteresis in Figure 2 b, d and f illustrates the difference of EMC between the adsorption path and the desorption path. The domain on the sorption isotherms where the dynamic moisture adsorption occurs lies between the adsorption and desorption curve, so it is necessary to determine both curves. It is noticeable that cement stabilisation has little effect on hysteresis (Figure 2b) but lime stabilisation decreases hysteresis (Figure 2d).

The effect of stabilisation on vapour permeability can be seen in Table 2 where all results are presented. As shown, the water vapour permeability is reduced with any form of stabilisation. Cement stabilisation resulted in a greater reduction in vapour permeability than lime stabilisation, as noted by previous researchers investigating plasters for buildings (Maravelaki-Kalaitzaki, 2007).

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	Sample properties		Measured steady-state properties				Measured dynamic properties			Calculated dynamic properties		
Sample	**Stabilisation**	**Density (kg/m^3)**	**Vapour resistance factor, μ**	**Water vapour permeability, δp (kg/(m.s.Pa))**	**ξ1 from DVS (kg/kg)**	**ξ2 from salt solutions (kg/kg)**	**MBV 50/85 @ 8h (g/m^2.% RH)**	**MBV 53/75 @ 8h (g/m^2.% RH)**	**MBV 53/75 @ 12h (g/m^2.%RH)**	**Moisture effusivity, bm ($kg/(m^2.Pa.s^{1/2})$)**	**MBV 53/75 @ 12h (g/m^2.%RH) with ξ1**	**MBV 53/75 @ 12h (g/m^2.%RH) with ξ2**
US1	None	1758	5.5	3.66E-11	0.0207	0.0225	3.1	3.1	3.2	6.42E-07	2.7	2.6
US2	None	1777	5.8	3.42E-11	0.0207	0.0246	3.6	2.9	3.1	6.24E-07	2.8	2.6
US3	None	1815	5.8	3.46E-11	0.0207	0.0195	3.5	2.9	3.1	6.34E-07	2.5	2.6
C41	4% cement	1769	6.8	2.92E-11	0.0213	0.0150	2.7	2.3	2.5	5.84E-07	2.0	2.4
C42	4% cement	1760	7.0	2.88E-11	0.0213	0.0190	3.1	2.2	2.4	5.78E-07	2.2	2.4
C43	4% cement	1683	6.5	3.09E-11	0.0213	0.0177	2.9	2.2	2.5	5.85E-07	2.2	2.4
C81	8% cement	1797	7.7	2.59E-11	0.0183	0.0214	2.3	2.1	2.1	5.14E-07	2.3	2.1
C82	8% cement	1731	7.0	2.84E-11	0.0183	0.0222	2.7	2.1	2.2	5.28E-07	2.4	2.2
C83	8% cement	1779	7.4	2.72E-11	0.0183	0.0221	2.5	2.2	2.1	5.23E-07	2.4	2.1
L41	4% lime	1770	6.1	3.30E-11	0.0209	0.0200	2.9	2.4	2.5	6.15E-07	2.5	2.5
L42	4% lime	1735	5.9	3.37E-11	0.0209	0.0220	2.7	2.5	2.5	6.15E-07	2.6	2.5
L43	4% lime	1747	6.1	3.27E-11	0.0209	0.0204	2.9	2.5	2.5	6.08E-07	2.5	2.5
L81	8% lime	1728	6.6	3.04E-11	0.0196	0.0173	2.6	2.1	2.4	5.65E-07	2.2	2.3
L82	8% lime	1742	6.7	3.00E-11	0.0196	0.0154	2.4	2.2	2.3	5.64E-07	2.0	2.3
L83	8% lime	1784	6.7	2.98E-11	0.0196	0.0192	2.4	2.0	2.3	5.68E-07	2.3	2.3
GP1	3% NaOH	1682	6.9	2.90E-11	0.0250	0.0275	2.4	1.9	1.9	6.15E-07	2.6	2.5
GP2	3% NaOH	1777	8.2	2.43E-11	0.0250	0.0276	2.0	1.8	1.7	5.79E-07	2.5	2.4
GP3	3% NaOH	1700	7.1	2.83E-11	0.0250	0.0300	2.1	1.9	2.0	6.10E-07	2.7	2.5

Table 2 Summary of results and material properties

Dynamic measurements

Effect of sample thickness

For sample thickness, the Nordtest recommends a sample thicker than the depth where the RH variation is less than 1% than at the surface. The ISO and Japanese standards recommend the usual thickness of the building material. In many situations the final thickness of the building material has not been determined which limits the applicability of the ISO and Japanese Standards. For this study, sample thicknesses of 30mm, 50mm and 70mm have been tested. For this series of tests, the density and initial (compaction) moisture content were kept as constant as possible. As no significant difference can be observed as shown in Figure 3, it has been concluded that the thickness is not a limiting factor and that 30mm is greater than the penetration depth during one daily cycle. All samples were therefore prepared at 30mm to characterise the moisture buffering of this particular soil.

Effect of test chamber and data recording method

The Nordtest time step enable manual logging and humidity change during an 8hr day. The methodology used differed from the standard because of the logging method. As more than one sample was tested at the same time, continuous logging with the scale in the chamber was difficult to achieve for series of samples, therefore manual weighing was done outside the chamber. This involved taking the samples out of the controlled environment. However, the short time (less than 2 min) that the samples are exposed to a different RH level does not seem to affect the results. In this way less data for each sample was acquired, but more samples could be tested at the same time, which is an important consideration as each test takes at least five days to complete. The error related to the weighing process may be increased compared to a continuous logging with a scale in the chamber from which the results can be averaged. However, this method avoids the noise recorded by a scale in a chamber because of the vibration due to the ventilation.

Table 3 MBV for different methods, Big chamber (BC), Small chamber (SC), weight recorded manually outside of the chamber (Manual), weight continuously logged on a scale (Logged)

Method	Sample	Density (kg/m^3)	$MBV_{practical}$ 50/85 (g/m^2.%RH)
BC Manual with windscreen	US30mm	1790	2.94
	US50mm	1790	2.84
	US70mm	1740	3.01
BC Logged with windscreen	US30mm	1790	3.00
	US50mm	1790	2.87
	US70mm	1740	2.92
BC Manual	US1	1740	3.10
	US2	1760	3.60
	US3	1800	3.50

SC Logged	US30mm	1790	3.36

The results are consistent when comparing both methods as show in Figure 4 where the manually recorded and logged results are presented. All measured MBVs for different methods are in Table 3, all samples were made with the same material and preparation method. For the BC Manual with windscreen and BC Logged with windscreen method similar results were expected, whereas higher MBVs were expected for the BC manual and SC Logged method which induces a smaller surface film resistance (stronger ventilation), this was confirmed by the results, Table 3. The inconvenience with the manual weighing is that for a 24h cycle, no results could be obtained for the night time period and it was necessary for someone to take measurements over at least 12 hours during the adsorption phase.

The surface resistance recommended by the ISO 24353 standard (ISO, 24353: 2008) is 13.3±1.3m^2.h.Pa/µg which after conversion corresponds to 4.8x10^{13} m^2 .s .Pa/kg. It seems that the most common proposed values as by the Nordtest is to set the surface resistance to 5.0x10^7±10% m^2.s.Pa/kg (Rode et al., 2005). The value presented in the ISO standard must present an error, as its conversion is a factor of 10^{-6} different to the value proposed by the JIS standard. It was therefore assumed that the value proposed in the JIS standard (JIS, A 1470-1, 2002) is correct. The chambers used for the testing have different air velocity and therefore a slight variation in results is observed between the two chambers when recording without a windscreen over the samples, as shown in Figure 4 and Table 3. The air velocity has been measured in the chambers, an average of 20 readings, 10 in horizontal direction and 10 in vertical direction. The obtained average in the big chamber (BC) is 0.65m/s and the average in the small chamber (SC) is 0.41m/s. The average measured when the samples are covered with a windscreen is 0.05m/s. In Rode et al. (2005) a method is given to estimate the magnitude of surface resistance based on air velocity. When logging the samples, sensitive scales (0.01g) record significant amplitude of noise due to vibration caused by the air velocity, therefore covering them with a windscreen allows a smoother recording. This is not necessary when the samples are measured manually outside the chamber.

The differences observed for each method are shown in Figure 4 for the sample US which has been tested under various conditions. For an air velocity of 0.05m/s the maximum adsorption at 8h is about 100g/m^2, whereas for an average air velocity of 0.65m/s the maximum moisture adsorption at 8h is about 125g/m^2. This difference of 20-25% should be taken into account when comparing results from different test setups.

Effect of relative humidity level and time steps

Figure 5 gives results obtained for the average of all unstabilised (US) samples in different time and RH cycles, the same variation was observed for all samples and is discussed later. The increase in peak relative humidity from 75 to 85% has a large effect on moisture

adsorption with a maximum adsorption nearly doubled whereas the actual absolute humidity available in the air only increased by 13%. Roels and Janssen (2006) have simulated the influence of time variation from an 8/16 h cycle to a 24/24 h cycle for a Wood fibreboard and a Gypsum plaster. The simulation predicted the same adsorption rate for both time steps, with only and increased maximum adsorption reached. The changes observed through the experimental results are different, the adsorption rate changes and the maximum adsorbed is less than expected.

Effect of stabiliser addition

In Figure 6 the results of moisture adsorption/desorption response for samples with different contents of stabilisers are represented. These results were obtained under cycles with 8h at 85 %RH and 16h at 50%RH. Each curve represented is the average of all three samples measured. It is noticeable that cement and lime stabilisation show very similar results. But that the geopolymer reduces the MBV considerably more.

5. Discussion

Steady-state conditions

The shape of sorption isotherm gives an indication of the sorption mechanisms. The single layer surface adsorption occurs at an early stage, characterised by a strong increase in moisture content at low RH levels. The multilayer surface adsorption occurs on the main section of the isotherm between 20% RH and 80% RH. A sharp bend is visible on the curve at around 10%RH which corresponds to the tipping point where the single layer reaches its limits and the multilayer phase starts. The sharp increase at high RH (>70%) is considered to correspond to the capillary condensation (Rouquérol et al., 1999).

It can be therefore ascertained that, based on the observation of the sorption isotherms (Figure 2), the main mechanism involved in the moisture buffering process at midrange RH levels where the MBV tests are performed is the multilayer surface adsorption. The cement and lime stabilisation affect principally the multilayer adsorption and consequently the occurrence of capillary condensation appears at a lower moisture content. Geopolymer stabilisation reduces the multilayer adsorption by dissolving the clay minerals responsible for this mode, but increases the capillary condensation activity by considerable amount by altering the pore size and structure. This is the perfect illustration of nonlinear hygric properties. The geopolymer samples may have a low buffering capacity on the average RH levels and better moisture buffering at high RH, therefore potentially outperforming the unstabilised material in these conditions. The sharp increase at high RH within the geopolymer sample indicates an increase in capillary condensation, whereas the multilayer adsorption is decreased. For all samples the single layer adsorption is not significantly affected by stabilisation.

Figure 2 b, d and f are the hysteresis variation compared to the unstabilised sample. Lime stabilised samples seem to decrease the hysteresis loop, whereas cement has little effect on

it. Hysteresis loops are generally associated with capillary condensation and mesopores, or pores between 2nm and 50nm in diameter (Rouquérol et al., 1999). A reduction of hysteresis would therefore signal a reduction of mesoporosity which is combined with a reduction in equilibrium moisture content. The hysteresis indicates that the moisture capacity has different values during the adsorption phase and desorption phase. This may be an important parameter to take into account when estimating the moisture buffering.

In addition to storage capacity (isotherms), moisture buffering is affected by the rate of moisture absorption. As mentioned earlier, stabilisation can reduce the vapour permeability of the material. For cement and lime stabilisation this is potentially due to crystal growth during hydration and carbonation which can reduce pore accessibility. For geopolymer stabilisation the mechanism of permeability reduction is not well understood. For the geopolymer type considered here, it may be because of unreacted sodium hydroxide reacting with atmospheric moisture and carbon dioxide forming sodium carbonate crystals which limit pore size, Scanning Electron Microscope studies into this aspect were inconclusive. A full investigation of this aspect is beyond the scope of this paper as the focus is on dynamic moisture buffering.

Testing of moisture buffering

The repeatability of the experimental results for the step response method has been assessed by calculating the standard deviation of the results of three samples per type of stabilisation. The average standard deviation obtained for 120 measured points over three cycles is 1.81g/m^2. This variation can be considered insignificant when compared to the maximum moisture adsorption which varies in this case (53/75 %RH, 12h12h) between 43 g/m^2 (geopolymer) and 71 g/m^2 (unstabilised). This expresses a good repeatability of the results for this test based on three samples of the same material.

A great variation can come from experimental set up. The influence of the RH cycles has clearly a major influence on the adsorbed moisture (see Figure 5). Figure 7 shows the results obtained in RH cycle of 50% to 85% against the results obtained in a RH of 53% to 75%. In Figure 7, a linear trend appears which is illustrated by the trend line. However it is not necessarily expected in all cases, the change of RH levels in the cycles does not induce a linear change in the sorption properties observed through the sorption isotherms in figure 2. The linear trend appears in this case as all samples use the same initial material and has similar sorption isotherms. A correlation analysis was performed with the 18 different samples. This was done by using Pearson's method which indicated a significant relation between all three test methods at the 0.01 level. The strongest correlation of 0.952 was between the two methods with the same humidity levels (53-75%) but different time steps and with weaker correlation of 0.861 between the humidity steps from 53-75% to 50-85% RH.

A linear trend suggests that the results are proportional. This is even truer with the variation of time steps at same RH cycles, Figure 8. This indicates that on the average RH ranges used the performance of the material varies but remains proportional, this can only be said for materials with similar steady state properties over the RH range. So for these cycles the unstabilised sample (US) would always have the highest performance. This may not be the case for high RH values (over 80%) where the hygric properties can show a very sudden change, as for example observed on the sorption isotherm of the geopolymer sample in Figure 2e in which case the GP samples may outperform the US samples

The influence of surface film resistance is confirmed, an increased air velocity reduces the surface film resistance and can therefore increase the moisture adsorption by up to 25% (US sample). This confirms the numerically predicted influence done by Roels and Janssen (2006) on conventional building materials (wood fibreboard, plywood, aerated cellular concrete and gypsum plaster). In a real building situation, intelligent ventilation could potentially be used to increase the moisture buffering capacity of an interior wall.

Comparison between calculated and measured MBV values

The theoretical calculation of MBV_{ideal} does not include the effect of surface film resistance and therefore a significant difference is usually observed with the experimental results. In this case a high air velocity (therefore reducing the surface film resistance) was used in the MBV test so a good agreement is found between MBV_{ideal} and $MBV_{practical}$. In Figure 9, the perfect correspondance is represented by the equal line. Samples of the same material are grouped which indicates that measurement error was maintained to a minimum. The calculated values remain in the same range as the measured values, with minor variation, however unstabilised sample MBV is underestimated whereas the geopolymer MBV is overestimated. This difference appears in figure 9 and 10 so it occurs with both methods used to measure the moisture capacity. This implies that the difference either appears from dynamic measured result or from the other steady state property, the vapour permeability. The experimental results are in close agreement so it is unlikely that the error comes from the $MBV_{practical}$.A good agreement between MBV_{ideal} and $MBV_{practical}$ was found for the samples stabilised with lime and cement when using the moisture capacity obtained with the DVS. This is shown in Figure 10 where the samples in good agreement are on the “equal line”. However , as only one measurement was done with the DVS for each material, therefore the variation of the results is to some extend artificially reduced, but it was also considered that the moisture capacity obtained from DVS presents less experimental error.

A single value Analysis Of Variance (ANOVA) has been done to compare the results between the calculated MBV_{ideal} and the experimental $MBV_{practical}$. This is a statistical tool used to confirm if a group of values equals another group of values. Based on this tool only for the C8, L4 and L8 samples it can be affirmed that there is no significant difference between the

results at a 95% confidence level. The C4 samples may be affected by the one sample with a lower density.

6. Conclusions

The influence of different conditions on the measurement of moisture buffering capacity of CEB has been determined. The results have shown that large variations can be observed due to air velocity in the climatic chamber influencing the surface film resistance confirming the calculated prediction of previous studies. The addition of stabilisers to the soils has reduced the adsorption properties in all cycles measured, by up to 40% in the worst case. There is a good correlation between results obtained in different time and humidity steps indicating that the variation to the MBV is proportional for a same material, stabilised and unstabilised.

Steady state parameters when measured accurately can be used to estimate the MBV in an ideal case with negligible surface film resistance and for similar RH conditions. The sorption isotherms obtained from two different methods, DVS and salt solutions, were compared and used to calculate the MBV_{ideal}. The calculated results based on the DVS data showed a good agreement with the experimental results. However, the MBV_{ideal} failed with the unstabilised (US) and the geopolymer (GP) stabilised samples. The measured value of the water vapour permeability is considered responsible for these variations. Understanding the non-linear variation of steady state properties and mainly water vapour permeability in various conditions will allow a better prediction of the moisture buffering capacity. The conditions affecting the measurement of water vapour permeability would need to be investigated in a future research.

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Figure captions

Figure 1: Particle size distribution of brick clay, sand and 50:50 mix.

Figure 2: DVS water vapour sorption isotherms and hysteresis, a. Cement, isotherms. b. Cement, hysteresis. c. Lime, isotherms. d. Lime, hysteresis. e. Geopolymer, isotherms. f. Geopolymer, hysteresis

Figure 3: Influence of sample thickness on dynamic measurement

Figure 4: Influence of test chamber and logging process on dynamic measurement

Figure 5: Influence of RH and time steps on dynamic measurement

Figure 6: Influence of stabilisation method on dynamic measurement

Figure 7: Correlation of MBV results for different humidity cycles

Figure 8: Correlation of MBV results for different time steps

Figure 9: Correlation between measured and calculated MBVs based on salt solution sorption isotherms

Figure 10: Correlation between measured and calculated MBVs based on DVS sorption istherms

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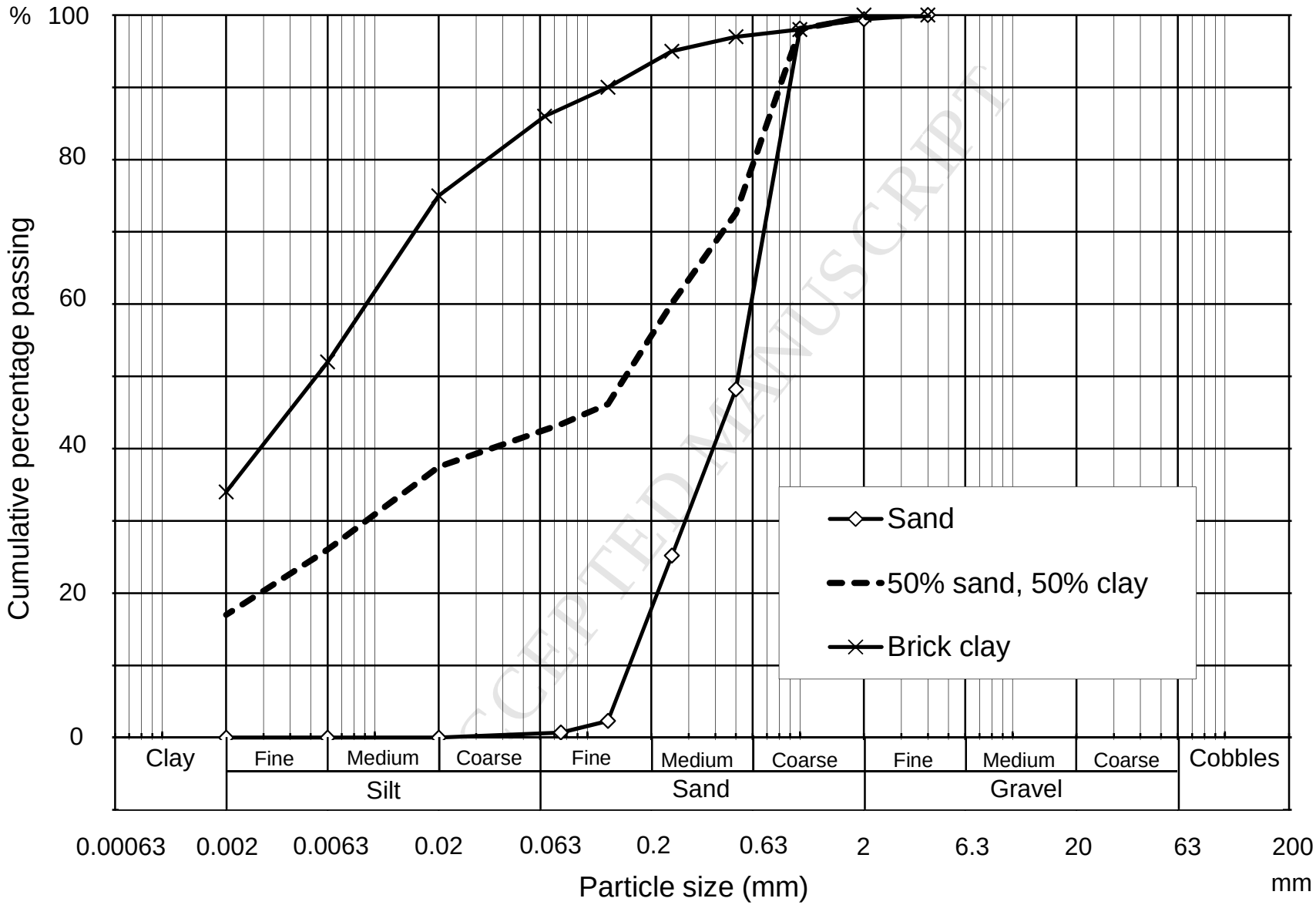

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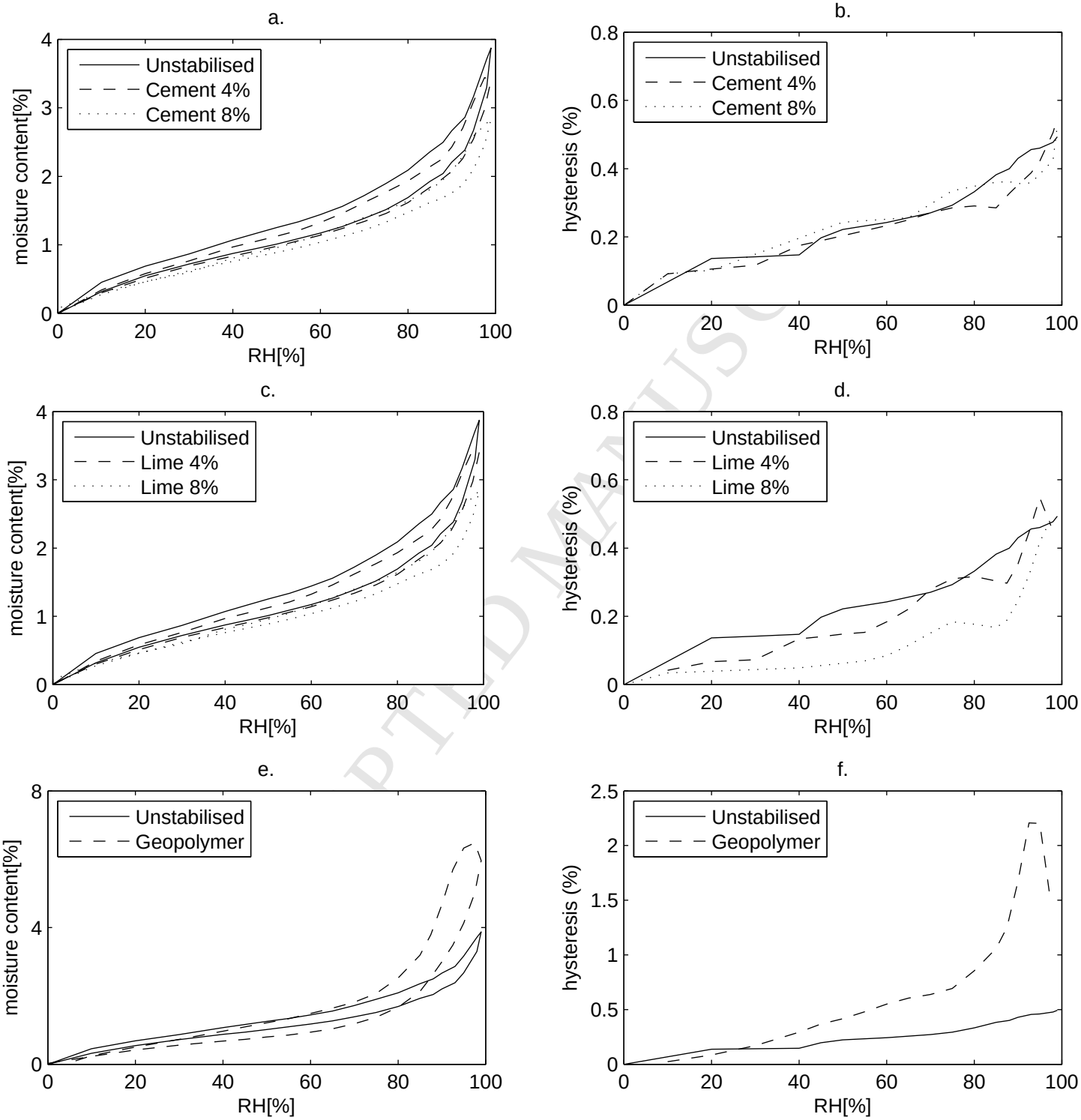
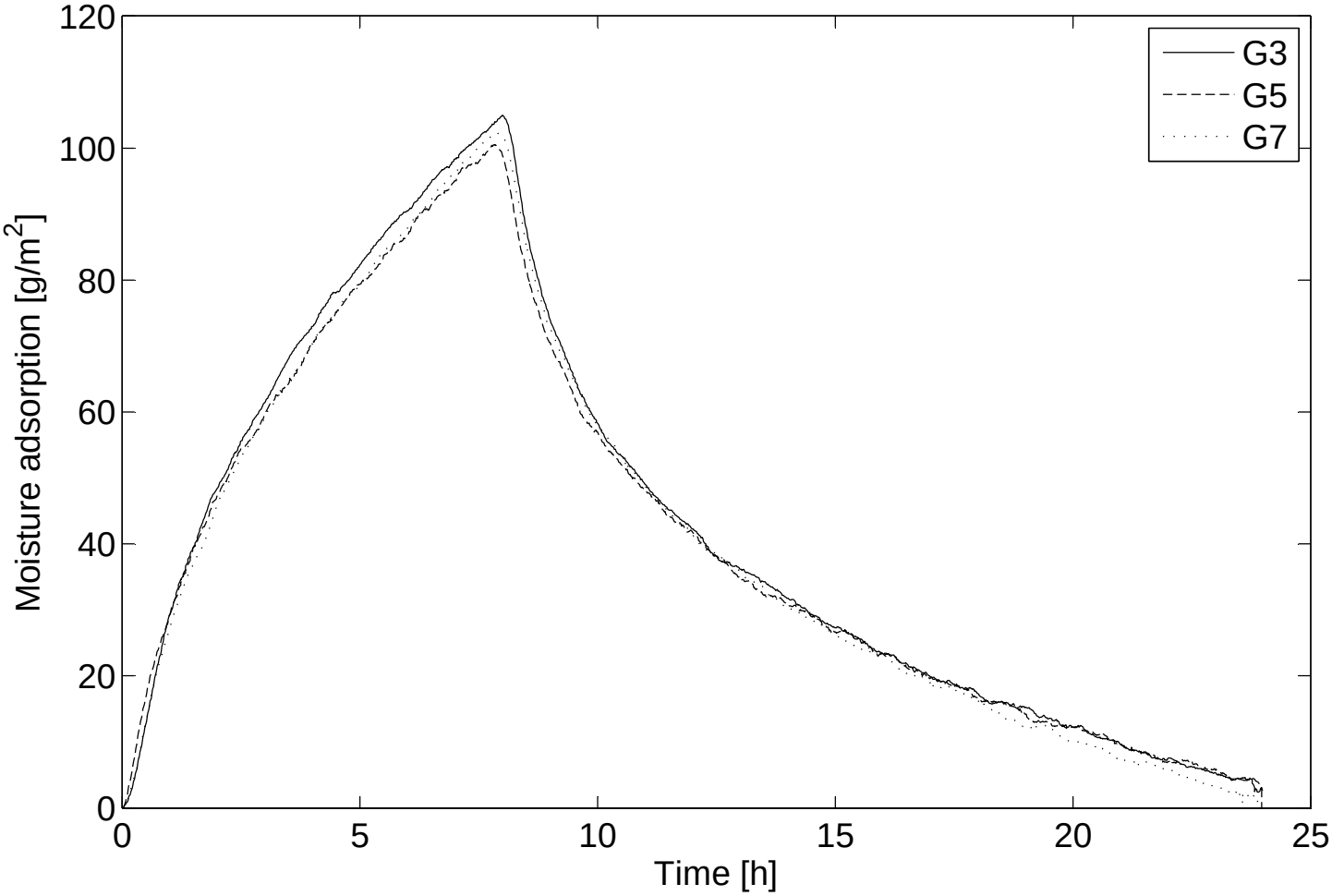
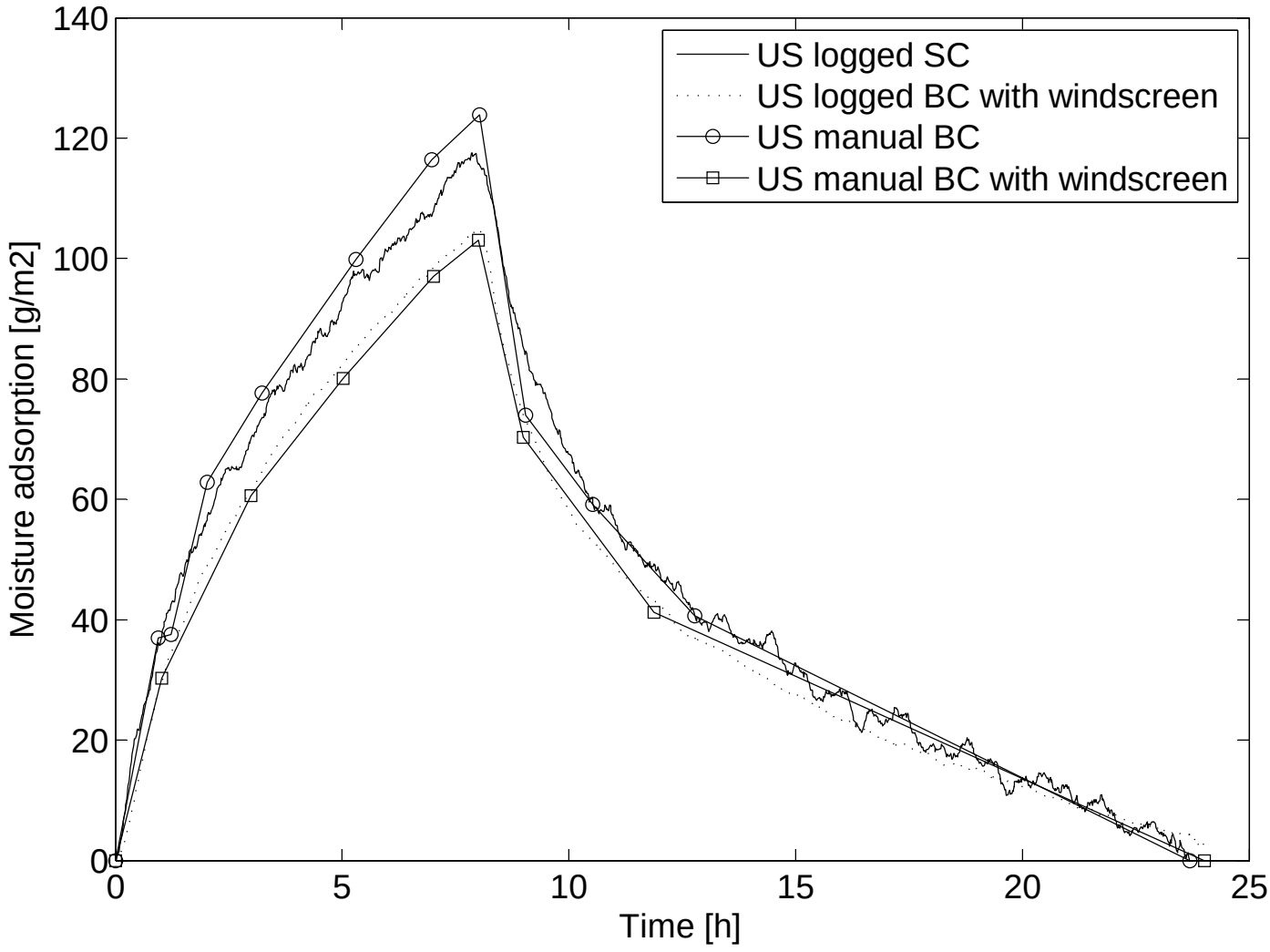
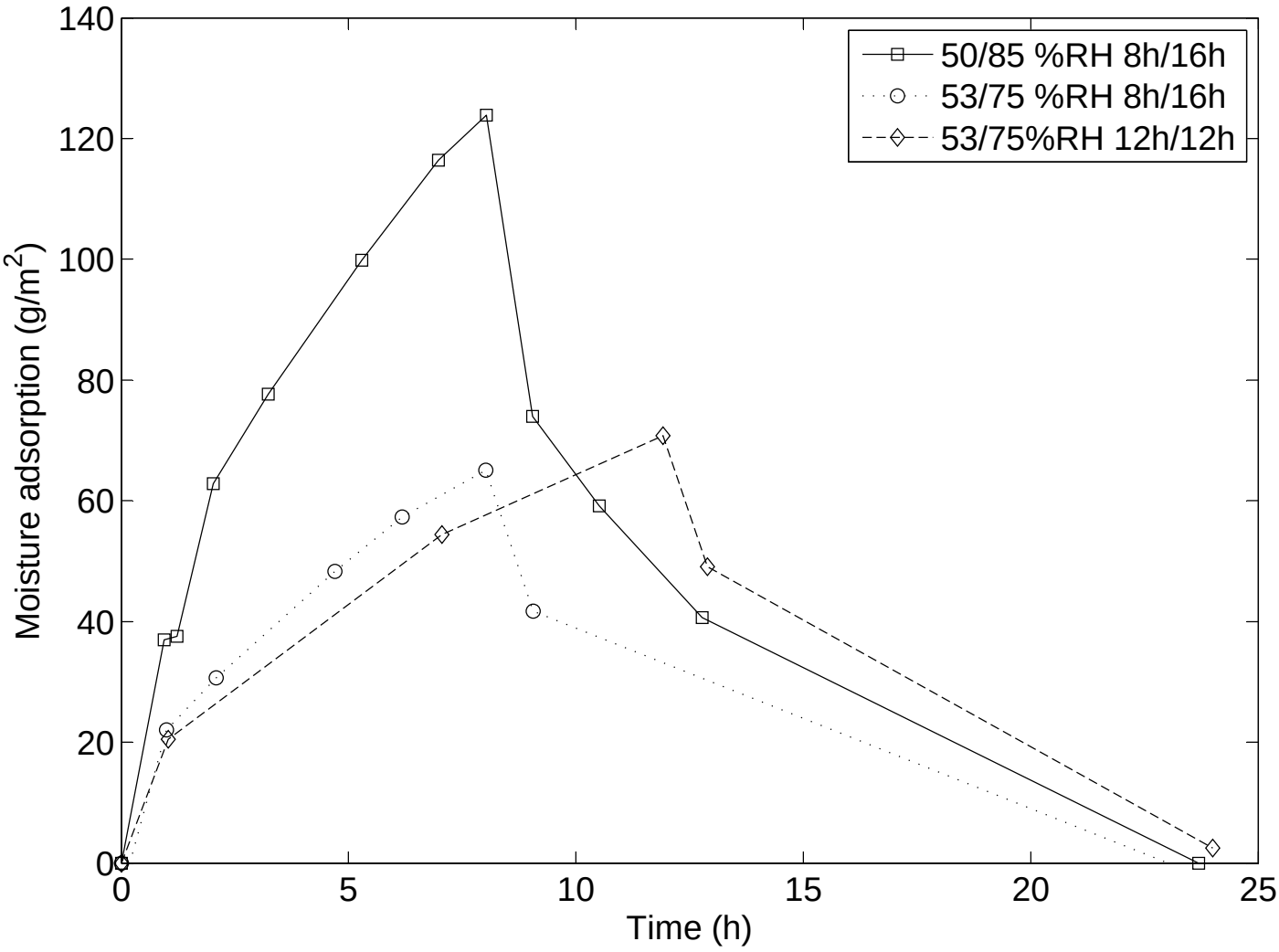
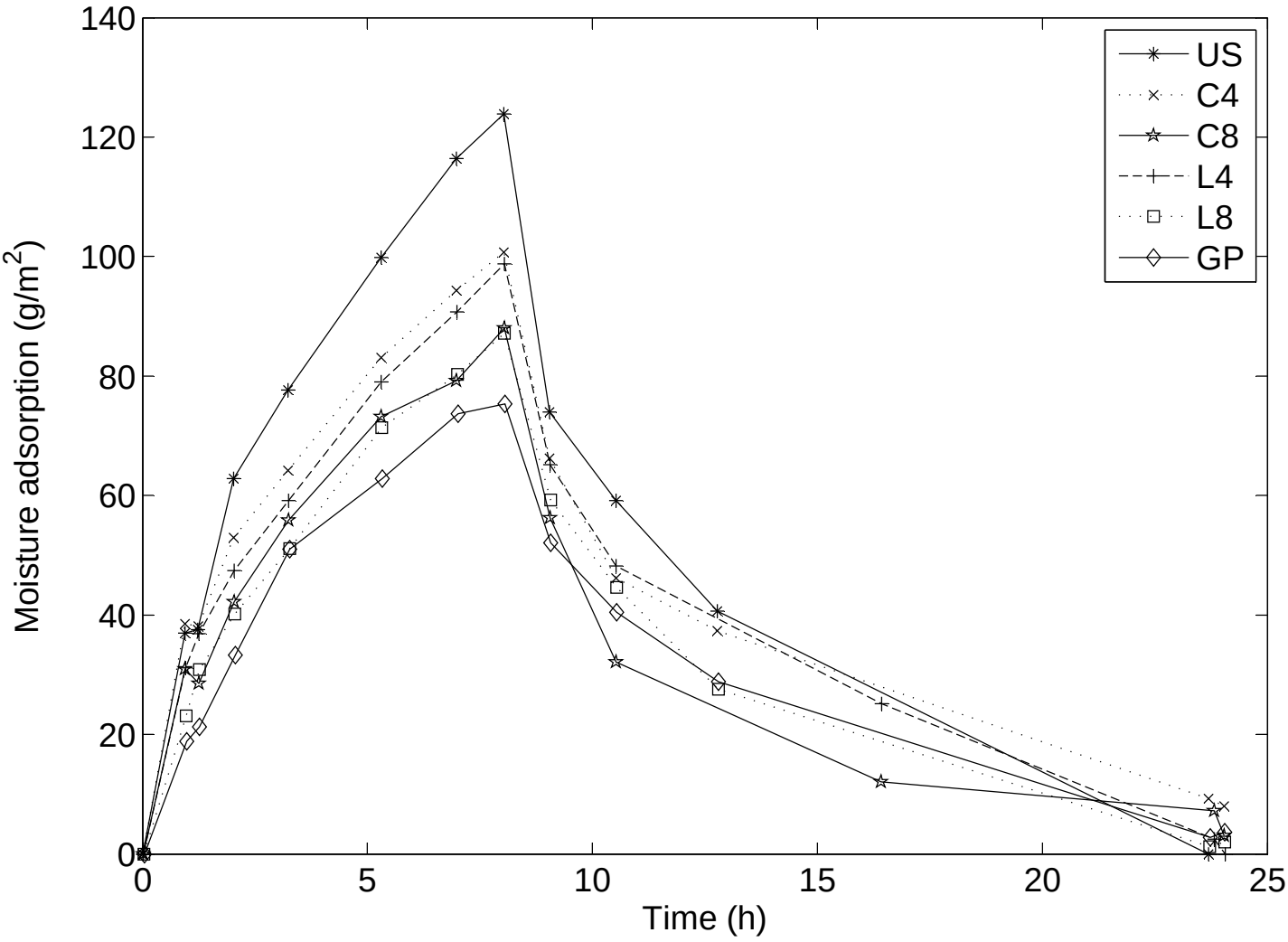
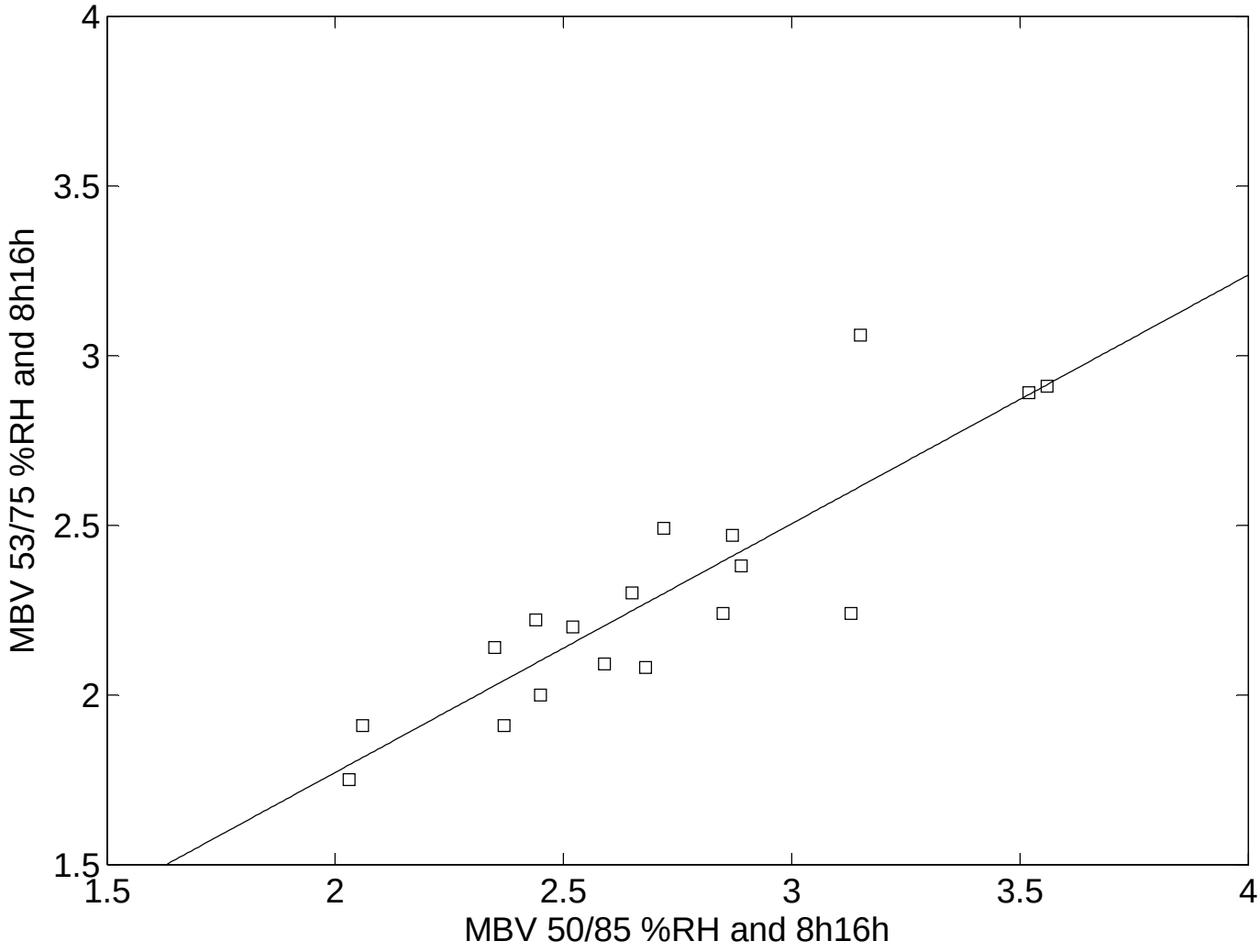

a.
moisture content[%]
RH[%]
Unstabilised
Cement 4%
Cement 8%
b.
hysteresis (%)
RH[%]
Unstabilised
Cement 4%
Cement 8%
c.
moisture content[%]
RH[%]
Unstabilised
Lime 4%
Lime 8%
d.
hysteresis (%)
RH[%]
Unstabilised
Lime 4%
Lime 8%
e.
moisture content[%]
RH[%]
Unstabilised
Geopolymer
f.
hysteresis (%)
RH[%]
Unstabilised
Geopolymer

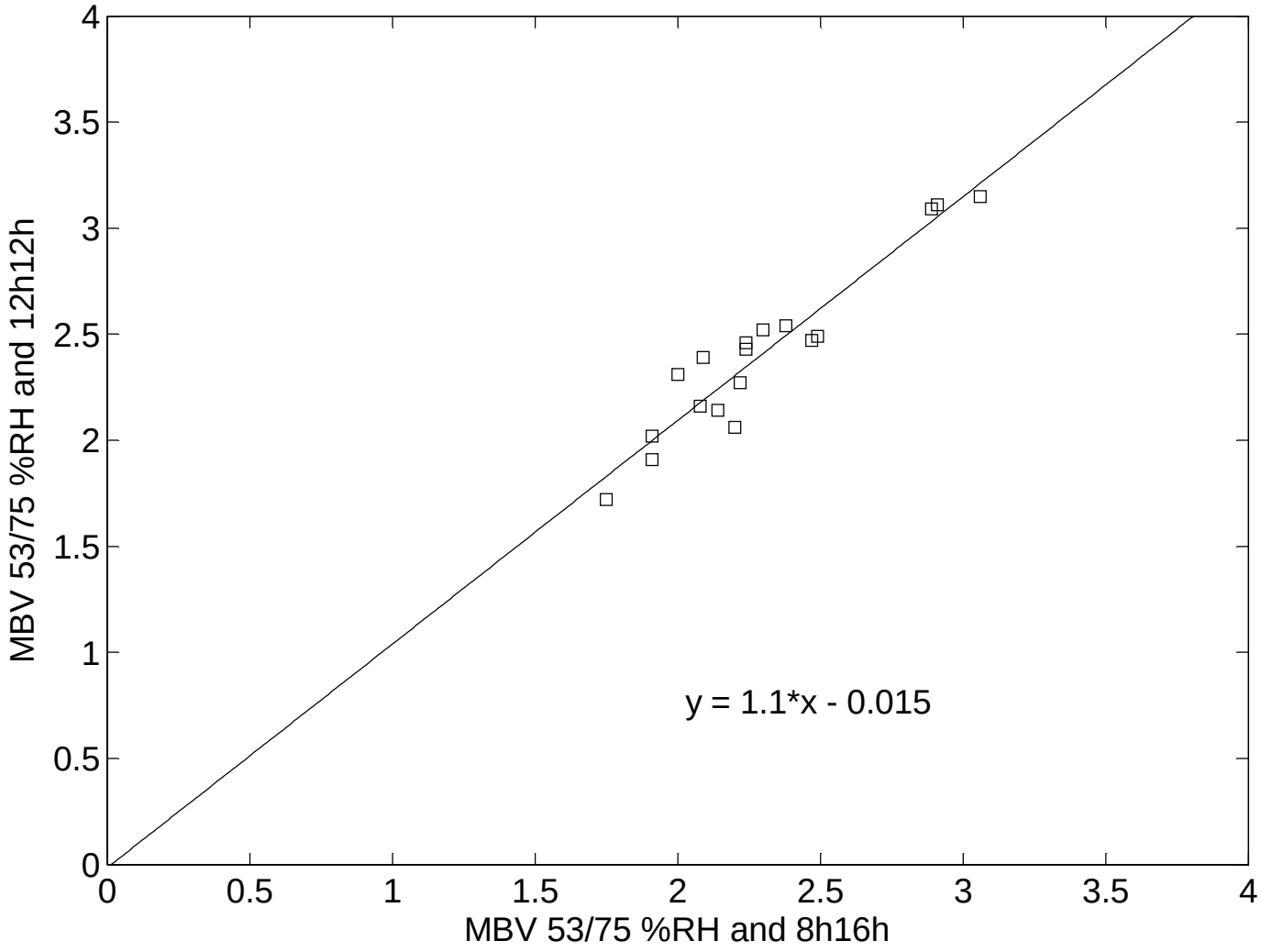

120
100
80
60
40
20
0
0
5
10
15
20
25
Moisture adsorption [g/m2]
Time [h]
G3
G5
G7

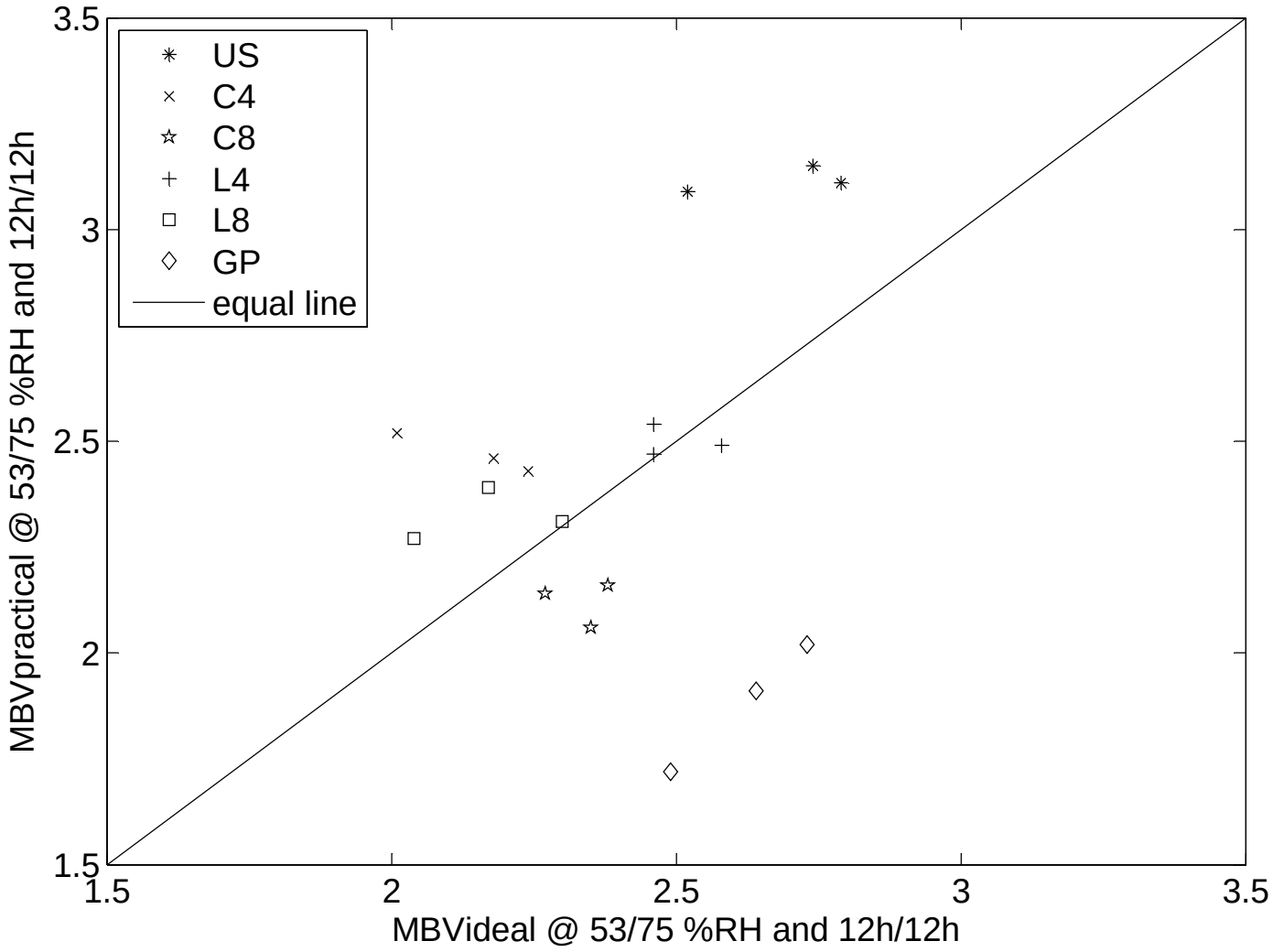

US logged SC
US logged BC with windscreen
US manual BC
US manual BC with windscreen
Moisture adsorption [g/m2]
Time [h]
0
20
40
60
80
100
120
140
0
5
10
15
20
25

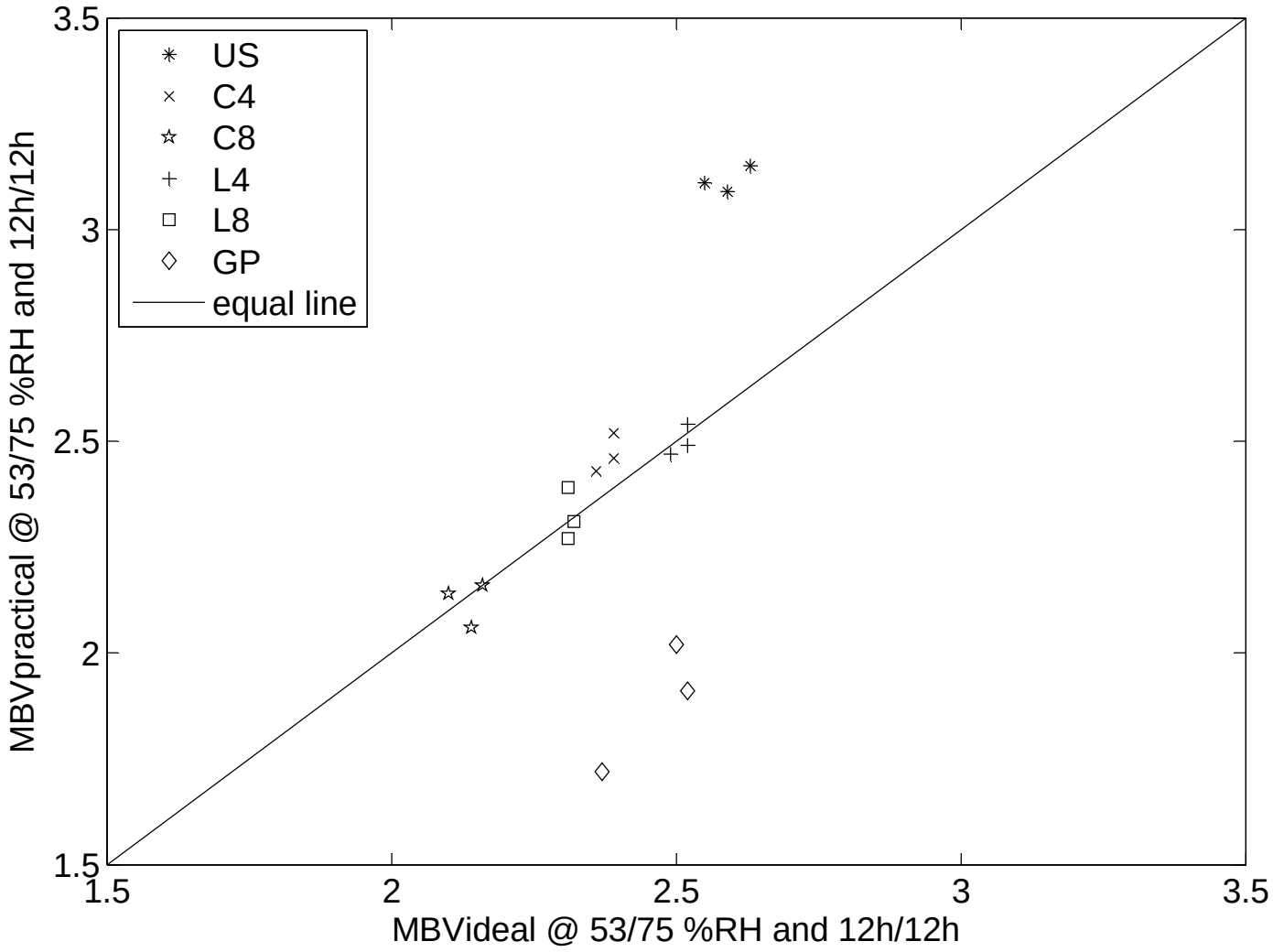

50/85 %RH 8h/16h
53/75 %RH 8h/16h
53/75%RH 12h/12h
Moisture adsorption (g/m2)
Time (h)
0
20
40
60
80
100
120
140
0
5
10
15
20
25


Moisture adsorption (g/m2)
Time (h)
US
C4
C8
L4
L8
GP
0
20
40
60
80
100
120
140
0
5
10
15
20
25


MBV 53/75 %RH and 8h16h
MBV 50/85 %RH and 8h16h
4
3.5
3
2.5
2
1.5
1.5
2
2.5
3
3.5
4


MBV 53/75 %RH and 12h12h
MBV 53/75 %RH and 8h16h
y = 1.1*x - 0.015
0
0.5
1
1.5
2
2.5
3
3.5
4


US
C4
C8
L4
L8
GP
equal line
MBVpractical @ 53/75 %RH and 12h/12h
MBVideal @ 53/75 %RH and 12h/12h
1.5
2
2.5
3
3.5


US
C4
C8
L4
L8
GP
equal line
MBVpractical @ 53/75 %RH and 12h/12h
MBVideal @ 53/75 %RH and 12h/12h
1.5
2
2.5
3
3.5

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Highlights

- Capacity of Compressed Earth Blocks to regulate indoor humidity.
- Experimental measurements of moisture buffering values (MBV) are provided.
- Conditions affecting these measurements are presented.
- Steady state properties are measured and used to calculate theoretical MBVs.
- On 3 out of 6 cases good agreement between experimental and theoretical values was found.

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