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## Strength and durability performance of stabilised soil block masonry units

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### Summary

This paper presents the findings from laboratory strength and durability tests on stabilised soil blocks (SSBs). SSBs are masonry units formed by compressing a mixture of soil and a stabiliser such as cement and water in a mould. The strength, density and stiffness of SSBs with 5%, 7.5%, 10% and 20% cement by mass were determined at 7, 14 and 28 days. The SSBs were subjected to different curing regimes to determine the best curing method. The ability of the masonry units to resist prevailing rain, wetting and drying cycles, freezing and thawing cycles, and chemical attack are critical if they are to be used in a European climate. The durability of these blocks was evaluated by cyclic freezing/thawing and wetting/drying tests, as well as by determining the shrinkage, sorptivity and absorption characteristics of the blocks. Through this extensive testing program, it was found that SSBs are a suitable and viable technology for use in a European climate.

**Keywords:** Stabilised Soil Blocks (SSBs), Supplementary Cementitious Materials (SCMs) sustainability, durability, brickwork & masonry, strength and testing of materials.

### 1. Introduction

Stabilised soil blocks (SSBs) are masonry units formed by compressing a suitable mixture of soil, cement and water into a mould. SSBs are extensively used in the construction of both structural and non-structural elements in many developing countries throughout the world (e.g. Figure 1). The soil used in SSB construction is usually local in origin, with minimal transport costs incurred. In general, SSBs have a lower environmental impact than alternative masonry technology, such as clay-fired bricks or concrete masonry blocks [1-3]. The most commonly-used stabiliser employed in the manufacture of SSBs is Ordinary Portland Cement (OPC), which is the most expensive and energy-intensive ingredient. The replacement of OPC with alternative waste materials and by-products is a cost-effective process, and their use in SSBs can benefit the environment, especially where disposal to landfill is the alternative.

Provided suitable soil (avoiding topsoil) is used and compression levels are adequate, the compressive strengths typically required for practical SSB applications are readily achievable, although the relative performances of different curing methods has not been widely researched. Durability tends to be the more stringent criterion to meet, and the ability of the soil in the blocks to resist prevailing rain, wetting/drying cycles, freezing/thawing cycles and chemical attack deserves special attention. Although there is ample literature on the application of SSBs in tropical countries, their potential for use in a European climate has not been fully investigated. In this paper, an experimental study of the strength and durability characteristics of SSBs is presented. Several different curing regimes were tried to establish the relative success of each. A range of cement contents was considered to assess its effect on



Figure 1: House built from SSBs.



the performance of blocks, with an overall objective of determining whether SSBs are applicable in a European context. Furthermore, the effect of replacing a percentage of cement with Ground-Granulated Blast-furnace Slag (GGBS) on the strength properties of SSBs was also investigated.

## 2. Literature Review

In addition to satisfying practical considerations such as cost, availability and transport, research has identified certain preferences in soil composition for SSB manufacture. The soil should have a combined silt and clay content (percentage passing the 0,075 mm sieve) no greater than 20% [1] and a particle size distribution bounded by that of a medium gravel and a fine sand is desirable. More specific guidance is given by Pave [4], who provides a table of basic soil requirements for low strength blocks ( $\leq 4$  MPa) and higher strength blocks (4-16 MPa) (see Table 1). The soil used must not contain organic material, which precludes the use of topsoil, or harmful quantities of salts [4]. Organic material biodegrades and uses up water in the process [5], which leaves pores in the finished block that can have a detrimental effect on the block's compressive strength and durability.

The production process has a significant influence on the quality and performance of soil blocks and the curing phase is essential for the blocks' future strength and durability. Kerali and Thomas [6] compared wet compressive strengths of SSBs produced under different curing conditions: (i) open exposure to the air, (ii) open exposure to the air but periodically damped and polythene sheet covered and (iii) fully immersed in water. As expected, those blocks cured rather than dried in open air achieved higher compressive strengths, with curing in a fully saturated environment producing the highest strengths. The average wet compressive strengths at 28 days were 1,13 MPa and 6,85 MPa for SSBs exposed in a dry laboratory at 25°C and those fully immersed in water, respectively. Kerali and Thomas [6] commented that SSBs are often cured in an exposed state, vulnerable to loss of water, and field conditions often resemble "drying" rather than "curing". Due to a lack of appreciation of the importance of the curing stage in soil block production and inappropriate curing methods, low-strength and low-durability blocks have been widely produced in the humid tropics.

In order to achieve strengths of between 4 and 16 MPa, Pave [4] suggests a cement content of between 7 and 16% by volume. Earlier research has shown that the compressive strength and durability of SSBs is improved by compactive effort (density) and increasing cement contents (correlations are generally approximately linear), but reduced by increasing moisture content, increasing plasticity index and increasing clay content [7-10]. Without exception, the mechanical characteristics (tensile and compressive strength) of wet blocks are consistently weaker than dry blocks for identical specimens. Therefore, it is recommended that the wet strength be used to predict the nominal compressive strength of SSBs [4, 8, 11].

Weathering resistance and durability performance is considered satisfactory for general construction if the total reduction in dry mass after 12 cycles of wetting and drying, outlined in Section 3.2, does not exceed 10% [9, 12]. Guettala et al. [13] commented that the weight loss limit of 10% is applicable to regions with an annual rainfall less than 500mm. Alutu and Oghenejob [14] reported that for good quality durable blocks, a maximum allowable total weight loss of 5% is specified.

Table 1: Soil requirement for SSB construction [4].

Soil Range*	% by mass passing 0.075mm sieve		Maximum Plasticity Index	% by volume of cement content	Estimated nominal compressive strength (MPa)
	Min	Max			
A	10	35	15	$\leq 7$	$\leq 4$
B	10	25	10	7 – 30	4 – 16

\* A – low strength blocks (e.g. superstructure walls); B – higher strength blocks (e.g. substructure walls and foundations)

## 3. Testing Programme and Methodology

### 3.1 Materials

In the present study, soil was obtained from an Irish site close to where there are plans to construct a building from SSBs. The material was characterised as per test methods in BS1377-2 [15]. The particle size distribution of the soil indicates a combined clay and silt content of 9,7%, with a plastic



limit of 14% and plasticity index of 6%. The material is therefore relatively compliant with the specification in Table 1. The average specific gravity and pH of the soil were 2,60 and 8,5 respectively.

### 3.2 Experimental Procedures

The air-dried soil is first passed through a 6,3 mm sieve as large lumps of clay soil can lead to non-uniform drying of the blocks and/or serve as stress raiser which is a potential source of cracking [11, 16]. The use of correct mix proportions is crucial to maximising the quality of the SSB product as well as to controlling production costs [17]. In the present study, SSBs stabilised with CEM I cement at contents of 5%, 7,5% and 10% by mass were tested. Soil and cement were manually dry-mixed; the addition of water was followed by wet mixing. Uniform distribution and thorough mixing of the stabiliser is crucial to ensure intimate contact between the stabiliser and the soil particles thereby maximising the impact of the stabiliser within the soil matrix [16, 18]. When soil is mixed with water, it is highly cohesive (unlike concrete) and can form lumps of compacted matter, which must be avoided as these lumps can be difficult to compress [17]. The optimum moisture content (OMC), i.e. the mix moisture content corresponding to its maximum dry density, was determined using the 2.5kg Proctor test according to BS 1377-4:1990 [19] for 0, 5, 7,5 and 10% cement contents by mass. Values of OMC fell in the range 7-10%, showing systematic variation with cement content. Therefore, a water content of 8% was adopted for all subsequent SSB mixes to facilitate direct comparison.

The specimens were prepared in accordance with relevant parts of ASTM D1632 [20] and ASTM D1633 [21]. The mix was compacted in Duriez (120 mm diameter × 250 mm high) cylindrical moulds to a pressure of 10 MPa using a hydraulic controlled ram with a pressure gauge. The stabilised soil specimens were extruded from the mould and cured. As shown in Table 2, different curing regimes were employed to identify the preferred curing method. The wet and dry compressive strengths of specimens were determined at 7, 14, and 28 days in the hydraulic compression testing machine and an extensometer was used to measure strain and deduce the Young's modulus of the specimens up to a stress corresponding to one third of its compressive strength, as outlined in BS EN 13412 [22].

*Table 2: Curing regimes investigated in the current study*

Curing Reference	Curing Method or Procedure
A	Stored under polythene, watered twice daily, and saturated for 24 hours prior to test
B	Stored under polythene, watered twice daily, and oven dried at 60°C for 24 hours prior to test
C	Stored in tank of water and tested
D	Stored in tank of water and oven dried at 60°C for 24 hours prior to test
E	Stored in air in lab and saturation for 24 hours prior to test
F	Stored in air in lab and oven dried at 60°C for 24 hours prior to test

The wetting and drying erosion test procedure is outlined in ASTM D 559 [23], which determines the resistance of SSBs to cyclic water erosion using a wire brush. Test specimens are subjected to twelve 48 hour wetting and drying cycles; with 6 hours immersed in water followed by 42 hours of drying in an oven. After the drying process of each cycle, each surface of the sample is abraded by two complete, firm strokes from a standard wire scratch brush to remove fragments of the material affected by the wetting-drying cycles. The freeze thaw durability test, outlined in ASTM D560 [24] was also conducted where specimens were subject to -23°C for 24 hours and thawed for the next 23 hours after which the surface is scratched with a wire brush. The shrinkage properties of the SSBs were investigated by following the procedures set out in BS 1920-8 [25], where shrinkage readings were recorded for 14 days. Although there are no definitive standard procedures to determine the absorption and sorptivity characteristics for SSBs, a concrete standard was adapted for use with SSBs. The absorptions tests were carried out in accordance with ASTM C642-06 [26] to determine the total absorption value of the SSBs. The sorptivity test, carried out in accordance with ASTM C1585-04 [27], involved measuring the increase in mass of the specimen resulting from the absorption of water as a function of time when only one surface of the specimen was exposed to water. The exposed surface of the specimen was immersed in water and water ingress of the specimen dominated by capillary suction during initial contact with water.



## 4. Results

The results of the initial testing phase, which followed the methodologies described in Section 3, are presented in the following sections. In particular, performance data for the SSBs in terms of strength, density, stiffness and durability are presented. Results presented are an average of 3 values in all cases. Strength and durability tests are on-going at NUI Galway to determine the performance of SSBs with alternative types and amounts of stabilisers.

### 4.1 Wet and Dry Compressive Strength

When carrying out compression tests on SSBs, it is well established that the confinement of specimens by platen restraint increases the apparent strength of the material. In this study, the platen restraint is taken into account to give an unconfined strength rather than a confined strength by multiplying the strength by a correction factor,  $k_a$ , a function of the aspect ratio (height/width) of the specimen. A correction factor,  $k_a$ , of 0,8 was employed for the specimens of aspect ratio 1,8. Characteristic strength (defined as the strength below which not more than 5% of test results fall) was approximately 70% of the average compressive strength.

The average compressive strengths of SSBs subjected to various curing regimes (outlined in Table 2) are presented in Figure 2(a) for specimens having 10% cement content. It is evident from Figure 2 that the availability of moisture for curing (to ensure adequate supply for the cement hydration reactions) is the key to unlocking strength gain potential; a finding which is consistent with results presented by Kerali and Thomas [6] and the International Labour Organisation [28]. In particular, curing conditions C and D, in which the specimens were immersed in a water tank, are more effective than curing conditions A and B, in which specimens were cured under polythene and watered twice daily, although the difference is not that great relative to the amount by which their strengths exceed those stored in the open air (conditions E and F). Blocks stored in air in the laboratory dry out too quickly and, therefore, adequate levels of moisture are not available for the full degree of hydration to occur. It is widely accepted that the dry compressive strength is greater than the wet compressive strength, as seen in Figure 2(b) and later in Figure 3(b). The ratio of wet to dry compressive strength is approximately 0,87, 0,75, and 0,80 for specimens stored under polythene (A and B), immersed in water (C and D), and stored in the open air in the laboratory (E and F), respectively.

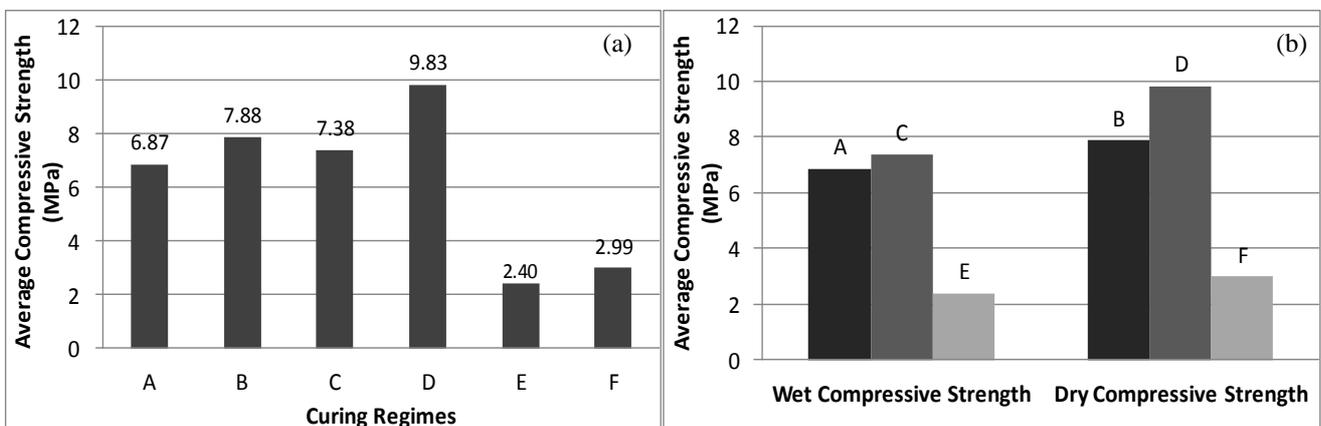


Figure 2: (a) 28 day strengths with 10% cement content for various curing regimes, (b) 28 day wet and dry compressive strengths using 10% cement content.

As expected, the compression strength increased with increasing cement content and age (Figure 3(a) and 3(b)). The reason for this increase in compressive strength is that products of cement hydration fill the pores that exist in the soil. The reduction of pore space improves the rigidity of the soil by forming bonds between the sand particles in the soil, thereby increasing compressive strength and improving durability characteristics of the blocks [29]. An increase in cement content from 5% to 10% resulted in an increase in the 28 day strength from 2,36 MPa to 6,87 MPa. These findings are broadly in agreement with those of Pave [4], who found that the increase of in compressive strength was directly proportional to the cement content of blocks up to a cement content of 10%. It is evident from Figure 3(a) that the increase in compressive strength with age is more dramatic at higher cement contents. In addition, Figure 3(b) shows that the ratio of wet to dry



compressive strength is similar for both 5% and 10% cement content and does not change significantly with time.

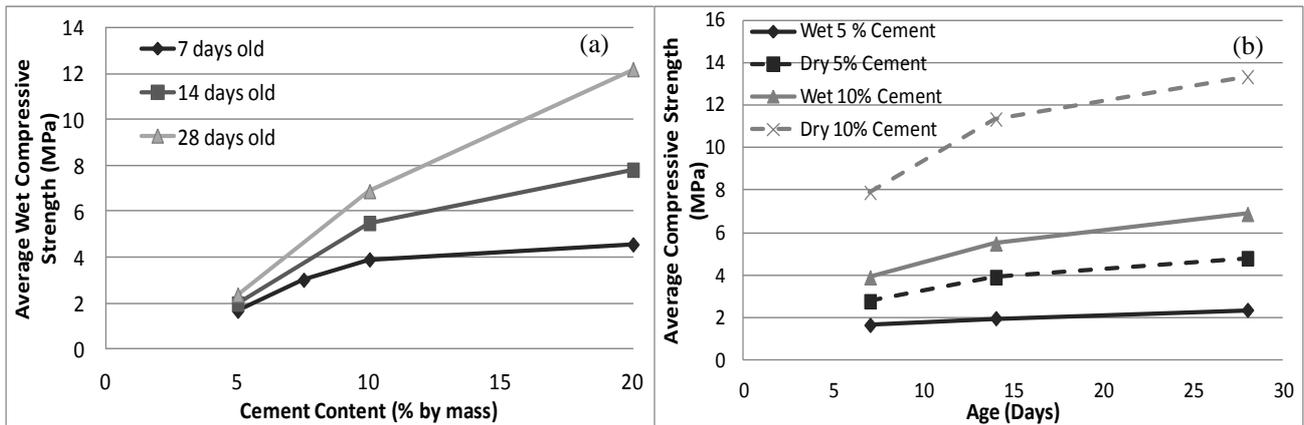


Figure 3: (a) Effect of cement content on compressive strength at the different ages, (b) Development of the wet and dry compressive strength with age.

Replacing half of the cement added with GGBS significantly enhanced the compressive strength, increasing the 7 and 28 day strengths by 66% and 25%, respectively (Figure 4a). This enhancement in strength is due to the fine GGBS particles filling extra voids between the soil particles, packing tightly together producing a dense matrix, which was evident from the increased densities associated with the use of GGBS. Using GGBS or similar waste products as a substitute for cement in SSBs not only reduces cost, but also can benefit the environment.

#### 4.2 Density

Average dry and saturated densities of the SSBs specimens were in the range of 2020 to 2120 kg/m<sup>3</sup> and 2165 to 2220 kg/m<sup>3</sup>, respectively, as shown in Table 3. Values of the coefficient of variation  $C_v$  (i.e. the standard deviation divided by the mean) are also shown. The dry compressive strengths are plotted against dry density in Figure 4(b), with the data for this study annotated with the age in days at the time of testing. It is evident that dry density (and in turn dry compressive strength) is a function of both age and cement content. Data from research by Walker and Stace [12] are also included in Figure 4(b), with the annotation in this case pertaining to a variation in clay content over the range 9-40%. Trendlines from the Walker and Stace [12] data have been extrapolated to higher densities to unify the data in identifying a general tendency for dry compressive strength to increase with dry density.

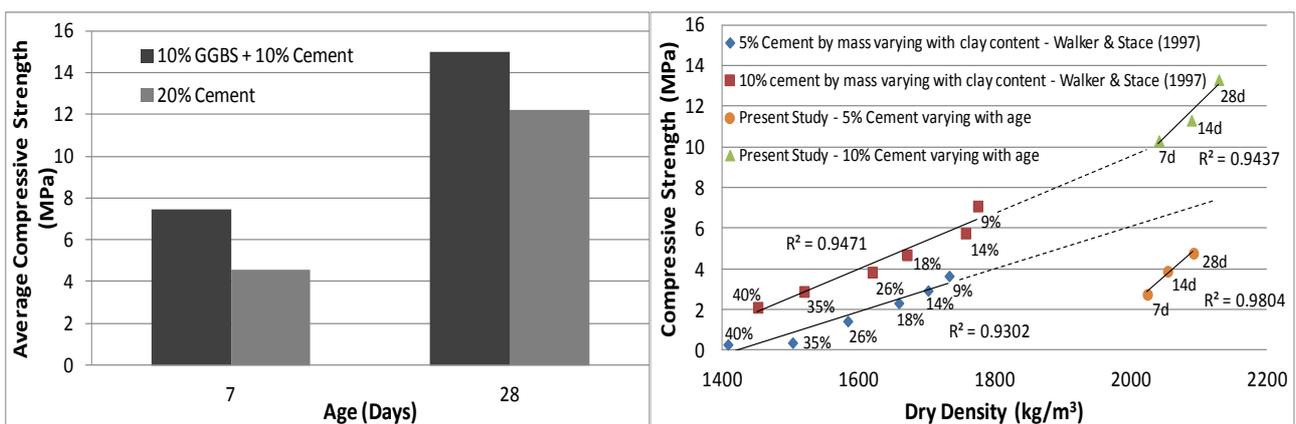


Figure 4: (a) Effect of GGBS on compressive strength, (b) Relationship between density and compressive strength.



Table 3: Average dry and saturated density values of SSBs with varying cement contents and increasing age.

	Dry Density (kg/m <sup>3</sup> )						Saturated density (kg/m <sup>3</sup> )					
	7		14		28		7		14		28	
	Av.	C <sub>v</sub>	Av.	C <sub>v</sub>	Av.	C <sub>v</sub>	Av.	C <sub>v</sub>	Av.	C <sub>v</sub>	Av.	C <sub>v</sub>
<b>5% Cement</b>	2024	0.007	2054	0.005	2092	0.006	2165	0.004	2170	0.011	2180	0.008
<b>10% Cement</b>	2080	0.019	2089	0.002	2112	0.014	2181	0.009	2205	0.004	2213	0.004
<b>20% Cement</b>	--	--	--	--	--	--	2197	0.004	--	--	2210	0.003

### 4.3 Young's Modulus

As part of this study, the Young's modulus was determined from the initial linear part of the stress-strain plot up to one third of the compressive strength, as outlined in BS EN 13412 [22]. The Young's modulus for SSBs was found to lie in the range of 1500 to 12000 MPa for cement contents of 5 to 20% which is in broad agreement with a similar study by Venkatarama Reddy and Gupta [30] as shown in Figure 5a. The values presented by Chan and Low [31] are much lower and cannot be compared easily with the other data as the modulus was determined by joining the origin to the peak strength of the plot. As a comparison, for concrete with a cement content of 16,5% by dry mass, the Young's modulus was found to lie in the range 38000 to 43000 MPa. Although there is some scatter, Figure 5(a) shows that there is a reasonable correlation between Young's modulus (E) and average dry compressive strength (C) for SSBs, applicable over the range of data plotted in Figure 5(a), which can be expressed as:

$$E = 706C + 573 \quad (1)$$

where the units of E and C are MPa. Young's modulus increases with age and increasing cement/stabiliser content, as is the case for concrete.

### 4.4 Durability

Preliminary results for durability tests outlined in Section 3 are presented in Figure 5(b), and span a greater range of stabiliser contents than other data also included in this figure. The total loss in mass due to scratching the surface of the specimens at each wetting/drying cycle decreases with increase in cement content. Hence, erosion resistance is improved with increase in stabiliser content. In addition, previous studies [13] have suggested that cement stabilisation is more effective than lime stabilisation (Figure 5(b)). For the present study, increasing the cement content from 5 to 10% reduced the percentage loss in mass due to the cyclic wetting and drying test from 2.6% to 0.4%. A similar trend was found in the freeze-thaw tests, with the percentage loss in dry mass after 12 cycles of freeze-thaw action decreasing with increasing stabiliser content.

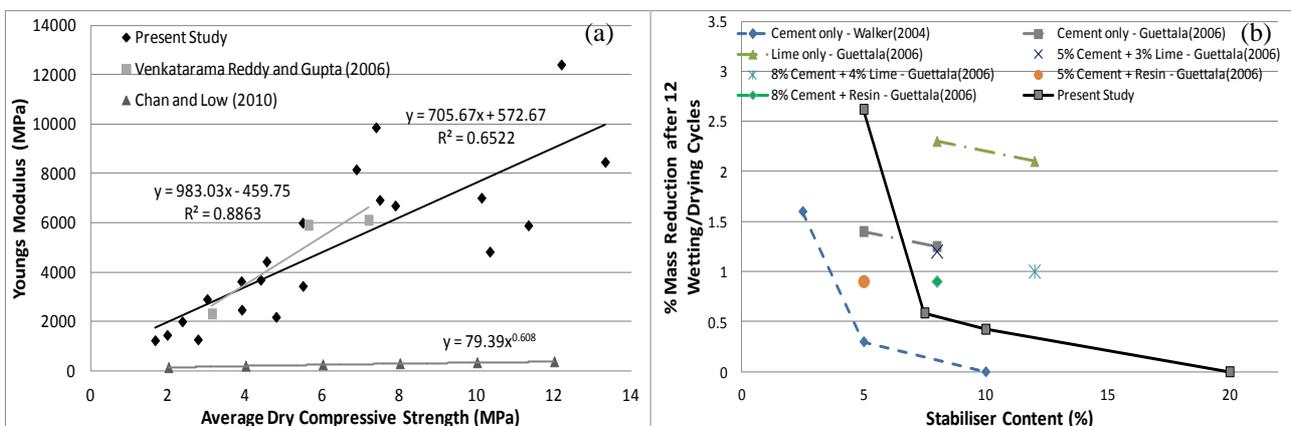


Figure 5: (a) Relationship between Young's Modulus and average dry compressive strength between 2 and 14MPa, (b) Effect of stabiliser content on mass reduction of SSBs after wetting/drying cycles.



Further evidence of cement (utilised at 9% of the overall mass of the SSB) acting as an efficient stabiliser in SSBs, is shown in Figure 6, where after 14 days, the shrinkage equilibrates at almost 0.1%. The present study found that the total absorption of the specimens were in the range of 9,7 to 10,5% of the dry mass. In terms of the sorptivity test, the initial rate of absorption was in the range 0,03 to 0,13  $\text{mm/s}^{1/2}$  while the final rate of absorption was in the range 0,0021 to 0,0169  $\text{mm/s}^{1/2}$ . In comparison to concrete, which was also investigated as part of this study, total absorption was in the range of 4 to 6%, while for sorptivity results, the average initial and final rate of absorption was 0,002  $\text{mm/s}^{1/2}$  and 0,0009  $\text{mm/s}^{1/2}$  respectively.

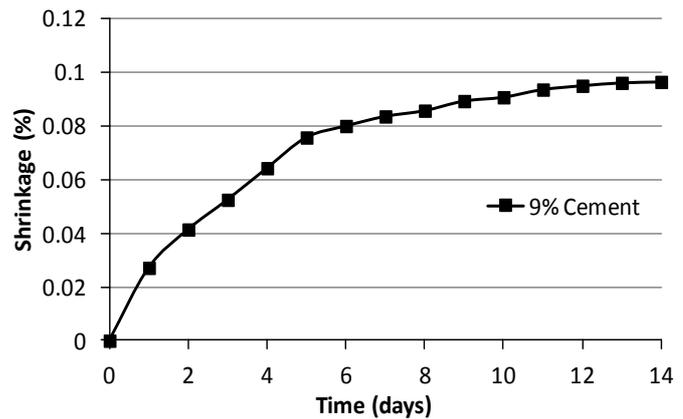


Figure 6: Shrinkage characteristics of SSB with 9% cement.

## 5. Conclusions and Discussions

Tests carried out by the authors have shown promising results in terms of both strength and durability for the application of SSBs in the European climate. The importance of adequate curing to strength development of SSBs has been identified. In most codes, the minimum strength for masonry is in the range of 2,0MPa to 2,8MPa. Apart from some of SSBs with 5% cement content, all other blocks had both wet and dry compressive strengths in excess of the minimum strength requirements for masonry in most codes, confirming their suitability for two or three storey buildings. Replacing half of the cement added with GGBS significantly enhanced the compressive strength, increasing the 7 and 28 day strengths by 66% and 25%, respectively. In terms of the durability performance of the blocks, the total reduction in dry mass due to the cyclic wetting and drying test with abrasion is well within both the 5% and 10% recommended limits. Finally, absorption and sorptivity results compare favourably with concrete. Further tests are ongoing at NUI Galway as part of this project.

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