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ORIGINAL ARTICLE

Use of brick dust to optimise the dewatering process of hydrated lime mortars for conservation applications

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Abstract The impact of dewatering on lime mortars modified using brick dust was studied, as it is of particular importance in conservation applications. Dewatering takes place when freshly mixed mortars come into contact with a porous substrate, such as brick or stone, during on site construction. Since the dewatering process between the mortar and its substrate can modify the mortar properties, understanding the dewatering process enables pozzolan-modified hydrated lime mortars to be optimised for the masonry units being bonded. Evaluation of the water transport kinetics on brick dust—hydrated lime binder systems demonstrated their more water releasing behaviour. Investigations of non-dewatered and dewatered specimens in the volume ratio of 1:1:2 (lime:brick dust:sand) showed that the addition of brick dust to lime mortar increased dewatering, which in turn led to greater compressive strength, carbonation depth, decreased porosity and depth of water penetration. These properties are of great importance in the conservation of historic masonry, as mortars that are too strong or possess low permeability can accelerate degradation. This study will enable identification of the most suitable mix designs thereby increasing the durability and prolonging the life of historic masonry.

Keywords Dewatering · Water transport kinetics · Disposal · Hydrated lime · Pozzolan · Waste brick dust

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1 Introduction

Lime mortars play a key role in the conservation and longevity of masonry walls. Traditionally lime mortars consist of high-calcium lime or lime putty with the addition of a pozzolanic material [1–4]. These mortars gain strength through both hydration and carbonation reactions [5–10]. In masonry walls, mortars provide mechanical strength whilst also providing physio-chemical plastic and the influence of the microstructural properties on the failure mechanism [5–8]. This in turn, aids moisture movement within the wall [9]. Lime mortars within the interior of a wall, when under

a tri-axial stress, modify the failure mechanism from a less desirable brittle failure to plastic deformation during collapse [11, 12]. Low strength mortars of 1 to 2 MPa can accommodate plastic deformation enabling them to adapt as the masonry settles [13, 14]. Hence low strength mortars are the preferable choice among practitioners. These properties are commonly found in hydrated lime mortars, which make them very attractive for conservation applications when compared to cement mortars, although there are barriers to use such as long setting time and high-water retaining character. The addition of pozzolans to hydrated lime allows the chemical and physical properties to be modified on a microstructural scale; this then allows the compatibility with historic masonry to be optimised [12]. This ability confers the possible use of hydrated lime with different materials and environments, ensuring compatibility with historical masonry walls especially for conservation purposes since dewatering elaborate the barriers of the hydrated lime mortars' use.

Historical masonry was traditionally built to allow excess water to escape through capillary flow and evaporation rather than preventing the ingress of water by producing a non-permeable structure [7]. For mortar, the main mechanism driving the dewatering process in a mortar-substrate system is the spontaneous dewatering mechanism described by the transfer sorptivity. It is a liquid transport between the fresh mortar and the porous substrate to breathe the masonry expelling moisture upon drying. The design of historic masonry enhances this process for the mortar joints with their permeability of the hardened mortars. Hence, the compatibility of mortar-substrate system can be better understood through the microstructural investigation of the substrate-mortar interface. The dewatering process ensues after the freshly mixed mortars are applied to a dry substrate unit (e.g. brick, stone). The interaction between dry solid substrates and freshly mixed mortars lead to loss of water from within the mortar. The dewatering between the mortar and its substrate can lead to change of the original mortar properties and this can have a direct effect on site practices [8, 13–17]. Thus, understanding the dewatering process is essential when dealing with pozzolan-modified hydrated lime mortars. The addition of pozzolan to the hydrated lime mortars changes their desorptivity (R), which favours a high-water releasing behaviour [18, 19]. Additionally, the modification of hydrated lime mortars with pozzolans aids the compatibility between original and replaced substrates. This is particularly important when dealing with conservation work where decay is a problem.

Barriers to the practical use of lime mortars including hydrated lime on site are their high-water-retaining characteristics and longer setting-time compared to cement based binders [19]. This results in a weaker interfacial bond between mortar and substrate which requires more time to gain strength, thus slowing the construction process [20]. However, the dewatering process leads to significant changes in the mortar properties in addition to other factors such as the addition of pozzolans such as brick dust. Pozzolanic additions reduce the setting time and increase the water-releasing ability of the hydrated lime mortars. It is important to note that, the standards [21, 22] do not consider the properties of the substrate and mortar in optimised mortar-substrate systems. In the standards, EN 196, EN 1015 [23], when it comes to mortar-substrate optimisation there is no mention of the water sorptivity character of the substrates and the mortar that is in contact with the substrate for mortar-substrate optimisation. For example, high-water retaining mortars in contact with a low sorptivity substrate can promote a weaker bond at the mortar substrate interface due to insufficient water transfer between mortar and substrate. Therefore, it is imperative to advance the knowledge in this area, which has the potential to have an immediate effect for practitioners.

Moreover, providing the right adjustments, the use and understanding of the dewatering mechanism can be applied to narrow the gap between the on-site and laboratory approaches. However, as it stands with the 'metal moulds specified' [9] in the standards [21, 23], dewatering cannot occur, as the moulds are impermeable [24]. For instance, in practice the mortars are subjected to dewatering depending on the sorptivity of the substrate (masonry unit) as well as the water retaining characteristics of the mixed mortars themselves [25–28]. Therefore, the transfer sorptivity which is the ability of a porous material to absorb water from a wet mix is a crucial parameter to control pozzolanic reactivity or the effectiveness of pozzolans on mortars. Therefore, the water/binder ratio in the mortar mix designs should account for the water that will be lost due to the transfer sorptivity of water in mortar-substrate systems.

The relationship between desorptivity (R) and pozzolanic behaviour of hydrated lime-pozzolan mortars has not been concerned in detail previously [18–20, 29]. However historically pozzolans have been used to enhance the hydraulic properties of hydrated lime-pozzolan mortars [28, 30, 31]. Desorptivity, the water retaining ability of a fresh state mix, is an important parameter for the enhancement of properties (mortar-substrate systems) when dealing with conservation work. There are limited studies on the role of pozzolans on the dewatering process. Studies have considered the water retaining ability of hydrated lime and compared this with cement and hydraulic limes [32, 33]; and also the effect of admixtures on cement [26]. Over the past 20 years, hydrated lime and cement mortars containing Fly Ash(FA), Silica Fume (SF), slag [30]; Zeolite and Bayburt stone [18]; Ground granulated blast-furnace slag (GGBS), Fly Ash, Metakaolin, Silica Fume, [28, 29]; NHL, and cement mortars containing FA [34]; limestone, and GGBS [35] have been studied. However very few studies have investigated the effect of pozzolanic materials on the water retaining ability of hydrated lime-pozzolan mortars [19, 26]. Therefore, the mortars, included only hydrated lime as a binder are uniquely studied to show the effect of dewatering on other parameters.

In this paper, the water retaining ability of brick dust-modified hydrated lime mortars is investigated, not only to modify the mortar's properties but also to help eliminate barriers of its on-site applications. The effect of brick dust in terms of its pozzolanic behaviour has also been studied. Firstly, how pozzolans such as brick dust modify high-water-retaining hydrated lime mortars to be more water releasing was demonstrated. Secondly, the effect of the pozzolanic brick dust and dewatering on the water retaining abilities of lime mortars was compared. It has been found that pozzolans enhance the performance of hydrated lime mortars and their interaction mechanism in mortar-substrate systems.

2 Materials and mix design

The raw materials used in this study consisted of hydrated lime, standard sand and brick dust as a pozzolanic additive. The hydrated lime including mortars were manufactured using CL80, certified to EN 459-1 and standard sand according to EN 196-1.

The brick dust is a by-product sourced from Gürdağ Trading and Industry Ltd of Northern Cyprus. The brick dust was air dried and sieved to remove any debris prior to its use. The average brick dust particle size is 2 mm. An X-ray diffraction pattern of the brick dust is shown in Fig. 1. A number of sharp peaks indicate crystalline phases including albite, quartz, calcite and anorthite [36–38]. The increase in the background observed between 2-theta values of 15 and 30 degrees are consistent with the broad diffuse scattering observed by Maddalena et al. [39] in amorphous silica. This suggested that the brick dust contains both crystalline and amorphous forms of silica. The fraction of silica in the amorphous form could be attributed to pozzolanic activity upon reaction with lime.

The control mortar was formed with 1:2 (lime:sand) volume fractions. Two mix designs were used comprising lime:pozzolan:sand in the by volume of 1:1/4:2 and 1:1:2. These mortars were designated in turn as C, 1/4P and 1P in. The mass of the materials used were calculated from the values of their density to attain the anticipated mix proportions by volume. Table 1 summarises the components used in each mix design and their quantities. The proportions of binder and pozzolanic additions by volume were comparable with previously reported studies in the literature which have demonstrated their suitability for conservation applications [40]. Dewatered specimens indicate a direct exposure of the freshly mixed mortars on

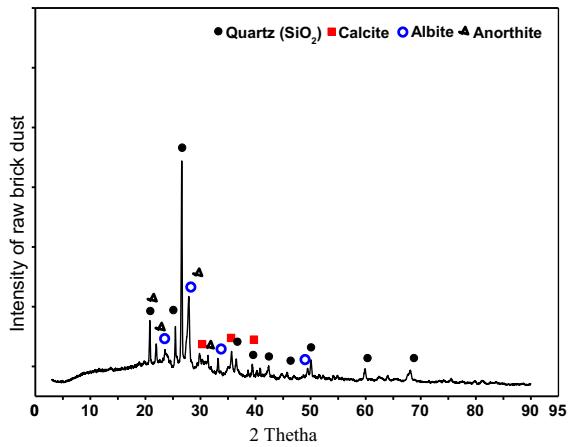

Fig. 1 X-ray Diffraction of raw brick dust

Table 1 Mix constituents of the raw materials

Specimen	Materials	Volume Proportions	Mass (g)	Consistency (mm) Non-Dewatered	Consistency (mm) Dewatered
Hydrated lime mortar Control (C)	Water	0.567	680	130	128
	Lime	1	792		
	Brick Dust	0	0		
	Sand	2	3672		
Hydrated lime with 0.09 volume fraction of brick dust (1/4 P)	Water	0.583	699	130	124
	Lime	1	792		
	Brick Dust	0.25	131		
	Sand	2	3672		
Hydrated lime with 0.36 volume fraction of brick dust (1 P)	Water	0.617	740	130	116
	Lime	1	792		
	Brick Dust	1	527		
	Sand	2	3672		

sorbent substrate units at the plastic stage whereas the non-dewatered specimens signify mortars that have not been in direct contact with a substrate with the ability to dewater.

After the dry constituents (lime and sand) were mixed, the water was included until all components homogenised as described in standard EN 1015-11 [41]. The quantity of constituents added into mortar was calculated in terms of the volume ratios above. The different additions of brick dust meant that the water to binder ratio had to be increased to yield a constant consistence across all mixes investigated in this paper.

3 Experimental procedure

3.1 Material characterisation

The elemental compositions of the raw materials were determined quantitatively using powder X-ray florescence spectroscopy analysis (XRF) with a Rigaku ZSX Primus II. A Malvern Mastersizer 2000 was used to determine the particle size distribution. A QUANTA 400F Field Emission scanning electron microscope (SEM) equipped with energy dispersive analysis of X-rays (EDX) was used for microstructural and elemental analysis. Prior to the SEM analysis, all samples were placed in vacuum for 24 h to remove the moisture from the raw materials. Surface charging of poorly conductive materials such as mortars was reduced through application of a 3 nm layer of gold using a sputter coater [42, 43]. Characterization of the crystalline phases was carried out using a Rigaku MiniFlex 300/600 X-ray diffractometer (XRD). CuKα, X-rays of wavelength 1.540598 Å were employed in combination with a D/teX Ultra2 detector. Scans were carried out over a 2-theta range from 3° to 90° with a step size of 0.02° and a time per step of 5°.

3.2 Fresh mortar characterisation

Consistence of the mortars was measured using the Flow test when they were freshly mixed [40, 44]. Setting time of these mortars was measured using the Vicat apparatus [45].

Transfer sorptivity was determined while contacting the substrate unit with a wet mortar mix [35, 46, 61]. The substrate units used in the transfer sorptivity measurements had a constant sorptivity of 2.1 mm/min$^{1/2}$. Adhesion formed between the unit

and wet mortar meant measurements could only be practically taken within a limited time period prior to the mortar hardening. Five equally sized rectangular compartments in the purpose-built mould. In each compartment, one brick section was then inserted in contact with the mortar to facilitate dewatering. Before contact with the freshly mixed mortars, the bricks, approximately sized to 46 mm × 46 mm × 100 mm, were placed in an oven and dried to a constant mass [41] as this is a requirement of (EN 1015-11). The constant mass of each brick was recoded and designated as the dry mass of the substrate [13, 46–49]. At increasing time intervals, the brick sections were weighed consecutively. Hence, the mass of the brick sections, and the volume of water absorbed were recorded at five-time intervals. Hence (1) transfer sorptivity, (2) time to dewater and (3) final water content of the dewatered mix could be determined at 5-time intervals from the data in Table 2. Cumulative absorbed volume of water per unit area (i) versus time to dewater (t_{dw}) was then plotted to determine transfer sorptivity and time to dewater. There are two distinct regions of the plot of cumulative absorbed volume of water per unit area, i versus time$^{1/4}$, ($t^{1/4}$). The first region represents the water removal from the freshly mixed mortars towards the dry substrate units and the second region represents complete dewatering. As time progresses, cumulative absorbed volume of water per unit area reaches a plateau indicating that the substrate samples cannot absorb more water from the freshly mixed mortars and that the freshly mixed mortars are also not able to deliver further excess water to the dry substrate units. This is not an extraction of all water from the freshly mix mortar, but the water would be transferred to the dry substrate when they come into contact. This condition represents the complete dewatering to the materials configuration and is the second stage of the plot. Time to dewater is determined from the extrapolation of the intersection of the two stages on the x-axis. The details of the calculations and its validation is described in Su-Çadırcı [46].

The mass and the volume of water in the wet mix mortar and the total mass of mixture produced were known. The total volume of the wet mix was determined by calculating the density of the mixture. A graduated cylinder was then used to determine the density from the mass of a known volume of the wet mix and the total volume of the wet mix. Therefore, the mass of the wet mix was known before dewatering, for each compartment in the mould. The absorbed water mass was also known for each substrate unit in contact with the mortar. Therefore, the total mass of the absorbed water from the wet mix could be calculated from the initial total wet mix mass. By subtracting the total mass of water absorbed by the substrate from the initial mass of water given to the mix, the volume of water left in the mix was estimated. Using density measurements, the volume of the dewatered mix was calculated.

The water loss was determined from the mortar mass in the 5th compartment as this was the last compartment that represents complete dewatering used for the water transport kinetics experiments. With the same compartment, absorbed volume of water by the brick unit in contact with the wet mix was calculated [46]. The water loss related to complete dewatering was calculated using data from the fifth compartment. The water loss was determined from the total mass of the wet mix. The total mass of the wet mix which was known. The water transport kinetics parameters, summarised in Table 2, are adopted from Su-Cadirci (2021) which we investigated specifically in order to conduct dewatering on hydrated lime mortars comprising brick dust. Water loss % from 4.62 to 5.31% is shown in Table 2. This amount of water did not result in a deceleration for the pozzolanic reaction which required high relative humidity (50–80%) [50], moreover dewatering accelerated the reaction as the water/binder ratio decreased.

Compressive strength test is widely accepted as a useful property which can indirectly be used to determine the pozzolanicity (ASTM C618) [51]. The strength of pozzolan-lime mortars can be compared

Table 2 Parameters of water transport kinetics [46]

Sample	Transfer Sorptivity, A (mm/min$^{1/2}$)	Time to dewater, t_{dw} (min)	Water loss (%)
C	0.41	41.28	4.62
1/4P	0.57	27.56	4.95
1P	1.02	14.28	5.31

with the non-pozzolanic mortars named as reference specimen [20]. While hardening the mortar, the carbonation and hydraulicity define the mortars with pozzolan. Therefore, the compressive and flexural strength analysis are highly likely to be related to the presence of the pozzolan in the mortar. Half of the specimens of three replicates (for each C, 1/4P, 1P) broken after flexural strength test are performed under compressive strength test [41, 45, 52]. Hydrated lime mortars are cured under laboratory conditions (RH 60 ± 10% and 20 ± 5 °C) for 7, 14, 21, 28, 91, 180 and 850 days and evaluated for compressive strength, flexural strength, and carbonation depth. Tests at 28 and 180 days were undertaken for porosity and water penetration depth measurements.

The depth of carbonation was determined by spraying a solution of phenolphthalein indicator onto a fractured surface of the sample. After a few minutes, the indicator turns from pink to clear in the carbonated areas. This is due to the corresponding lower pH attributed to carbonation. The carbonation depth was determined from an average value of distances from the surface of samples after phenolphthalein application.

Open porosity was determined using the Archimedes method which required weighing the sample dry, M_1, followed by weighing after vacuum saturating with water at 25 mbar, M_3 [17]. The weight whilst submerged in water was also determined, M_2. Porosity, ρ, was determined using Eq. (1).

$$\rho = \frac{M_3 - M_1}{M_3 - M_2} \times 100 \quad (1)$$

Water penetration depth test was carried out according to BS EN 12390-8:2000 [53] which required the application of pressure to one surface of the sample. Samples were then split in a perpendicular direction from the injected face to determine the depth visually.

Thermogravimetric Analysis (TGA) was carried out using a Perkin Elmer Pyris 1 under nitrogen gas from 20° to 900 °C with a temperature increase of 10 °C/min for pozzolan-lime mortars.

4 Experimental results and discussion

4.1 Material characterisation

The materials were characterised using X-ray fluorescence (XRF), particle size distribution and scanning electroscopic microscopy (SEM). Quantitative elemental analysis of the brick dust using X-ray fluorescence spectroscopy indicated its pozzolanicity according to the standard EN450-1 [50] and ASTM C618 [51] since the sum of the main oxides present, 41.0% silicon dioxide (SiO_2), 13.4% aluminium oxide (Al_2O_3), and 10.2% iron oxide (Fe_2O_3) was 64%. The hydrated lime CL80 binder complied with BS EN 459-1 due to its 94% CaO content [45]. Lime has 2.93% MgO, 1.84% SO_3, 0.513% SO_2, 0.23% Al_2O_3, 0.23% Fe_2O_3, and 0.078% Cl. The standard sand used in this study complied with BS EN 196-1 in terms of the elemental composition [22] which was 0.463% CaO, 0.142 MgO, 91.9% SiO_2, 3.91% Al_2O3, 0.659% Fe_2O_3,

Particle size distributions of the raw materials in the mixed mortars indicated that the highest fineness was found for the lime particle sizes ranging between 0.6 and 30 µm. The standard sand was distributed among 3 µm to 2 mm ranges for its particle sizes, whilst the brick dust fell within the range 0.6 µm to 478 µm, therefore spanning that of the lime binder and the standard sand. Although particle size distribution does not change significantly, a corresponding increase in the water demand due to the increased surface area effectively dilutes the cementitious content, often referred to as the filler effect [54].

Figure 2 shows scanning electron microscope (SEM) images of brick dust. Angular particles with a variety of sizes from 3 to 20 µm are shown in Fig. 2a, while the brick dust sample at higher magnification (20 µm scale bar), revealing irregular clustered glassy particles is shown in Fig. 2b. EDS spectra showed the silica elemental content in Fig. 2c.

4.2 Consistence and setting time

The consistence of dewatered and non-dewatered hydrated lime mortars containing brick dust are presented in Fig. 3. For the dewatering experiment, a control sample (non-dewatered mortar) and remaining specimens (dewatered mortars) were investigated, as shown in Fig. 3 by presenting consistence versus

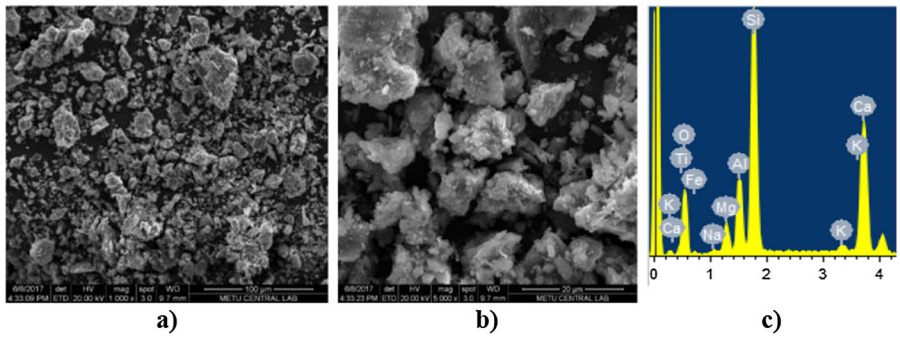

Fig. 2 Scanning electron microscope (SEM) images of brick dust **a** scale bar 100 μm, **b** scale bar 20 μm, **c** the elemental analysis by EDS

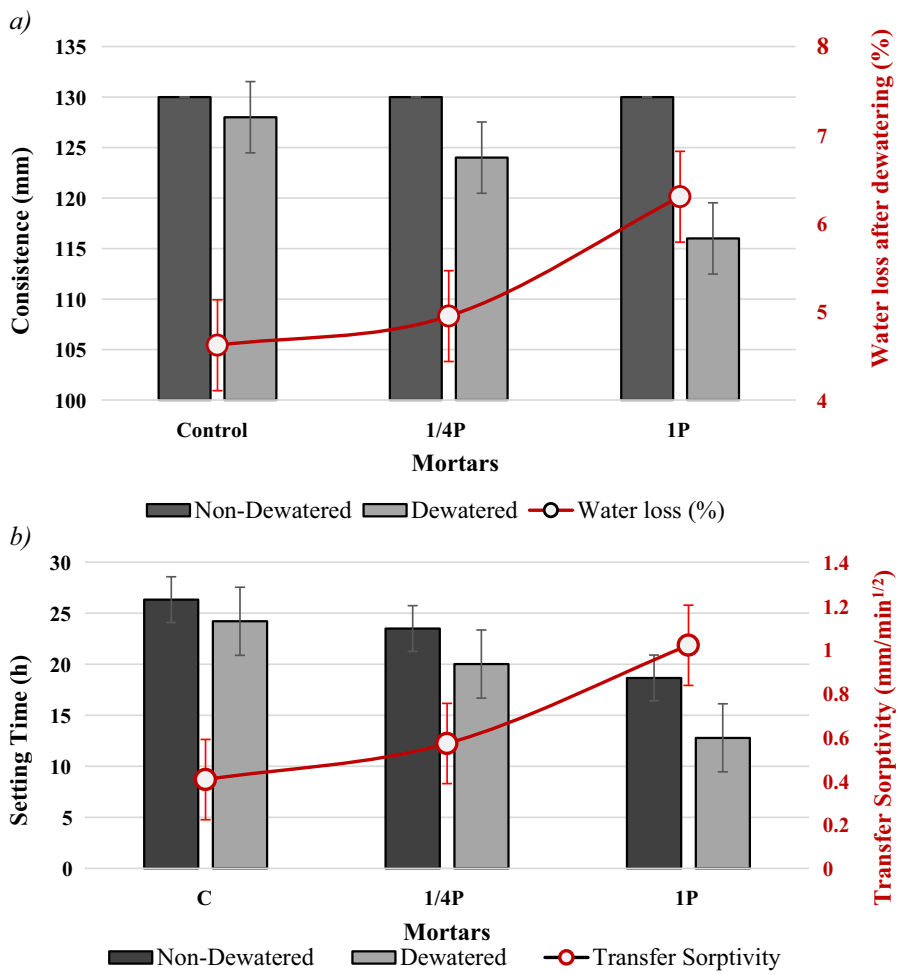

Fig. 3 **a** Comparison between the consistence and water loss of non-dewatered and dewatered mortars. (Control): hydrated lime mortar, (1,4P) and (1P): hydrated lime-brick dust mortars. **b** Comparison between the Setting time and the transfer sorptivity of non-dewatered and dewatered mortars. (C): hydrated lime mortar, (1,4P) and (1P): hydrated lime-brick dust mortars, error bars are standard error

water loss %. Dewatering occurs when freshly mixed mortars (at the plastic stage) are in direct contact with the dry substrate units, and therefore loose water, ultimately changing the original w/b ratio. Non-dewatered mortars, on the other hand, represent mortars that have not been in direct contact with the dry substrate and therefore their water to binder ratio remains unchanged. The consistence of mortars is

measured by the flow test. The water loss after dewatering, plotted in the secondary axis in Fig. 3a, was determined through the transfer sorptivity experiment previously described in Sect. 3. It is worth noting that the water content of each mortar mixture was determined to establish constant consistency of control, 1/4P and 1P mortars which is demonstrated to be 130 mm in Fig. 3a. Due to the increase in the total solid fraction of the mixture from control to 1/4P then to 1P, the water content of the mortars, previously summarised in Table 1 have also systematically increased to attain constant consistence. The brick dust incorporation increases the transfer sorptivity of such mortars meaning that the mortars have become more water releasing when in contact with the dry substrate units. This is already demonstrated in Table 2 where water loss experienced after dewatering is systematically increased from control to 1/4P then to 1P mortars at the plastic stage. The amount of water loss experienced by the mortars with increasing incorporation levels of brick dust is in agreement with the decrease observed in the consistence of mortars following dewatering. The highest water loss was experienced with 1P mortar as this mortar type is the most water releasing that resulted in a greater reduction in consistence compared to the non-dewatered form of the mortar. It should however be noted that the reduction attained in consistence was not sufficient to cause problems in practical application.

The effect of dewatering on the lime-pozzolan mortar setting time versus transfer sorptivity for dewatered and non-dewatered mortars is shown in Fig. 3b. The setting time of mortars with increasing additions of brick dust led to a greater decrease in the setting times. This is attributed to the increase in the solid volume fraction within the mixture that also resulted in an increase in surface area of the solids. This has further resulted in a higher consumption of water to wet the solids and hence much less free water to set. This incidence is largely responsible from the decrease in setting time of hydrated lime mortars comprising increasing amounts of brick dust. Therefore, incorporating greater amounts of brick dust resulted in a higher amount of water removal from the wet mix when in contact with the dry substrate unit and hence much less water was then available in the mixture for setting. This feature resulted in a reduced setting time of mortars comprising brick dust. The increase in transfer sorptivity from C to 1P mortars showed the ability of the brick dust enhanced mortars to attain a greater water releasing character that played a key role on the setting of such mortars. The increase in transfer sorptivity with the increase in the addition of brick dust is previously noted in Table 2. Hydrated lime included mortars set when the excessive water totally escapes, and the reactions start to use water for itself. With dewatering, the hardening of the mortar is accelerated, and the setting time is shortened. Compared to lime mortar (C), the higher fineness feature of pozzolan-lime mortars (1/4P, 1P) causes reduced porosity in the matrix accelerating the setting time. Therefore, incorporation of higher amounts of brick dust resulted in greater water removal from the wet mix when in contact with the dry substrate unit and hence much less water was then available in the mixture for setting. This feature resulted in a reduced setting time of mortars comprising brick dust. The increase in transfer sorptivity from C to 1P mortars showed the ability of the brick dust enhanced mortars to attain a greater water releasing character that played a key role on the setting of such mortars.

The gradual increase of water loss (%) between the mortars 1/4P and 1P is higher than the water addition (%) in mixtures shown in Table 3. The proportional increase of water addition percentage of 3 times (2.94 to 8.82%) is proportionally higher than the increase of water loss percentage of 1.27 (4.95 to 6.3%). This is because brick dust increased the mixtures' solid consistency. Lime-pozzolan mortars become more water releasing with the addition of brick dust. This modification elaborates on these the barriers to the use of the mortars on site.

4.3 Pozzolanic activity of brick dust

The pozzolanic activity for the brick dust is evaluated in this section. The relative compressive strengths of mortars with pozzolan additions were compared to that of control mortars. The use of compressive strength as an indirect test method is a common procedure for the assessment of pozzolanic activity. In this study, pozzolanic brick dust was used within the hydrated lime mortars specified with lime:pozzolan:sand in the ratios of 1:1/4:2 and 1:1:2 and designated as 1/4P and 1P respectively, shown in Table 1. The strength difference between the control mortar and mortars with pozzolans (the 1/4 P and 1P) is indicated in Fig. 4. The rate of strength increases for

Table 3 The effect of the brick dust additions on the water releasing character of mortars with reduced water/binder ratio

Mortar	Initial Water content (g)	% of Water addition	Water loss %	Water loss (g)	Dewatered final water content (g)	Original Water/ Binder Ratio	Dewatered Water/ Binder Ratio
C	340	0	4.62	15.70	324.3	0.86	0.82
1/4P	350	2.94	4.95	17.30	334.2	0.76	0.72
1P	370	8.82	6.30	23.23	346.7	0.56	0.53

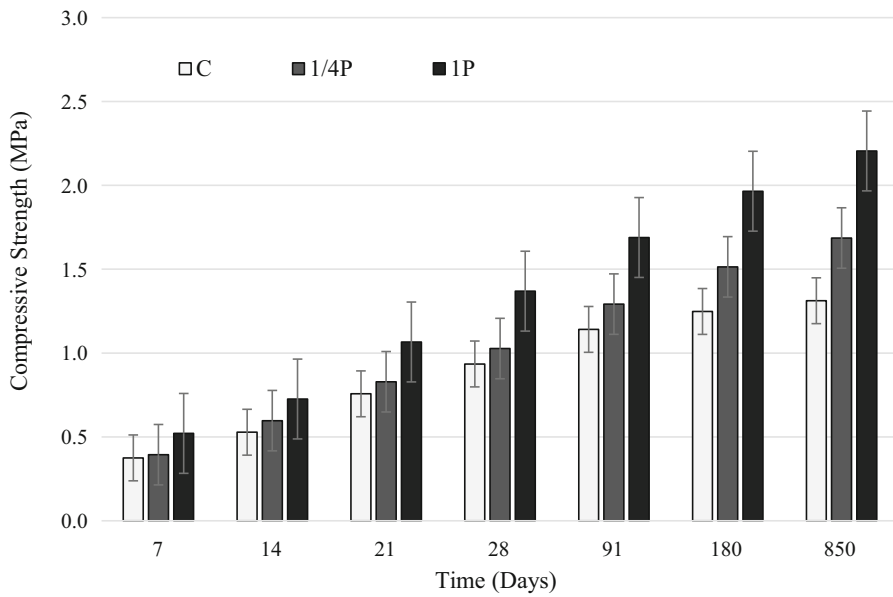

Fig. 4 Pozzolanic activity of brick dust. (C): hydrated lime mortar, (1,4P) and (1P): non-dewatered hydrated lime-brick dust mortars, error bars are standard error

1/4P and 1P mortars, was higher up to 180 days. The control mortar gained strength only through carbonation, while the strength increase of mortars with brick dust additions (1/4P and 1P) was a combination of pozzolanic and carbonation reactions. The relative standard deviation of compressive strength is in the range of 1.2% to 3.5% for three replicates.

There are some misconceptions between the physical and chemical impact of pozzolans. The first one being the filler effect on strength, which effectively dilutes the binder at constant w/b ratio [54, 62]. But in this study, it is not considered due to the changing w/b ratio. Secondly, due to the particle size, some pozzolans behave as aggregate accelerating the carbonation reaction by increasing the diffusion rate of carbon dioxide into the material. The aggregate behaviour of pozzolanic additions is reduced for brick dust when its fineness range is below that of the aggregate. The physical parameters generally have a greater influence on the mortars at earlier ages, while the chemical reactions take time, such as the pozzolanic reaction involving brick dust, which is one of the slowest reactions. The greatest increase in the strength is clearly observed at 180 and 850 days, indicating that the chemical reaction such as pozzolanic reaction has occurred as well as carbonation reaction. The relative rate difference of reactions, included carbonation and pozzolanic reaction, are increased by the pozzolanicity and filler effect (at early stages) of the brick dust. The SAI (strength activity index [(1P – Control mortars) / Control mortar] was 68% and 75% for nondewatered and dewatered mortars at an age of 850 days respectively. The dewatered specimens which were achieved 75% SAI value is a strong indicator of pozzolanic reaction.

The thermogravimetric analysis was used to show three temperature ranges which are designated the mass losses of the decomposition of CSH, $Ca(OH)_2$,

$CaCO_3$ in Fig. 5a. The pozzolanic reaction of brick dust is indicated with the two of these temperature ranges of thermogravimetric analysis. The dehydration of CSH and dehydrolaxation of $Ca(OH)_2$ are occurred in 100–180 °C and 400–520 °C respectively [56–59]. The mass losses of $Ca(OH)_2$ and CSH are indications of pozzolanic activity, calculated in Fig. 5b. The increase of the mass losses of CSH dehydration shows the production of calcium silicate/aluminate hydrates as a result of pozzolanic reaction. Thermogravimetric analysis spans three temperature ranges which are designated to determine the mass losses attributed to the decomposition of CSH, $Ca(OH)_2$, and $CaCO_3$, as shown in Fig. 5a. The pozzolanic activity of brick dust is indicated by two of these temperature ranges which relate to the dehydration of CSH and dehydrolaxation of $Ca(OH)_2$ at 100–180 °C and 400–520 °C respectively [56–60]. The calculated mass losses of $Ca(OH)_2$ and CSH are indications of pozzolanic activity and presented in Fig. 5. The increase of the mass losses of CSH dehydration shows the production of calcium silicate/aluminate hydrates attributed to pozzolanic reaction. The weight loss in the table is water lost from the CSH, between 100 and 180 °C. The increase in CSH from control to 1P indicates the reaction and pozzolanic activity with an increase of brick dust in the mixture. Secondly, the trend of a decrease in hydroxide indicates the consumption of $Ca(OH)_2$ through reaction with the pozzolan.

The carbonate content is generally reduced for mixes containing a pozzolan. This could be attributed to the presence of CSH decreasing the porosity and hindering the diffusion of CO_2 required for carbonation. However, the carbonation of the mixes with greater quantities of pozzolanic additions (1P) is higher than the mortars with lower amounts of pozzolan. The extent of carbonation in the mortars containing pozzolans is less than that in the control mortars. Consumption of calcium hydroxide in the pozzolanic lime mortars promotes the formation of CSH rather than calcium carbonate. Additionally dewatering accelerated the carbonation reaction as shown in the table comparing the dewatered and non dewatered mortars.

The microscopic analysis of lime and lime-brick dust comprising mortars are integrated. Since Fig. 6 shows that the CSH gels seen for 1P mortars at 20 k.

a)

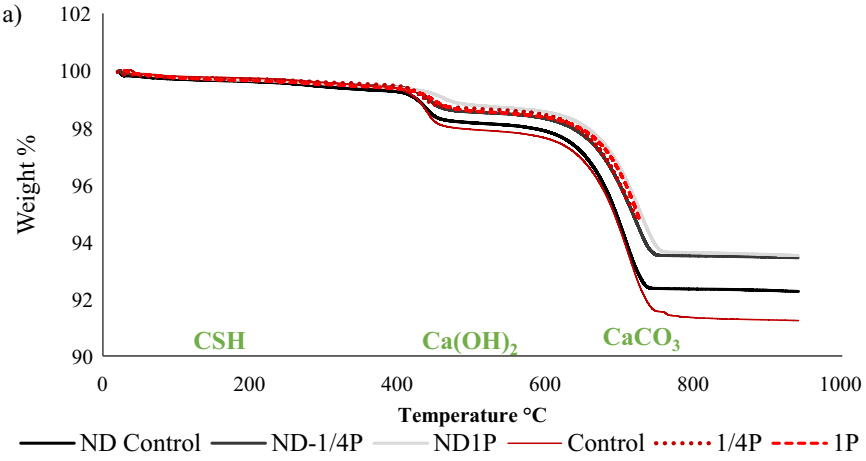

Fig. 5 **a** The mass loses attributed to dehydration of CSH and dehydroxylation of $Ca(OH)_2$. and decarboxylation of $CaCO_3$; **b** The mass loses values for each mortar

b)

Mortars	Mass loss%		
	C-S-H	$Ca(OH)_2$	$CaCO_3$
ND control	0.068	4.59	12.55
ND 1/4P	0.083	3.99	10.91
ND 1P	0.09	2.64	11.19
Control	0.052	6.01	14.27
1/4P	0.048	3.32	8.70
1P	0.094	3.32	12.66

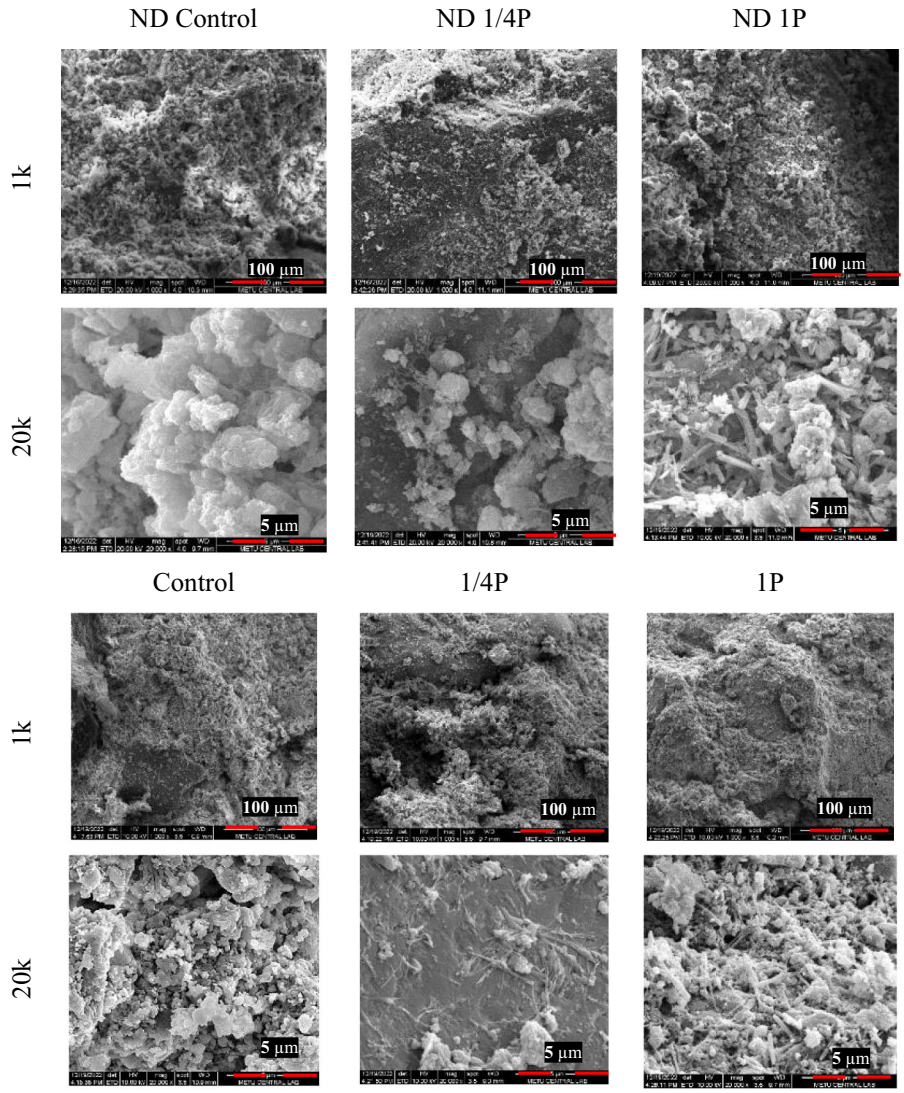

Fig. 6 The CSH gels and surface morphology of mortars by SEM imagining

This is an indicator of pozzolanic activity resulting in formation of the hydration components (Calcium silicate hydrate and calcium aluminate hydrate) from pozzolanic activity. The mortar matrix structure became denser with gels, decreasing the porosity, seen in Fig. 6. The compressive strength results, presented in Fig. 4 are correlated with these results to prove the increased mechanical strength due to denser matrix with CSH gels. Hence, the greatest reduction in porosity is attained in sample dewatered 1P mortar at 180 days. This attainment is attributed to the consumption of $Ca(OH)_2$ and brick dust through of a pozzolanic reaction and consequently the CSH formation gels over the time. As it is previously noted the addition of CSH gels occupied pore spaces available in the mortar matrix therefore densified the whole mixture and providing better consolidation. Hence this resulted in the increase in the mechanical strength.

4.4 Influence of dewatering on strength

The impact of dewatering is analysed in this section together with compressive strength of specimens at the age of 7, 14, 21, 28, 91, 180, 850 days and flexural strength of specimens at the age of 28, 180, 850 days.

Mortars of the same age are classified for each mixture in Fig. 7, where the enhancements of the dewatered mortars' strengths are shown. More significant increases in compressive strength were observed with the increased addition of brick dust over the long term. Furthermore, the difference between non-dewatered and dewatered mortars within the same ages increases with the addition of pozzolan. The increase in the compressive strength of dewatered hydrated lime mortars is mainly due to the fact that the excess water usually required to attain standard consistence is absorbed by the dry substrate unit during dewatering. This incidence results in a denser mortar matrix with reduced water: binder ratio and hence yields a greater increase in the compressive strength of dewatered hydrated lime mortars.

The increase in dewatered mortar strength accelerated at a higher rate compared to non-dewatered mortars. Dewatering indicates the importance of the water/binder ratio where the lower ratios provide

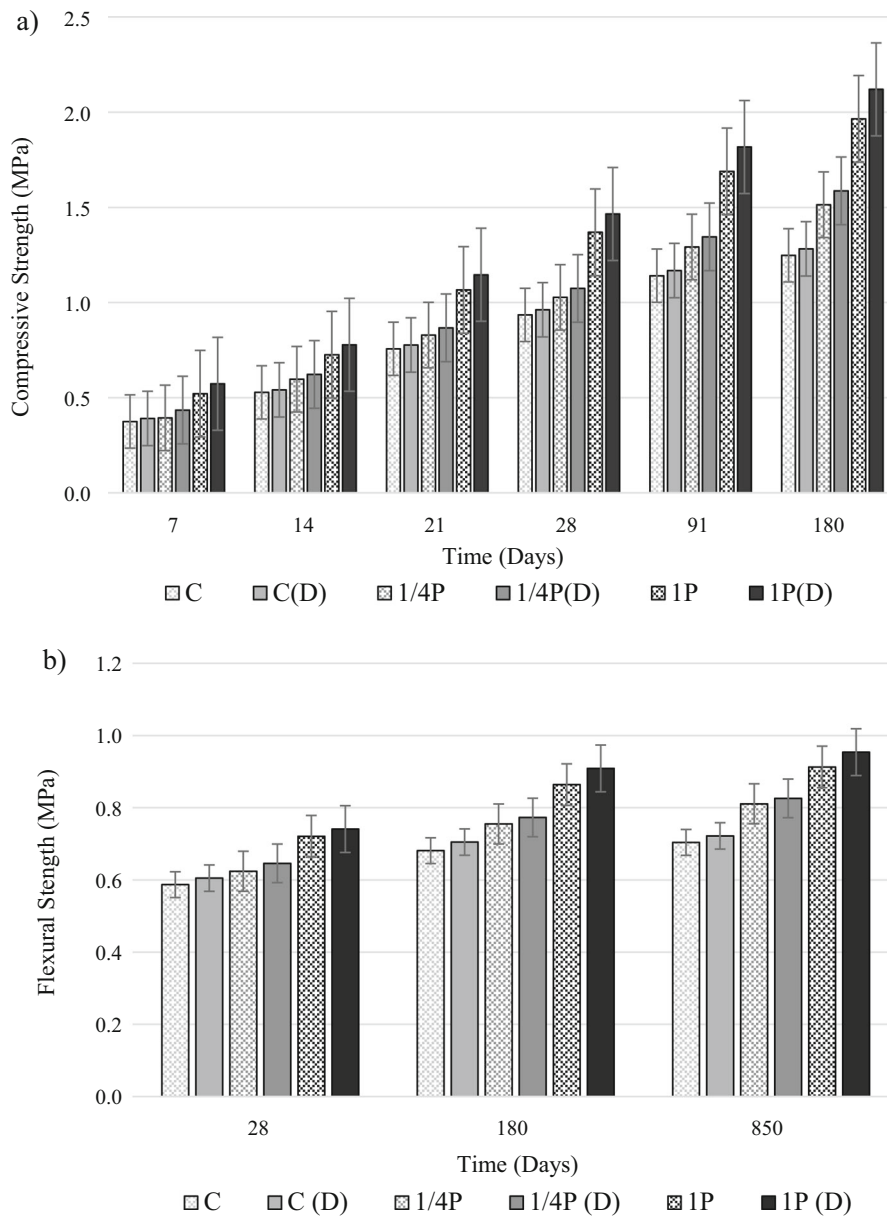

Fig. 7 **a** Compressive strength of non-dewatered and dewatered mortars; **b** Flexural strength of non-dewatered and dewatered mortars. (C): hydrated lime mortar, (1,4P) and (1P): hydrated lime-brick dust mortars, (D): dewatered samples, error bars are standard error

greater strength. Control mortars strengthen by carbonation exhibited the lowest strengths and lowest dewatering levels compared to the other mortars. However, the mortars comprising brick dust from 1/4P towards 1P mortars were influenced by dewatering to a greater extent. Hence, the difference between the strength levels of non-dewatered and dewatered mortars is increased because the ability to release water increased with the addition of brick dust. It was noted that the 1P mortars dewatered the most. In turn this directly affected the actual amount of water present in the mix, effectively leading to a reduction of water in the mixes. Therefore, the dewatering process leads to an inevitable reduction of w/b. This is an important finding as the nominal w/b will not represent the actual w/b for those mixes with an ability to dewater. The dewatering mechanism indicates that in these mixes, the water remaining following dewatering is sufficient to allow hydration to continue. Dewatering that enabled excess water removal from the matrix, resulted in a greater increase in the strength development of hydrated lime mortars. This might be seen the increase of SAI at 850 days old mortars that 68% SAI for nondewatered mortar is increased to 75% SAI for dewatered mortar. The long terms strength increase reached to 75% is achieved with the dewatered mortars.

The flexural strength of the early age specimens, particularly younger than 28-days could not be detected often due to the very low strength development at this stage and therefore, 28 days, 180 days and 850-day flexural strengths were reported for dewatered and non-dewatered mortars.

4.5 Influence of dewatering on porosity

The influence of dewatering on porosity is described in this section. The analysis included mortars aged at the ages of 28 days and 6-months. Figure 8 shows that the hydrated lime-brick dust mortars exhibit a decrease in porosity and increase in compressive strength. This can be attributed to water/binder ratio [25] which leads to a denser matrix and the increase in mix fineness. Dewatered and non-dewatered control mortar and 1/4P lime-brick dust mortars exhibited a decrease of porosity, while their compressive strengths remained similar. When the fineness of mixture increased with brick dust, the porosity increased as expected. Still, the reduction in porosity attributed to the addition of brick dust illustrates how the mortar matrix becomes denser due to the brick dust's pozzolanic reactivity in the mortars. The porosity is decreased more on the dewatered mortars compared to non-dewatered mortars because the mortar attained a denser structure with lower water/binder ratio. The relative standard deviation of compressive strength is in the range of 1.2% to 3.5%, while that of porosity is between 2.5 and 3.8% for three replicates.

At the age of 180 days the decrease in porosity and the difference between dewatered and non-dewatered mortars increased compared to 28-day-old results in Fig. 8. There is small difference between the C and 1/4 P mortars; a greater influence is seen for 1P mortars. The influence of dewatering is demonstrated through the observed increase in compressive strength and reduction in porosity with age. The porosity decreased with (1) age, (2) brick dust additions and (3) higher loss of water by dewatering. The lowest porosity is seen for sample 1P dewatered mortars at 180 days. Since $Ca(OH)_2$ and the brick dust (aluminosilicate) have been consumed to form CSH over the time, the additional formation of calcium silicate hydrate gel occupied part of the porosity which were shown in Fig. 6.

4.6 Influence of dewatering on the water penetration depth

The effect of dewatering on the water penetration depth (mm) of 28-day and 6-month-old samples is presented in Fig. 9. When increasing the brick dust addition, a decrease in water penetration depth is seen for both dewatered and non-dewatered mortars. However, the dewatered lime mortars show less water penetration compared to non-dewatered lime mortars. The difference between non-dewatered and dewatered mortars clearly shows the ability to make modifications allowing a lower porosity and higher mechanical strength. The denser the microstructure formed, the lower the water penetration depth observed since the denser matrix restrict breathing of the mortar.

4.7 Influence of dewatering on carbonation depth

The carbonation depth (carbonated zone extending from surface) and strength were compared over the ageing period. The carbonation depth and the compressive strength increased over time for the control

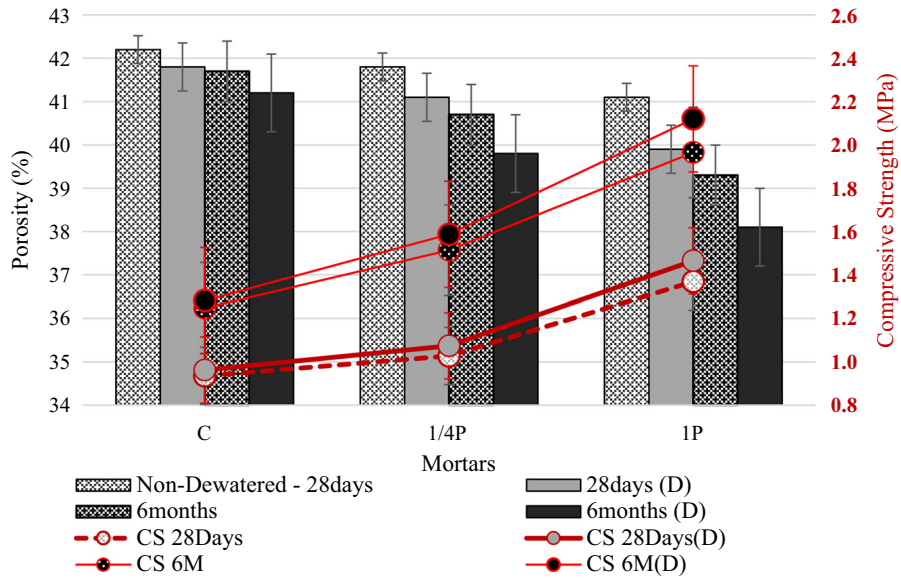

Fig. 8 Porosity of non-dewatered and dewatered mortars at 28 days and 180-days; (C): hydrated lime mortar, (1,4P) and (1P): hydrated lime-brick dust mortars, (D): dewatered samples, error bars are standard error

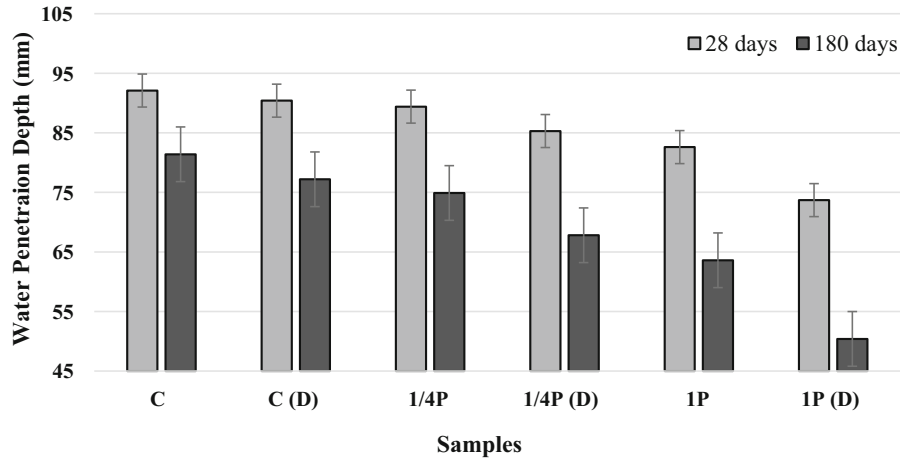

Fig. 9 Water penetration depth of non-dewatered and dewatered mortars at 28 days and 6 months; (C): hydrated lime mortar, (1,4P) and (1P): hydrated lime-brick dust mortars, (D): dewatered samples, error bars are standard error

sample (C) as seen in Fig. 10. However, a greater increase of carbonation depth was observed for the hydrated lime-mortars containing brick dusts (1P and 1/4P). The brick dust addition increased the carbonation due to the particle size of brick dust which is higher fineness than the particle size of lime. The effect of dewatering became more apparent after 28 days when the dewatered 1P mortar showed a significant increase in depth of carbonation and strength, compared to non-dewatered hydrated lime mortars in Fig. 10. The lime-brick dust mortars exhibited more extensive carbonation compared to hydrated lime mortars (without pozzolan). This is consistent with a reduced amount of free-lime throughout the material (due to its reaction with the brick dust) requiring CO_2 to diffuse further into the denser mortar in order to react. Although the pozzolanic reactivity decreased the porosity; the carbonation depth and compressive strength increased for all mortars.

4.8 Influence of dewatering on cost-effectiveness

The use of waste brick dust is an effective method to improve sustainability, the cost of mortars and the use on site [10, 43, 44]. An economic analysis has been carried to investigate the effects of dewatering on the cost-effectiveness of hydrated lime mortars. The cost-

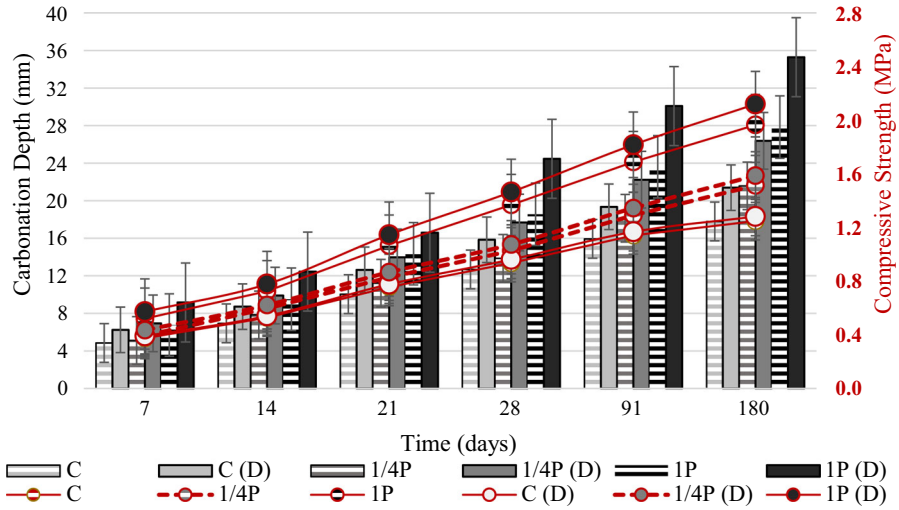

Fig. 10 Relationship between compressive strength and carbonation depth of non-dewatered and dewatered mortars. (C): hydrated lime mortar, (1,4P) and (1P): hydrated lime-brick dust mortars, error bars are standard error

effectiveness factor (CEF) was calculated using Eq. (2), which is the ratio of the compressive strength f_c (Nm^{-2}) of hydrated lime mortars divided by the total materials cost per unit volume C ($\$m^{-3}$).

$$\text{CEF} = \frac{f_c}{C} \times 100 \tag{2}$$

CEF was employed to determine the cost per kg for dewatered and non-dewatered mortars', including the costs of lime and sand for each mix design, at 28 days and 180 days. Results are presented in Table 4. Not only dewatering, but also brick dust additions increased the cost effectiveness of mortars. For both cases, 1P mortar's cost efficiency factor increased considerably while others exhibited a small increase, seen in Fig. 11. The highest effectiveness in cost is seen for the dewatered hydrated lime included mortars which contained the highest amount of brick dust (1P). Therefore, the 1P mortars were compared as dewatered and non-dewatered to determine the effect of dewatering on CEF. The cost effectiveness increase for 1P non-dewatered mortars was 44% at 28 day and 40% at 180 days, while the cost effectiveness increase for 1P dewatered mortars was 48% at 28 days and 45% at 180 days. Hence, the difference between non dewatered and dewatered mortars is seen distinctively for 1P hydrated lime–brick dust mortars.

Table 4 Cost efficiency factor of non-dewatered and dewatered mortars containing hydrated lime and hydrated lime-brick dust at 28 days and 180 days. Cost in USA dollars

Mix	Dewatering	Mix Constituents		Mix Cost		Average compressive strength		Cost	Cost-effectiveness factor	
		Lime (kg)	Sand (kg)	Lime ($)	Sand ($)	fc_{28d} (Nm^{-2})	fc_{6m} (Nm^{-2})	C ($\$m^{-3}$)	CEF_{28d} ($N\$^{-1}$ m^{-1})	CEF_{6m} ($N\$^{-1}$ m^{-1})
C	Non dewatered	153.9	713.8	9.60	2.13	0.935	1.248	11.74	7.97	10.64
1/4P		149.5	693.4	9.33	2.07	1.027	1.514	11.40	9.01	13.28
1P		138.2	640.7	8.62	1.92	1.369	1.965	10.54	12.99	18.64
C	Dewatered	153.9	713.8	9.60	2.13	0.962	1.282	11.74	8.20	10.92
1/4P		149.5	693.4	9.33	2.07	1.074	1.587	11.40	9.42	13.92
1P		138.2	640.7	8.62	1.92	1.465	2.120	10.54	13.90	20.12

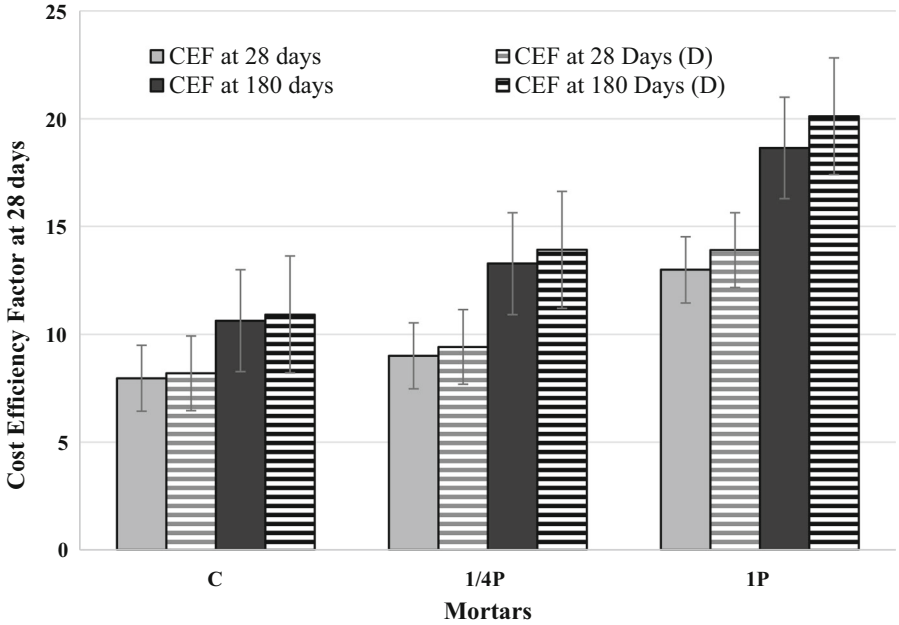

Fig. 11 Cost efficiency factor of non-dewatered and dewatered mortars at 28 days and 180 days; (C): hydrated lime mortar, (1,4P) and (1P): hydrated lime-brick dust mortars, (D): dewatered samples; error bars are standard error

5 Conclusions

This study investigated the effect of brick dust additions on the dewatering, mechanical properties and cost-effectiveness on hydrated lime mortars. The addition of brick dust into hydrated lime mortars has an important role in the modification of their physic-ochemical properties. The most significant change was observed in lime mortars containing the highest amount of brick dust used in this study, which was in the ratio of 1:1:2 (Lime: Brick dust: Sand). This indicated that the increase of interfaces between lime and brick dust (pozzolanic reactivity) and the fineness of the pozzolan significantly impacted the mortars.

To conclude, the following findings are highlighted:

- When dewatering is influenced by the presence of brick dust, the loss of water and decrease of consistency are affected by the substrate type.
- Water loss due to dewatering was higher for mortars containing brick dust demonstrating an increase in the water releasing ability.
- Setting time decreased and transfer sorptivity increased with the addition of brick dust.
- Additions of brick dust promoted dewatering attributed to gain in strength which increased with age.
- The addition of brick dust had a cumulative effect of reducing porosity which was attributed to dewatering and the ageing time. The lowest porosity was observed at 180 days in the dewatered mortar of mix volume ratio of 1:1:2 (Lime: Brick dust: Sand).
- Water penetration depth of dewatered mortars was lower than that of the non-dewatered mortars. As the microstructure became denser, the ability of water to penetrate reduced.
- An increase in carbonation depth was observed for the non-dewatered (from 17.79 to 27.84 mm) and dewatered (from 21.39 to 35.29 mm) -mortars containing hydrated lime and hydrated lime-brick dust.
- Mortars with higher brick dust additions and greater water loss due to dewatering had the greatest cost efficiency factors.

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Declarations

Conflict of interest The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper. The authors declare the following financial interests/personal relationships which may be considered as potential competing interests.

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