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Use of brick waste for mortar-substrate optimisation of mortar-masonry systems

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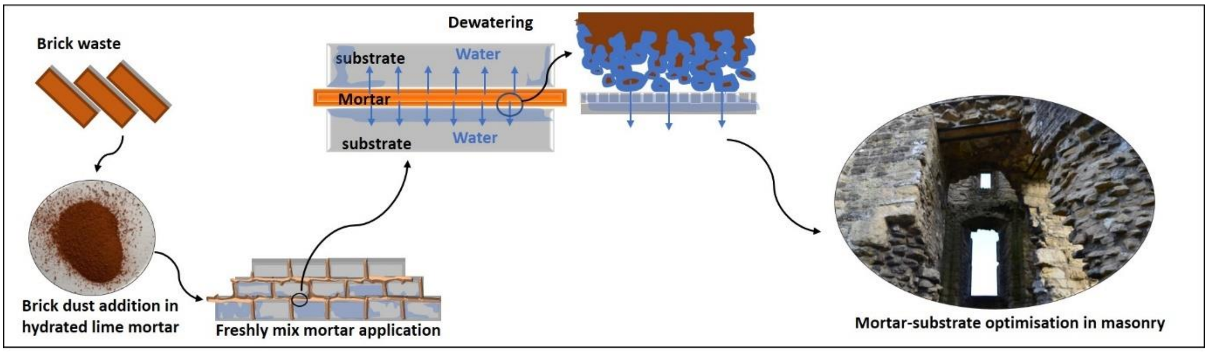
Abstract

This paper investigates the effect of brick dust on the water-releasing properties and dewatering of hydrated lime mortars. Dewatering in masonry occurs when freshly mixed mortar is applied to a dry substrate (e.g. fired bricks, stone) and can influence the physical and mechanical properties of the mortar and the mortar-masonry bond. Controlling these properties provides an important opportunity to optimise performance. This study evaluates the water transport kinetics of hydrated lime-brick dust mortars. The study demonstrates that the particle size distribution of the brick dust can effectively control transfer sorptivity and dewatering time. The measured dewatering times correlated to theoretically calculated values demonstrating the ability to accurately predict the dewatering characteristics of a mortar from a knowledge of the mix design. The use of waste brick dust in hydrated lime mortars provides an environmentally friendly alternative to waste disposal by routes such as landfill.

Keywords:

Dewatering, water transport kinetics, waste, waste disposal, hydrated lime

Graphical Abstract



Summary of the effect of brick dust addition on mortar dewatering. When freshly mixed mortar is applied the dewatering phenomenon occurs. The addition of brick dust increases the dewatering which provides mortar-substrate optimisation in masonry.

1. Introduction

In recent years interest in the utilisation of hydrated lime mortars has revitalised, particularity in the conservation and restoration of historic masonry [1]. The reintroduction of hydrated lime binders ensured mortar compatibility with historic masonry walls and provided benefits such as low shrinkage, ability of accommodate movement and improved resistance to salt and frost damage [1-5]. The use of cement plasters and mortars, particularity in restoration of masonry walls originally built from lime, often leads to progressive degradation due to incompatibility of the mechanical and chemical properties [6-10]. Hydrated lime, extensively used in historic masonry, sets and hardens due to carbonation [6,8,9], whereas natural hydraulic lime (NHL), lime-pozzolan and cement undergo chemical reactions with water that provide hydraulic binding characteristics [7,11-14]. Mortars containing hydrated lime set more slowly than hydraulic lime but nevertheless can still be used in load-bearing applications soon after application. Hence, the elasticity of these mortars can accommodate deformation during early settlement [12]. Therefore, the lower compressive strength, usually in the range of 0.8 to 2 MPa, attained as a result of the utilisation of hydrated lime is ideal for conservation and restoration of historic masonry walls [10,14], opposed to NHL and cement based mortars that produce much higher strengths [9].

Dewatering is the term used to describe the transfer of water from a freshly mixed mortar into a dry porous substrate [14]. Considering that plasters, renders and mortars are applied whilst in their fresh state on to the absorbent substrates (usually a masonry unit such as fired bricks and stone) dewatering takes place. The degree of dewatering depends on the water retaining ability of the mortar and the sorptivity of the substrate. In the case of high-water retaining mortars in contact with a low sorptivity substrates, an inadequate bond is prone to develop between the mortar and the substrate. This is due to insufficient water transfer between mortar and substrate. However, in the case of high-water releasing mortars in contact with a high sorptivity substrate, a greater amount of water is absorbed from the freshly mixed mortars by the substrate. It is previously reported by Ince et. al. (2010) [15] that 40%-60% of the original mix water from the freshly mixed mortars could be lost during dewatering. This in turn adversely influences the mortar-brick interaction and causes detrimental effects to the fresh and hardened state properties of the resulting mortar [12-14].

There are some key issues to consider in the dewatering phenomena of masonry. Replacing the substrate unit is often not possible in conservation and restoration work. This is due to the structural and architectural compatibility of the original substrate unit with the existing masonry wall. In previous research, adhesion and slaking methods of hydrated lime mortars are studied mostly for their effects on mortar workability [17]. Through their influence on dewatering, the water retaining ability of repair mortars play a key role in determining the characteristics of the mortar-substrate bond, and consequently the degree to which they are optimised. However, plasters and mortars containing hydrated lime are known to have high water retaining characteristics and this is the main barrier to their use in restoration and construction practice. The high-water retaining ability of hydrated lime mortars can be considered the main impediment of mortar-substrate optimisation in masonry walls particularly when applied to low sorptivity substrate units.

There is a misconception that relevant standards do not comprehensively address the dewatering phenomenon. The process of dewatering starts as soon as the mortars and renders are cast. The casting often uses impervious steel moulds specified in testing standards. These moulds do not absorb any water therefore the dewatering process does not take place as is the case when mortars and renders are applied onto absorbent substrates units on-site. Generally during the dewatering process the water that is transferred to the substrate is the proportion of water in the mix which provides the required consistence rather than that required for hydration. Discrepancies between the standards and on-site practices are based on the differences between the water absorbent characteristics of on-site brick units versus the use of impermeable moulds used for laboratory measurements. It is well known that the water demands necessary to attain the standard consistence is often greater than the amount of water required for the hydration reactions. High water demand materials such as high fineness hydrated lime binders will absorb the excess water added to obtain the standard consistence. This in turn can minimise the dewatering effect of mortars. It is essential to note that, regardless of the degree of intensity, dewatering is unavoidable, and it will influence, both, the fresh and hardened paste properties of mortars and renders.

There are few published studies in the literature that focus on the in-situ dewatering mechanism of freshly mixed mortars with absorbent substrates (masonry wall units) [15]. Some of these studies focus largely on the ability to manipulate the high-water retaining characteristics of mortars using supplementary cementitious materials [15-20]. Ince et al. (2010) [15] were the first to derive an equation to quantify the time to dewater when freshly mixed mortars are placed on absorbent substrates. The factors affecting the water-retaining properties of freshly mixed mortars, and the effect of dewatering freshly mixed mortars and the associated effects on the hardened state properties of these mortars have also been reported by Ince et al. (2011) [20]. Despite the challenges in designing and carrying out the dewatering experiments, there is a growing need to study and control the water transport kinetics. The latter will provide an insight into the mechanisms responsible for water movement in mortar-substrate systems.

Production of lime releases less CO_2 emissions compared to cement clinker [21] since coal-fired kilns are used primarily in manufacturing. Manufacturing lime is more energy efficient as lower temperatures of around 900°C are sufficient to allow the chemical reactions required to take place. This is in contrast to cement which requires heating in the range of 1400-1500°C to convert raw materials into Portland cement clinker. The complete life cycle and closed-loop associated with hydrated lime plays a significant role in decreasing the CO_2 emissions as the substantial portion of the CO_2 generated during calcination is reabsorbed by the binder during hardening (carbonation) [22]. The reduced CO_2 emissions bring associated advantages such as improved air quality and reduced dependence of the global economy on fossil fuels. The use of softer and lighter hydrated lime mortars with a low bond strength that can be easily removed also enables substrate units such as blocks, bricks and stone to be recycled when a structure reaches the end of its life span [7-9]. This modality further contributes in saving the energy and the associated CO_2 emissions that would be required to manufacture the substrate materials [24].

Existing alternatives for waste disposal, such as landfilling and recycling, could be utilised for waste brick dust produced from surplus production and debris during manufacturing [25]. Although each of these alternatives has its own credentials, landfilling brick dust waste could result in the formation of leachates such as Pb, Cs [26], As, Zn, sulphates, Ca, S, Si, Mg and Fe [27] . Recycling can be utilised to compensate the adverse effects of landfilling depending on the associated costs. The methane that is produced during decomposition of any organic materials, such as hemp and natural fibres, which are used in combination with lime-based binders can also accelerate global warming and ozone depletion. The waste disposal approach adopted in this paper, enables the reuse of the brick dust waste in the production of hydrated lime mortars. Reusing brick dust waste, as a pozzolanic addition, does not require any prior processing allowing direct use of these materials in mortar manufacture. Therefore, incorporating brick dust waste in hydrated lime mortar does not only encourage the re-introduction of the greener hydrated lime binders in engineering practices but also fosters a cleaner route for the disposal of the brick waste.

This paper investigates the extent to which water-releasing mortars can control the dewatering mechanism. The high-water retaining ability of modified hydrated lime mortars with brick dust has been used to attain mortar-substrate optimisation. Hydrated lime mortars and mortars with two incremental additions of brick dust were prepared. Following characterisation of raw materials, the influence of brick dust on the consistence and setting time is reported. The influence of brick dust on the mortar sorptivity, transfer sorptivity and dewatering time is also explored. This paper specifically focuses on how substrate sorptivity and pozzolanic brick dust and its fineness influence the water transport kinetics of hydrated lime mortars. The experimentally measured values of dewatering time were then validated using the calculated time to dewater for all cases examined. The environmental implications and the associated sustainability impact of the utilisation of brick dust, obtained from the local industry, in hydrated lime mortars is also assessed in the paper. The brick dust used in this research is both classified as a surplus by-product and as a waste material with the potential to play an important role in minimising CO_2 emissions [28]. The results reported in this study have important practical implications in conservation and restoration of masonry walls and encourage the reutilisation of modified hydrated lime binders in construction and restoration practices. The use of the waste materials in hydrated lime mortars, such as brick dust, provides a cleaner alternative for waste disposal management, particularly when compared to the conventional waste disposal routes.

2. Theoretical background

To quantify the dewatering process for a fresh mortar-substrate system, a few parameters need to be identified. These parameters are desorptivity (R) and sorptivity (S) and transfer sorptivity (A). The desorptivity, R, defines the water retaining ability of a wet mix such as a mortar in this study. A low R value indicates a high water retaining characteristic of the mix [23,24]. The sorptivity, S, defines the ability of a porous material to absorb water by capillarity. The sorptivity is measured by placing a dried substrate in contact with water and involves removing and weighing the substrate at intervals [25,26]. The sorptivity is represented as the gradient of a plot of the cumulative absorbed volume of water per unit area of absorbing surface versus the square root of time. The transfer sorptivity, A, is a function of both R and S and characterises the ability of a porous material to absorb water from a wet mix, as seen in equation (1) [31] . The transfer sorptivity is measured by placing a dried substrate in contact with a wet mix and involves removing and weighing the substrate at intervals. The transfer sorptivity is defined as the gradient of a plot of the cumulative absorbed volume of water per unit area of material in contact with the wet mix versus the square root of time. These parameters are related by [33]:

$$\frac{1}{A^2} = \frac{1}{R^2} + \frac{1}{S^2} \qquad (1)$$

Sharp Front theory is then used to derive an equation describing the time taken to dewater a wet mix, t_{dw}, by an absorbent substrate [15]. The Sharp front theory is described in detail in [25,31]. The assumption that the wetted zone behind an advancing wet front is uniform rather than diffuse simplifies the analysis considerably. A full derivation of equation (2) can be found in [15]:

$$\mathrm{t_{dw}} = \left(\frac{\mathrm{L\alpha}}{\mathrm{A}}\right)^2 \qquad (2)$$

The t_{dw} corresponds to the time at which no further water can be absorbed by the substrate. A is the transfer sorptivity, L is the mortar depth and α is a complex parameter to account for the initial and final volume fractions of water and solid contents. Substrate–mortar–substrate joint is considered to represent the idealised case of two bricks (substrate) concurrently placed in contact with wet mortar. The bricks are initially dry so that at time $t = 0$ the volume fraction water content of each brick, $\theta = 0$. The wet mix, of thickness L, has an initial volume fraction water content θ_{i} and a volume fraction solids content φ_{i} so that $\theta + \varphi = 1$. A uniform distribution of the solids throughout the wet mix was considered. As water is absorbed from the wet mortars by the bricks, an advancing wetted zone is created within each brick. As desorption of water proceeds, the solids are transported to the mortar-substrate interfaces where they consolidate forming a filter cake. Desorption eventually ceases when all the wet mix has been converted to filter cake. As for the α, a full derivation of equation (3) can be found in [15], comprises the initial and final volume fractions of water and solid contents:

$$\propto = \theta_{\mathrm{i}} - \emptyset_{\mathrm{i}} \frac{\theta_{\mathrm{c}}}{\emptyset_{\mathrm{c}}} \qquad (3)$$

Where θ_{i} and θ_{c} are the initial and final volume fractions of water and the φ_{i} and φ_{c} are the initial and final volume fractions of solids respectively. When the timescale of the dewatering process is considered, the withdrawal of water from a wet mix by the dry substrate is described by

$$i = At^{1/2} \qquad (4)$$

Where A is the transfer sorptivity [33]. It has been previously shown that $i = L\alpha$ [15] and so, from equation *(4)*, $L\alpha = At^{1/2}$. All the wet mix will be converted to filter cake at time $t = t_{\mathrm{dw}}$ given by $t_{\mathrm{dw}} = (L\alpha/A)^{1/2}$.

3. Experimental Materials and Scheme

The hydrated lime, standard sand and brick dust, as a pozzolan addition, are the main raw materials used in this study. CL80, which conforms to EN 459-1 was used to obtain the hydrated lime mortars. Standard sand also follows EN 196-1. The brick dust, attained as a surplus production was supplied by 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 study comprises a control mortar with volume fractions of lime: sand of 1:2 and two types of mortars comprising lime: pozzolan: sand in the ratios of 1:1/4: 2 and 1:1:2

respectively. The mortars assigned as C, 1/4P and 1P respectively. The mass of the constituent materials, essential to produce the envisaged mix proportions by volume, were calculated from density. Mix constituents of the raw materials are summarised in Table **1**. The volume proportions of pozzolanic additions used in this study are in a good agreement with those previously reported in the literature for conservation applications [34]. The standard mixing regime described by [35] is followed. It must be noted that the water content is deliberately increased with the increasing additions of brick dust to attain a constant consistence of each mixture investigated.

Table 1

Mix constituents.

Specimen	Materials	Volume Proportions	Mass (g)
Hydrated lime mortar Control (**C**)	Water	0.567	340
	Lime	1	396
	Brick Dust	0	0
	Sand	2	1836
Hydrated lime with 0.09 volume fraction of brick dust **(1/4 P)**	Water	0.583	350
	Lime	1	396
	Brick Dust	0.25	65
	Sand	2	1836
Hydrated lime with 0.36 volume fraction of brick dust **(1 P)**	Water	0.617	370
	Lime	1	396
	Brick Dust	1	263
	Sand	2	1836

Three cases were examined as shown in Table 2. Case 1 was designed as a reference, whereas Cases 2 and Case 3 address the effect of substrate sorptivity as well as the fineness of the pozzolanic addition on the transfer sorptivity and time taken to dewater freshly mixed lime mortars.

Table 2

Three cases examined in the paper.

Case	Specimen	PSD	Sorptivity of substrate
Case 1	C	PSD 1 (0.6μm to 478μm)	2.1mm/min$^{1/2}$
	1/4P		
	1P		
Case 2	C	PSD 1 (0.6μm to 478μm)	3.2mm/min$^{1/2}$
	1/4P		
	1P		
Case 3	C	PSD 2 (100μm to 478μm)	2.1mm/min$^{1/2}$
	1/4P		
	1P		

PSD = Particle Size Distribution.

Consistence of freshly mixed mortars was measured using the flow test [34] and the setting time using Vicat apparatus [36]. Powder X-ray Florescence spectroscopy was conducted to determine the elemental compositions of the raw materials used to produce mortars specimens. A Rigaku ZSX Primus

II with 0.1-50 Å wavelength X-rays was employed for this analysis. Particle size distribution was determined using a Malvern Mastersizer 2000. Scanning electron microscopy was carried out using a QUANTA 400F Field Emission SEM. All samples were held under vacuum for 24 hours prior to imaging to reduce moisture levels. A specimen penetration energy of 10eV was used for all samples. Surface charging effects were reduced by the application of a sputtered layer of gold metal to the surfaces under investigation.

The measurement of transfer sorptivity was conducted by placing the substrate unit in contact with a wet mortar mix [33]. Performing these measurements are experimentally challenging due to the adhesion between the substrate and the wet mix as well as the limited time available prior to the stiffening of the wet mix. Hydrated lime mortars were placed into five equally sized rectangular compartments in a purpose-built mould. One brick section was then placed in contact with the mortar in each compartment as shown in Figure 1. Each brick of size 46mm × 100mm was dried to a constant weight at 105°C. Brick sections were removed from the mortar consecutively at increasing time intervals and weighed. The mass, and hence the volume, of water absorbed at five-time intervals was then obtained. The experiment was designed, from prior knowledge of the relevant parameters, so that transfer sorptivity, time to dewater and the final water content of the dewatered mix could be obtained from the same set of data in the experimental results section. Transfer sorptivity and time to dewater were determined from a plot of cumulative absorbed volume of water per unit area (i) versus time to dewater (t_{dw}). These experiments were designed to generate 3 data points for the first stage where the gradient of this data defines the transfer sorptivity [20,29,31-33]. The second stage was then defined using two data points which indicate complete dewatering. The intersection of these two distinct stages provided the time to dewater on the X-axis.

Figure 1. The purpose-built mould used to obtain the transfer sorptivity.

As explained previously, the computation of α relied on the experimental measurements of θ_i and φ_i. The initial volume fraction water content of the wet mix, θ_i, is defined with the fraction of volume of water added to mix, V_{WA} and Volume of wet mix, V_{WM}:

$$\theta_i = \frac{V_{WA}}{V_{WM}} \tag{5}$$

The mass and the volume of water contained in the wet mix was known, as the total mass of wet mix produced. To determine the total volume of the wet mix, the density of the mix was calculated initially. Density was obtained using the graduated cylinder, which involved measuring the mass of a known volume of the wet mix. The density and the total mass of the wet mix measured was then used to determine the total volume of the wet mix. The volume fraction water content of the dewatered mix (i.e.

the filter cake) is defined with the fraction of volume of water remaining in mix, V_{WR} and volume of dewatered mix, V_{DM}:

$$\theta_C = \frac{V_{WR}}{V_{DM}} \tag{6}$$

For any compartment in the mould, the mass of wet mix was known before dewatering. The mass of absorbed water by the associated substrate is also known. By recording the total mass of the wet mix, it was possible to obtain the total mass of the absorbed water. The volume of water remaining in the mix was determined by subtracting the total mass of absorbed water by the substrate, from the initial mass of water added to the mix. The volume of the dewatered mix was then determined using density measurements. From these measurements, the volume fraction of water in the dewatered mix was established.

The water loss was calculated based on the mass of mortar in the 5th compartment used in the dewatering experiments, and the absorbed volume of water by the brick unit in contact with the wet mix in the 5th compartment. Data of the 5th compartment was used to calculate the water loss to ensure complete dewatering. The water loss was calculated in percent as the total mass of the wet mix was known.

4. Results and Analysis

4.1. Characterisation

Elemental analysis of the hydrated lime (CL80), brick dust and sand obtained from an X-ray fluorescence (XRF) analysis is summarised in Table *3* and was used to confirm compliance of the raw materials with the appropriate standards. *CL80* binder, showed a 94% CaO content and hence compliance with BS EN 459-1. 64% of the brick dust, used as a pozzolanic material, in this study comprised of silicon dioxide (SiO_2), aluminium oxide (Al_2O_3), and iron oxide (Fe_2O_3). Although this is less than the 70% required according to the American Standard [39], the 21.6% CaO content and the quantity of SO_3 being less than 4% enabled compliance with ASTM C618 and validated the moderate pozzolanic nature of the brick dust. The chemical composition of the standard sand complied with BS EN 196-1.

The particle size distribution of the raw materials used as constituents in mortar, are shown in Figure 2. The hydrated lime showed the highest fineness with the particle size ranging from 0.6μm to 30μm. The particle size distribution of the standard sand was in the range of 3μm to 4 mm and the brick dust particle size distribution was in the range of 0.6μm to 478μm, shown in Figure 2, is designated as PSD 1, which spanned that of the lime binder and the standard sand. As previously reported in Section 3, one of the objectives of this study was to investigate the effect of the brick dust fineness on the water transport kinetics of hydrated lime mortars. The particle size distribution of brick dust chosen to be in the range 100μm to 478μm, is designated as PSD 2. Case 3 was used to investigate the effect of coarse particles size of the brick dust on the water transport kinetics of hydrated lime mortars.

Table 3

Chemical composition of constituent materials determined from X-ray florescence spectroscopy.

Chemical composition	**Lime (%)**	**Brick dust (%)**	**Sand (%)**
CaO	94.0	21.6	0.463
MgO	2.93	6.03	0.142
SO_3	1.84	3.02	0.0411
SiO_2	0.513	41.0	91.9
Al_2O_3	0.234	13.4	3.91
Fe_2O_3	0.234	10.2	0.659
Cl	0.0783	0.0728	0.0178
V_2O_5	0.0688	0.0866	-
K_2O	0.0669	1.91	1.31
Na_2O	0.0522	1.06	0.498
SrO	0.0457	0.0841	0.0152
NiO	0.0225	0.0465	-
P_2O_5	0.0094	0.238	0.0597
TiO2	-	0.935	0.832
MnO	-	0.293	0.0398
SrO	-	0.0841	0.0152
Cr_2O_3	-	0.0554	0.0241

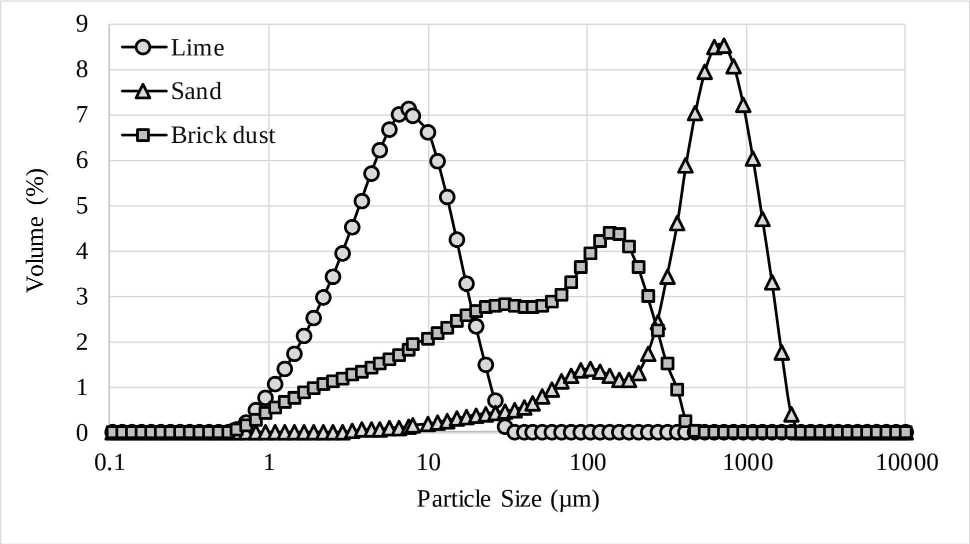
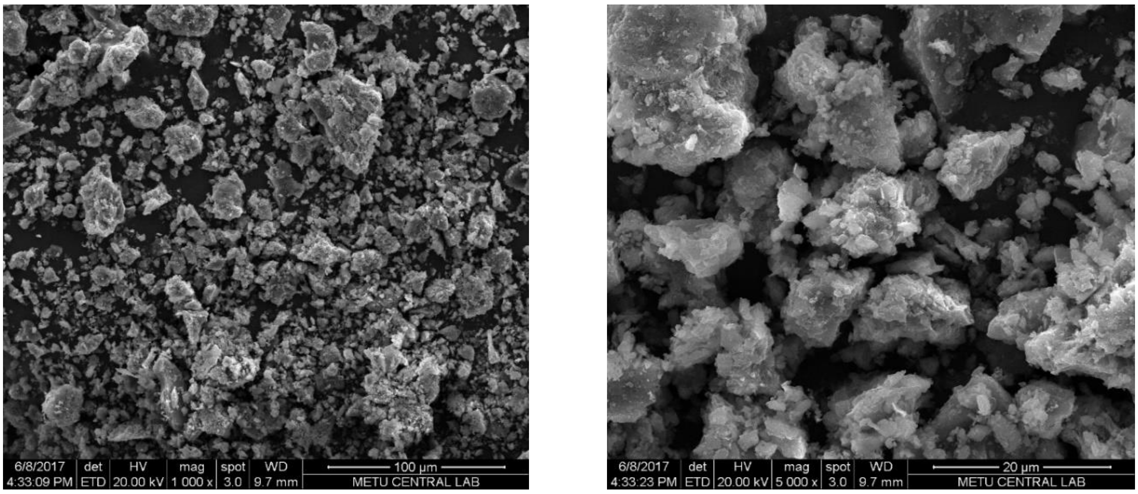


Figure 2. Particle Size Distribution of hydrated lime, brick dust, sand.

Scanning electron microscope (SEM) images of brick dust with varying angular size of particles are shown in Figure 3(a). Irregular glassy particles can be seen in Figure 3(b).

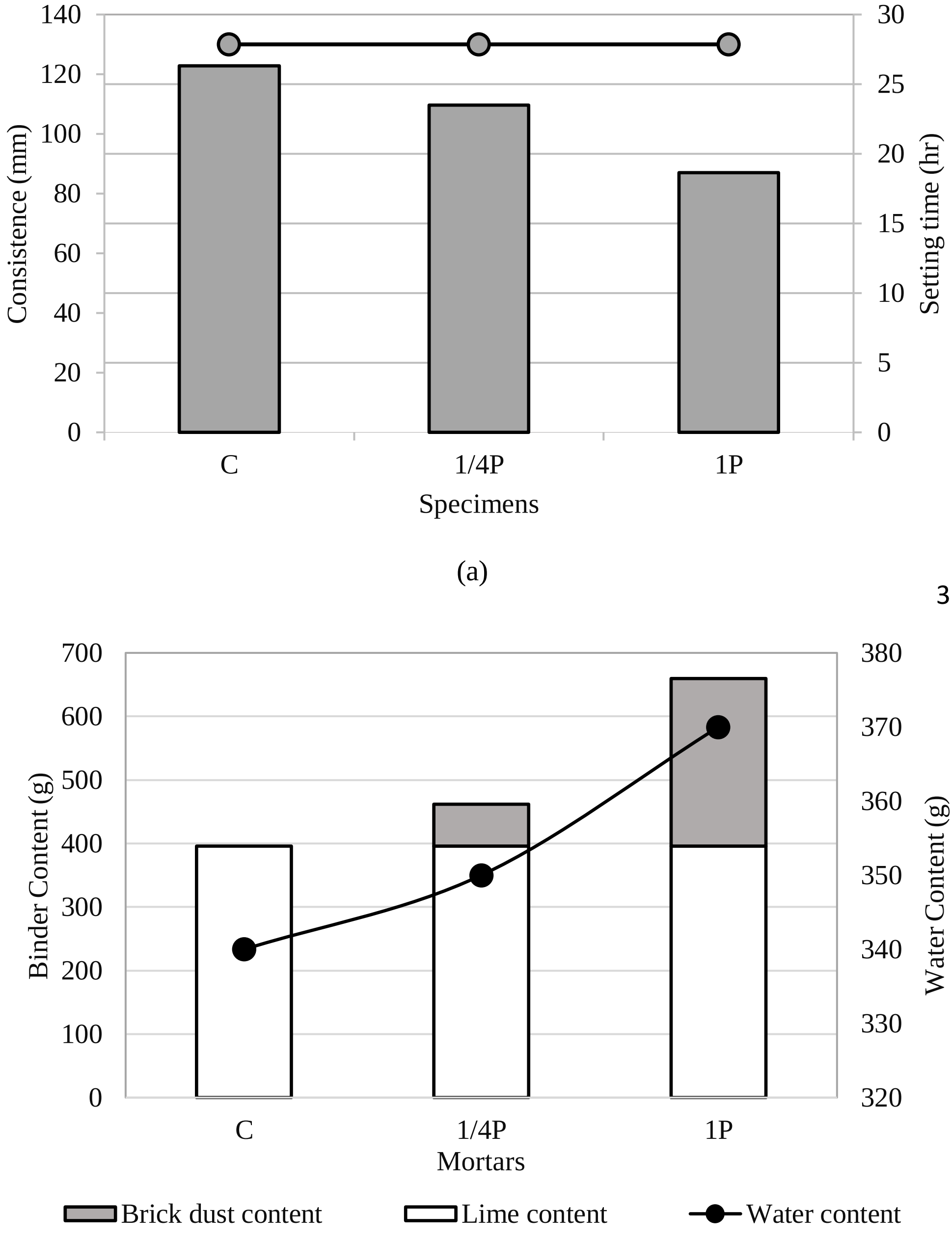


(a) (b)

Figure 3. Scanning electron microscopy (SEM) images of brick dust (a) scale bar 100µm, (b) scale bar 20µm.

4.2. Consistence and Setting Time

The influence of brick dust on the consistence and setting time of the mortars is described in this section. Figure 4(a) shows that the consistence, measured using the flow table, was 130 mm for all mortars examined. It is noteworthy that the water content was increased deliberately with the increased additions of brick dust to attain constant consistence of 130 mm for all mortar types. Increasing the water content was essential to attain constant consistence because of the overall increase in the fineness of the mixture due to the increased level of pozzolanic additions. The mortar setting time decreased systematically with the addition of brick dust as shown in Figure 4(a). The decrease in the setting time was attributed to the coarser matrix resulting from the brick dust additions. Less dense and more porous matrix development, as a result of the inclusions of coarser particle sizes of brick dust, enabled water to follow more distinct pathways to evaporate and hence accelerated the setting of these mortars [40]. Long setting times of hydrated lime often forms a barrier for the use of these binders in construction practice. Considerable decreases in the setting time of the hydrated lime mortars, attributed to the brick dust enhancement, could promote the re-introduction of these enhanced binders in conservation and restoration work. The binder contents of the hydrated lime mortars were plotted against the water contents, as shown in Figure 4(b). This figure shows that the addition of brick dust resulted in an overall increase in the solid content. In turn, this resulted in increasingly more water being required to provide a constant consistence for all the mixes examined.



(a)

(b)

Figure 4. (a) Consistence and setting time, and (b) binder content versus the water content of hydrated lime mortars with brick dust.

4.3 Transfer Sorptivity and Time to Dewater

The effect of brick dust as a pozzolanic addition on the transfer sorptivity and time taken to dewater freshly mixed lime mortars is described in this section. Three cases including 4 specimens for each were examined as previously noted: Case 1, designed as a reference case, comprises substrates of constant sorptivity of 2.1 mm/min$^{1/2}$ with brick dust, used as a pozzolanic addition, particles size range of 0.6μm to 478μm (designated as PSD 1). Case 2 comprises substrates of constant sorptivity of 3.2 mm/min$^{1/2}$ with brick dust of PSD1, Case 3 comprises substrates of constant sorptivity of 2.1 mm/min$^{1/2}$ with brick dust particle size range of 100µm to 478µm (designated as PSD2). These cases were essentially created to address the effect of substrate sorptivity as well as the fineness of the pozzolanic addition on the transfer sorptivity and time taken to dewater freshly mixed lime mortars. These cases are shown in Figure 5, Figure 6 and Figure 7 respectively.

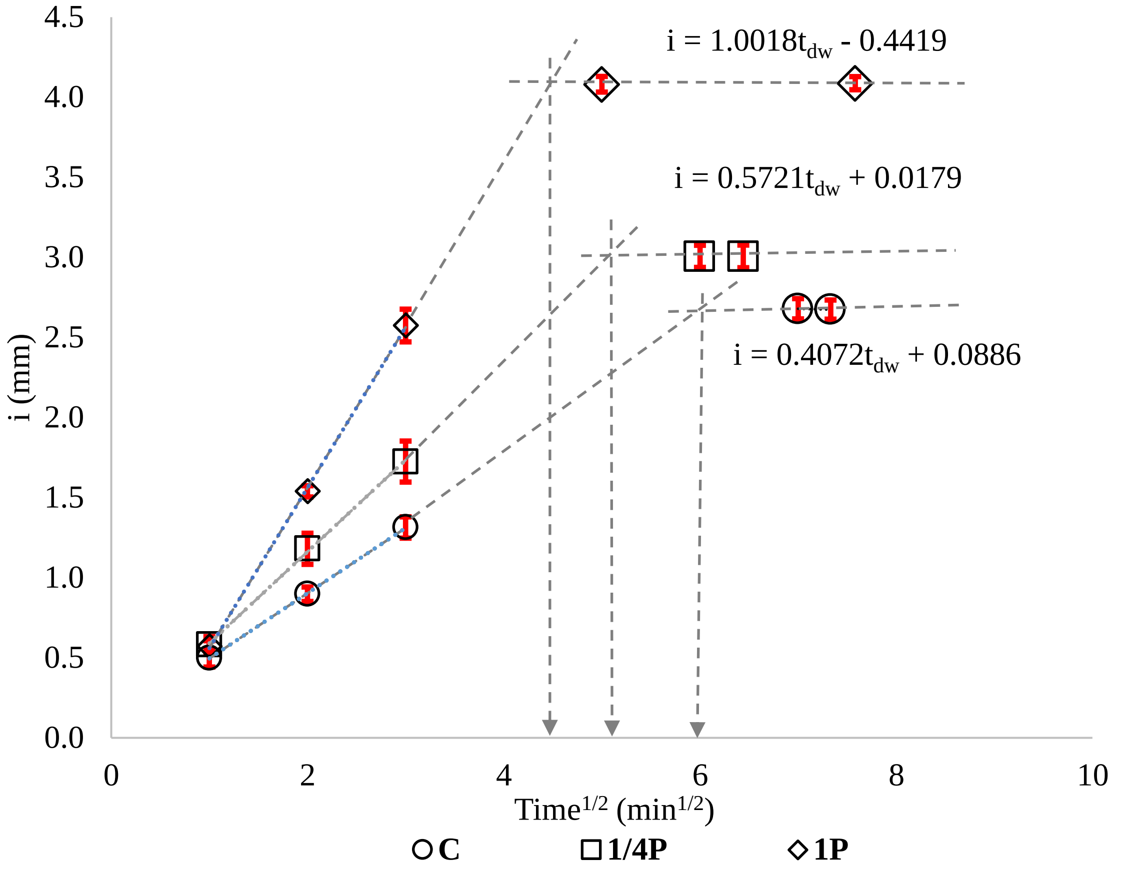


Figure 5. Cumulative absorbed volume of water per unit area i versus $t^{1/2}$ for Control; 1/4P and 1P. (S=2.1 mm/min$^{1/2}$ PSD 1, Case 1).

Three cases were examined as shown in Table 2. Case 1 was designated as a reference. Case 2 was different to the reference as the particle size distribution of the brick dust was modified to show the effect of pozzolanic addition fineness on the transfer sorptivity and time taken to dewater freshly mixed mortar. Case 3 demonstrated the effect of a changing the substrate sorptivity on transfer sorptivity by using a brick with a different substrate sorptivity.

Case 1, designed as a reference case, comprises substrates of constant sorptivity 2.1 mm/min$^{1/2}$ with brick dust, used as a pozzolanic addition and particle size range of 0.6µm to 478µm. It is shown in Figure 5 that the increasing additions of brick dust resulted in a systematic increase in the transfer sorptivity of hydrated lime mortars. The increase in the transfer sorptivity, attained using the constant sorptivity substrate, is an indication of the formation of more water-releasing hydrated lime mortars containing brick dust. These results clearly demonstrate that the high-water retaining ability and hence the low transfer sorptivity of hydrated lime mortars can be manipulated using the brick dust as a pozzolanic addition. In addition, the relatively long-time taken to dewater can also be significantly lowered allowing mortar-substrate optimisation to be achieved.

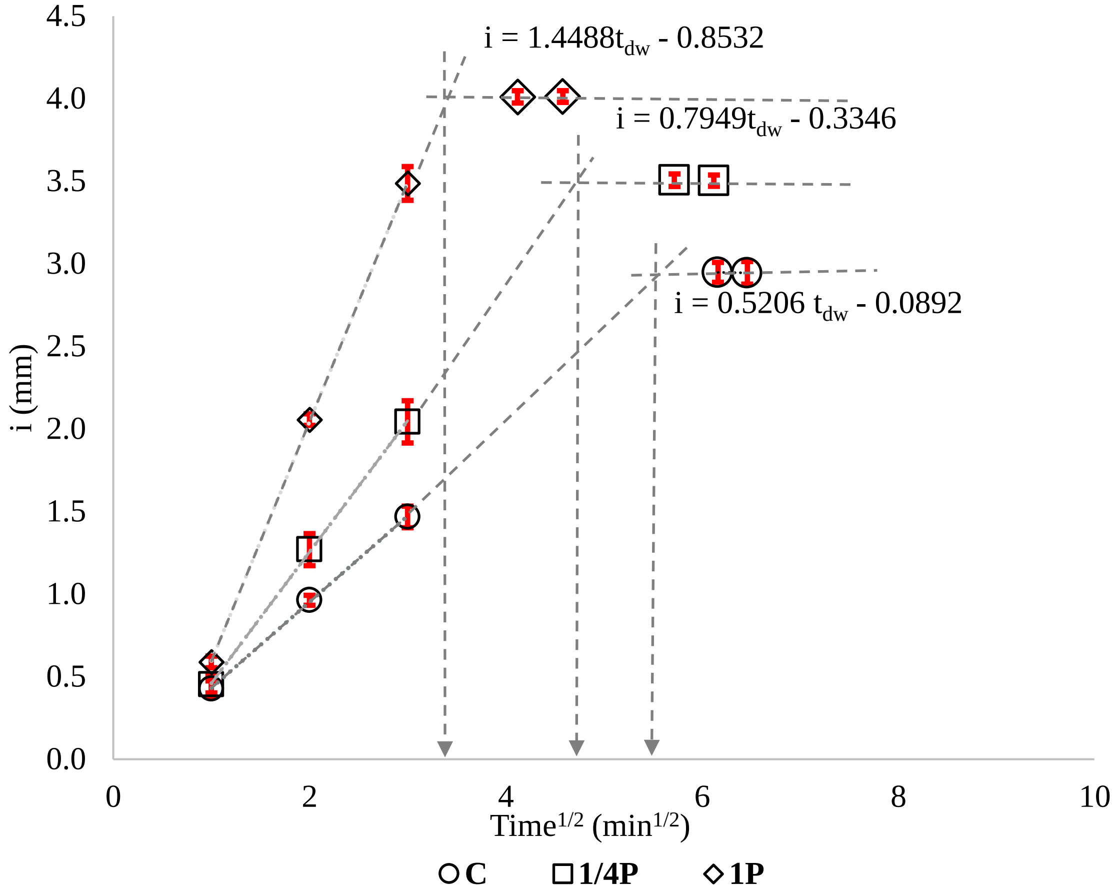


Figure 6. Cumulative absorbed volume of water per unit area i versus $t^{1/2}$ for Control; 1/4P and 1P ($S=3.2mm/min^{1/2}$ – PSD 1, Case 2).

Case 2 comprises substrates of constant sorptivity of 3.2 mm/min$^{1/2}$ with brick dust of PSD1. Figure 6 shows that the use of higher sorptivity bricks during the dewatering experiment did not significantly change the overall trend of the result. The increase in the addition of brick dust once again, resulted in a systematic increase in the transfer sorptivity and consequently resulted in a systematic decrease in the time taken to dewater the hydrated lime mortars. However, it must be noted that a greater increase in transfer sorptivity and greater decrease in the associated time to dewater of the mortars containing brick dust could be attributed to the higher sorptivity substrates used. These enabled more water to be withdrawn which significantly lowered the time taken to dewater the mortars in the fresh state.

Case 3 comprised substrates of constant sorptivity of 2.1 mm/min$^{1/2}$ with a brick dust particle size range of 100µm to 478µm (designated as PSD2). The influence of fineness of brick dust, used as a pozzolanic addition on the transfer sorptivity and time to dewater is described in this section. The results shown in Figure 7 support those in Figure 5 and Figure 6.

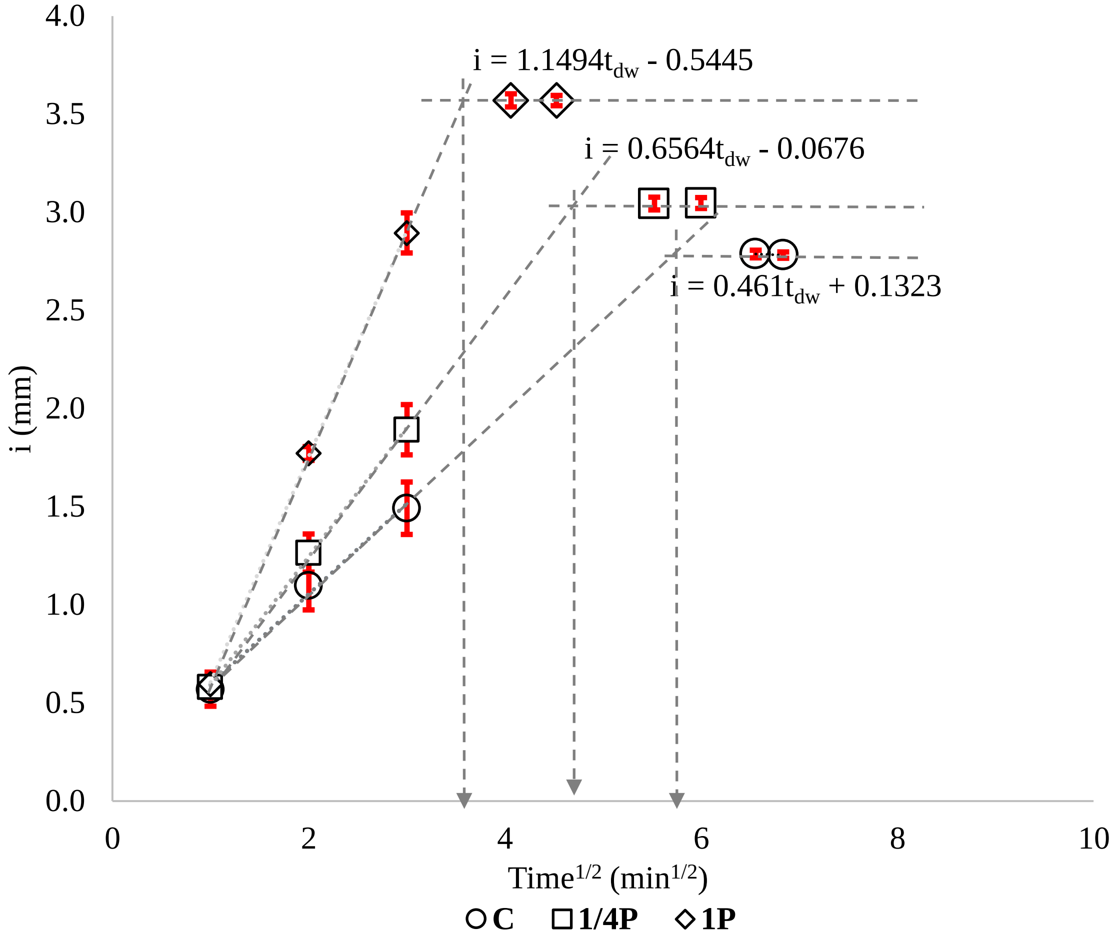


Figure 7. Cumulative absorbed volume of water per unit area i versus $t^{1/2}$ for Control; 1/4P and 1P ($S=2.1 mm/min^{1/2}$ – PSD 2, Case 3).

The increase in the addition of brick dust resulted in a systematic increase in the transfer sorptivity and consequently resulted in a systematic decrease in the time taken to dewater the mortars. Nevertheless, a greater increase in transfer sorptivity and greater decrease in the associated time to dewater of the brick dust mortars, demonstrated in Figure 7, is attained when compared to the control, Case 1 was solely attributed to the increased particle size of brick dust, used as a pozzolanic addition, that resulted in a coarser matrix allowing more water-releasing mortars to be generated.

The results shown in Figure 5, Figure 6 and Figure 7 are also summarised in Table 4 for case of comparison. Case 1, the control case, provided the basis to investigate the effect of brick dust on the water transport kinetics of fresh lime mortars.

It should be noted that the experimental error ranges from 1% - 8% for the directly measured values of transfer sorptivity, A, whereas the experimental error could approach 20% for the directly measured values of time to dewater, t_{dw}. The associated error bars are indicated in Figure 5, Figure 6 and Figure 7.

Referring to Equation (1) from Section 2, it is evident that the formation of more water releasing mortars was due to the addition of brick dust. This in turn was primarily responsible for the increased transfer sorptivity observed which was a result of the constant sorptivity of substrates used in both cases. The effect of increased substrate sorptivity as well as the effect of decreased fineness of the brick dust was investigated in Cases 2 and 3 respectively. It is evident that in both these cases greater transfer sorptivity values were attained. This implies that the high-water retaining ability of these mortars could be decreased simply by using an increased substrate sorptivity and/or increasing the pozzolan particle size used. However, it should be noted that in Case 2 the substrate sorptivity characteristics were specifically chosen to promote the dewatering characteristics studied. The increased sorptivity of the substrate used in Case 2 and the coarser particle size of brick dust used in Case 3 were not chosen to indicate any particular case in practice, but rather to demonstrate that these parameters have significant influences on the water releasing ability of hydrated lime mortars. An important finding of this study is that the transfer sorptivity can be manipulated using the aforementioned parameters to achieve mortar-substrate optimisation. The associated dewatering time values, as expected, were also substantially decreased by the factors as summarized in Table 4.

Table 4

Water loss, transfer sorptivity, time to dewatering of freshly mixed mortars during dewatering.

CASE	Specimen	Mass of freshly mixed mortars before dewatering in the 5th compartment(g)	Mass of the absorbed water from the freshly mixed mortars in the 5th compartment (g)	Water loss during dewatering (%)	Transfer Sorptivity (mm/min$^{1/2}$)	Time to dewater (min)
CASE 1 S=2.1mm/min$^{1/2}$ PSD 1	C	262.08	12.1	4.62	0.406	41.28
	1/4P	273.00	13.5	4.95	0.571	27.56
	1P	299.52	15.9	5.31	1.020	14.28
CASE 2 S=3.2mm/min$^{1/2}$ PSD 1	C	261.90	13.5	5.15	0.518	33.64
	1/4P	273.20	16.2	5.94	0.796	22.56
	1P	298.80	18.6	6.22	1.449	11.39
CASE 3 S=2.1mm/min$^{1/2}$ PSD 2	C	268.32	12.8	4.81	0.451	36.00
	1/4P	282.36	14.0	4.96	0.641	24.10
	1P	308.88	16.5	5.34	1.139	12.96

4.4 Water Loss

The water loss values attained during dewatering of hydrated lime mortars comprising brick dust, are summarised in Table 4. Water loss during dewatering was calculated using the mass of the freshly mixed mortars prior to dewatering and the mass of the absorbed water by the absorbent substrate from the freshly mixed mortars, both from the 5th compartment. The measurements were conducted ensuring the complete dewatering in the 5th compartment. Results summarised in Table 4 demonstrate that the increased addition of brick dust resulted in a systematic increase in the water loss attained during dewatering in all cases. As previously shown in the paper, the addition of brick dust enabled the formation of more water-releasing hydrated mortars and hence the desorption of higher amounts of water by the absorbent substrate. Results presented in Table 4 demonstrate that higher water losses are attained in Case 2 and Case 3 for mortar types when compared to the water losses reported for Case 1. Although the increase in substrate sorptivity as well as the increase in particle size of pozzolans had an increasing effect on the water loss during dewatering the hydrated lime mortars, it is apparent that among the cases investigated, increasing substrate sorptivity to 3.2 mm/min$^{1/2}$ (Case 2) increased the water loss during dewatering more effectively.

4.5 Measurement of α

Alpha (α) which comprises the initial and final volume fractions of water and solid contents, is determined by firstly measuring the θ_i and θ_c using equations (5) and (6) respectively. α is then calculated using equation (3) since for all stages $\theta + \varphi = 1$. The results shown in Table *5* demonstrated that θ_i increases with the addition of brick dust in such mortars. The increase in water content, θ_i, of the mix volume was attributed to the increase in the volume of water added. Considering that these mortars are not being dewatered from a constant value of θ_i, the difference obtained between the θ_i and θ_c which represents the amount of water withdrawal from the freshly mixed hydrated lime mortars should be used to evaluate the influence of brick dust on dewatering. Table *5* illustrates that the difference between θ_i and θ_c increases with increasing brick dust in the mortars. As previously explained in the paper, the increase in brick dust additions enabled more water releasing hydrated lime mortars to be formed and hence higher water withdrawal from these mortars when in contact with the substrate units. Contrary to this, the difference between φ_c and φ_i increased systematically with the addition of brick dust in hydrated lime mortars, meaning that higher amounts of solid particles were attained in the mixture after dewatering.

4.6 Validating t_{dw}

The experimentally measured and theoretically calculated values of t_{dw} of hydrated lime mortars containing brick dust are summarised Table *5*. Experimentally measured values of L, A and α were used to calculate the t_{dw}. The results validated the precision in determining the directly measured values of t_{dw} for these mortars as they had an excellent agreement with the theoretically calculated t_{dw} values. The greatest difference between the measured and calculated values of t_{dw} was 1.05% which provides a high level of confidence in all cases examined. This validation was crucial to assess the accuracy of the experimental results presented in this study.

Table *5* also summarises the standard deviation and the error associated within the directly measured and calculated t_{dw} values. Out of the 36 specimens used for the measurement and calculation of t_{dw}, the standard deviation was in the range of 0.192 – 1.250. However, the error was in the range of 0.1%-6.71% which falls well within the commonly accepted error range for these measurements.

Table 5

Experimental values of volume fraction, mortar depth, transfer sorptivity, complex parameter and a comparison of the calculated and directly measured time to dewater including % error and standard deviation for Case 1, Case 2 and Case 3. Values are an average of 4 specimens tested.

		Volume fractions				**Mortar depth (mm)**	**Transfer sorptivity (mm/min$^{1/2}$)**	**Complex parameter**	**Time to dewater (min)**			
		Liquids		**Solids**		**Directly measured (from the experiment)**			**Calculated**	**Directly measured**	**Comparison of calculated and directly measured**	
		initial	**final**	**initial**	**final**							
CASE	**Specimen**	θ_i	θ_c	ϕ_i	ϕ_c	L	A	α	$\left(\frac{L\alpha}{A}\right)^2$	t_{dw}	**Error (%)**	**Standard Deviation**
CASE 1 S=2.1mm/min$^{1/2}$ PSD 1 (actual)	C	0.224	0.155	0.776	0.844	32.1	0.407	0.081	40.945	41.28	1.14	0.638
	1/4P	0.231	0.156	0.768	0.844	33.7	0.572	0.089	27.825	27.56	3.05	0.367
	1P	0.252	0.144	0.748	0.855	35.8	1.00	0.126	20.395	19.58	1.55	0.718
CASE 2 S=3.2mm/min$^{1/2}$ PSD 1 (actual)	C	0.224	0.147	0.776	0.853	33.0	0.52	0.091	33.128	33.64	3.23	0.445
	1/4P	0.231	0.138	0.768	0.861	35.0	0.795	0.108	22.558	22.56	4.13	0.418
	1P	0.252	0.146	0.748	0.854	39.4	1.449	0.124	11.47	11.39	2.87	0.192
CASE 3 S=2.1mm/min$^{1/2}$ PSD 2 (0.5mm and above)	C	0.223	0.150	0.777	0.850	31.46	0.461	0.086	34.608	36.00	4.23	1.250
	1/4P	0.232	0.154	0.767	0.845	34.14	0.657	0.092	23.29	24.01	2.57	0.901
	1P	0.253	0.162	0.747	0.838	37.61	1.149	0.109	12.7	12.96	1.99	0.218

4.7 CO_2 emissions

The lime demand for each mortar mixture and their corresponding CO_2 emissions is presented below. Figure 8 shows that the production of 1 ton of lime results in the emission of 0.597 tons of CO_2 which is released into the atmosphere. It is also previously reported by Flower and Sanjayan (2007) [41] that producing fine aggregates results in the release of 0.0139 tons of CO_2 per ton of aggregate. The CO_2 emissions of hydrated lime mortars incorporating brick dust for 1 ton of material is shown in Figure 8. The results indicate that there is a substantial decrease in the amount of lime required to manufacture 1 ton of mortar with the increased addition of brick dust. The results have also shown that the CO_2 emissions are reduced by 2.86% and 10.21% with the 1/4P and 1P mixes, respectively.

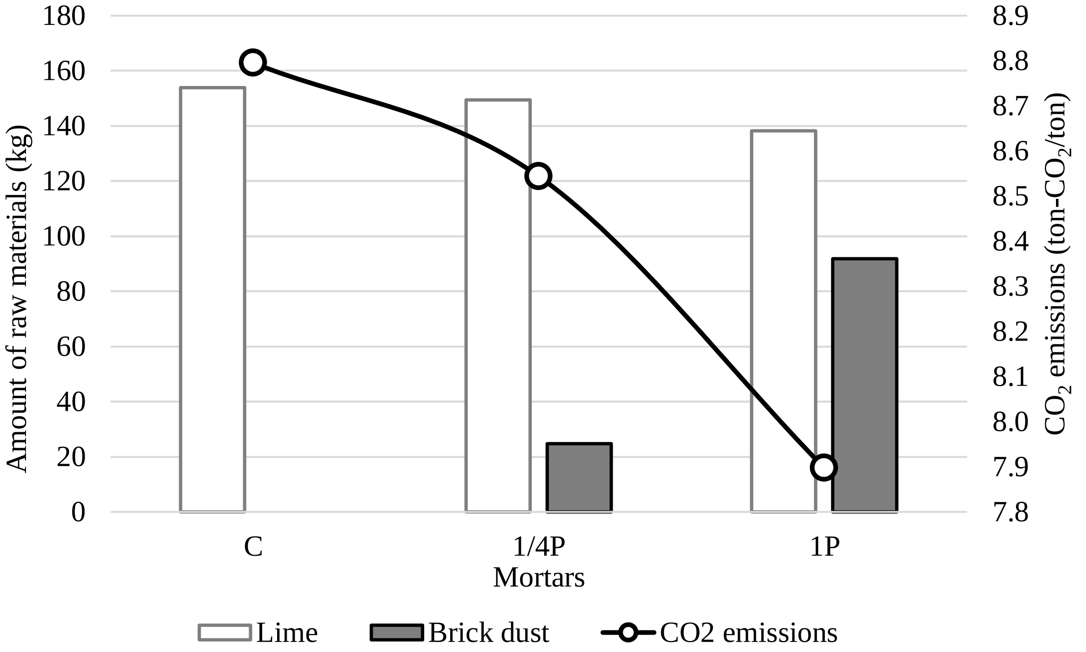


Figure 8. The amount of hydrated lime and brick dust used in making 1 ton of mortars versus the CO_2 emissions (ton-CO_2/ton).

It is interesting to note that because the CO_2 emissions of fine aggregates are much lower than that of the lime binder, reducing the quantity of sand does not have a significant influence. However, adverse effects of the demolition and destruction of natural resources to acquire aggregates for mortar mean the environmental sustainability is often underestimated [42]. Decreasing the volume fraction of fine aggregates through the use of brick dust enables a greater reduction in the demand on natural resources and hence reduces the ecological deprivation.

5. Conclusions

This study demonstrates that the strong water retaining ability of hydrated lime mortars can be utilised through brick dust additions. Using brick dust as a pozzolan enables improvements in the freshly mixed characteristics of lime mortars. The main conclusions are shown below:

- The increased addition of brick dust, used as a pozzolanic material, resulted in a systematic increase in the transfer sorptivity and associated decrease in time to dewater of hydrated lime mortars. The development of more water releasing mortars, due to the additions of brick dust, was the primary reason for the increase in transfer sorptivity. The increased sorptivity of substrate used for dewatering and the decreased fineness of the brick dust, (Case 2 and Case 3) enabled a greater transfer sorptivity of hydrated lime mortars to be achieved. Therefore, incorporation of brick dust in hydrated lime mortars enabled optimisation of the mortar - substrate interface.

- Dewatering results in a substantial decrease in the water: binder ratios. As this influences the fresh and hardened state properties of the resulting mortars it should be taken into consideration in relevant standards.

- The influence of transfer sorptivity and time to dewater in hydrated lime mortars could be simply systematised to a required degree which enables mortar-substrate optimisation in masonry construction to be attained. Comparison of the directly measured and calculated values of t_{dw} showed a difference of 1.05% demonstrating the high precision of the experimental measurements.

- Increasing additions of brick dust resulted in a systematic increase in the water loss attained during dewatering of hydrated lime mortars in all cases examined.

- The setting time of hydrated lime mortars decreased systematically with the addition of brick dust and was attributed to the coarser matrix attained resulting from the pozzolanic additions.
- When hydrated lime mortars are evaluated in terms of their CO_2 emissions a substantial reduction in carbon footprint can be achieved by the incorporation of brick dust. Benefits include a reduction in air pollution associated with the mortar production. Use in mortars is also a greener alternative for the waste management options particularity when compared to the commonly used routes such as landfilling, incineration and recycling that often have adverse effects on human and environmental health.

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