

# Towards Sustainable Composite Building Material: Integrating Lime with Slag for reduced Mortar Thermal Conductivity

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**Abstract**—Lime Based Mortar became very popular due to its outstanding features of flexibility, permeability and low carbon emissions. However, lime's characteristic delayed setting, late hardening time, low mechanical strength, among others, overshadowed significance of its outstanding features, thereby putting its overall use into decline, particularly, with the 19th century Portland cement discovery. This study therefore aims at reviving lime usage through a sustainable lime composite, by integrating an industrial by-product, Ground Granulated Blast Furnace Slag (slag) with lime, in form of lime-slag mortar, with a view to reducing the mortar thermal conductivity. The methodology involved mortars with the same Binder/Aggregate (B/A) mix ratio (1:3) using five separate volumetric compositions of 'slag-lime' binders (i.e. 1:1, 1:2, 1:3, 2:1 and 3:1). Physical properties of the mortars involving their Water/Binder (W/B) ratios, Air Contents and Bulk Densities were recorded. Comparative evaluations of the compositions in hardened state, involving thermal conductivities were carried out at specific intervals through a twelve-month curing period. These were partly monitored through assessments of the composites' microstructural behaviours over a six-month period. Results of the investigation show that addition of slag to mortars facilitate slightly larger pores with increased porosities. However, these effects are minimal (i.e. from 23.42% to 25.37% porosity) when slag content is at equal volumetric content with lime. A general reduction (not in a linear trend) in the thermal conductivities of the mortar with increasing slag content was observed, cumulating in 25% decrease in the composites having thrice volumetric content of slag, relative to lime. Composite's reduced thermal conductivity would be of utmost importance in construction especially, where material's limited thermal conductivity property is of utmost importance.

**Index Terms**—Carbon Emissions, Climate Change, E-value, Flexibility, Lime, Mortars, Thermal Conductivity.

## I. INTRODUCTION

In the recent years, rapid urbanization had played a major role in degrading the urban environment through construction processes. However, as construction processes facilitate infrastructure developments, they equally constitute major sources of carbon dioxide production and energy consumption [1], [2]. Climate change and global warming are associated with CO<sub>2</sub> emission and Green House Gases (GHG) for which the current global level needs to be cut by about 50% by 2050 [3]. Studies show that buildings account for 30-40% of the world's energy

consumption [4], [5]. While a considerable part of this energy is commonly used to control internal microclimate conditions, other part is used to extract raw materials, transport them, make building components and, finally, to dispose of them. Therefore, interventions in this important productive sector through promotion of low-impact building techniques and materials should be encouraged, to address the global challenge [6]-[8]. Thus, efforts must be directed at exploring alternative methods, and search for new technical standards, towards development of sustainable building materials [9]-[11]. Those are materials which reduce the use of resources, minimize the environmental impacts, pose no or low human health risks, assist with sustainable site design strategies and materials with sustainable social, environmental and corporate policies. One major step in this direction is revival of a partially abandoned age-long environmentally sustainable building material, lime mortar.

Lime mortar is obtained from a proportional mixture of lime, sand and water constitutes. It is an age-long building material that is slow to harden but allows movements within the mortar joints, without compromising its structural stability [12]-[14]. It exhibits great permeability and breathability, and characterised with less carbon dioxide emissions during manufacture (20% less than that of cement) and subsequent adsorption during carbonation [15]-[20]. However, Lime Mortar is associated with exaggeratedly long setting and hardening periods, low internal cohesion, relatively low mechanical strengths, some volumetric changes and a high water absorption capacity through capillarity, among others [21]-[26]. These shortcomings, coupled with the absence of rigorous studies about the mortar's characteristics and properties (among others) resulted in its relative disuse. This study therefore sought to revive this age-long sustainable building material through integration of an industrial by-product, 'Ground Granulated Blast Furnace Slag' (slag), in form of a composite material, by formulating lime based blended mortars with varying proportions of slag.

Slag is a granular glassy amorphous waste material, formed as a by-product from production of steel and iron. [27], [28]. It is widely used as a construction material due to its latent cementitious property when mixing with lime, alkali-hydroxides or Portland cement [29]-[33]. In some cases, it has been used as a successful replacement material for Portland cement [34], [35]. Recent advancements in Slag utilisation, as an alternative binding material in concrete production indicate its possible blend with lime, for improved lime mortar performance [36], [37]. Utilisation of

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slag in this area has significant environmental benefits (with less CO<sub>2</sub> emission to the atmosphere during this process) as its production requires less energy than the production of Portland cement [37]. Also, the requirement to recycle industrial wastes and by-products, rather than landfilling this potentially valuable material (slag) makes its integration acceptable [38]-[40]. Hence, its potential re-use as a constituent in blended lime mortar would solve the associated problem related to its disposal [37], [40], [41]. Consequently, in line with this research project, using the binders' varying compositions, effects of lime partial substitution by slag in the evolving lime-slag mortars could be explored. This would attempt to synergise individual qualities of the constituents as the resulting composite would be characterized by faster setting and hardening (than lime), with overall improvements on their applications [42]-[44]. Through this effort, growing interests in reviving sustainable lime based materials particularly mortar, would be enhanced.

## II. EXPERIMENTAL PROCEDURE

### A. Materials and Mortar Preparation

Materials used for this study were commercially available. Natural Hydraulic Lime of the class NHL-5.0 (St Astiers, UK), characterised with the lime's highest compressive strength (based on the 28-day test in accordance with [45], [46]) was adopted. Selection of the lime class was based on its relatively short setting time for optimal strength yield, its availability, ease of handling and

the need to maximise lime performance behaviour [2], [47], [48]. 90% of the lime particles have sizes below 91.88 μm (by volume), with main equivalent diameter of 33.99 μm (by volume) and 10.19 μm (by Surface Area) as shown in the average Particle Size Distribution of Table I. Lime's chemical compositions (by elements) determined by Energy Dispersive Spectrometry are given in Table II. Ground granulated blast furnace slag (slag) for this investigation was obtained from 'Hanson Cement', United Kingdom. 90% of its particles have sizes below 49.78 μm (by volume) with main equivalent diameter of 25.50 μm (by volume) and 11.20 μm (by Surface Area) as shown in the average Particle Size Distribution of Table I. Slag's chemical compositions (by elements) are given in Table II. Siliceous fine kiln dried sand, obtained from Fife Silica Sands (a division of Patersons of Greenoackhill Ltd, United Kingdom) constituted the aggregates. The aggregate was passed through a sieve analysis in accordance with the requirements of [49], and the particle size distributions in compliance with [50]. Results of Standard Test Method for Sieve Analysis of Fine Aggregates are shown in Fig. 1. The sand had Particle Size Distribution of 0-2 mm (i.e. 0.05 mm < Ø < 2 mm). The suitability of the gradation of the tested aggregate as a mortar aggregate was evaluated by comparing the obtained gradation curve with the suggested particle size ranges (according to [51]) Standard Specification for mortar Aggregates). The results indicate that the sand has a suitable grading but with slightly lower particle sizes.

TABLE I: PARTICLE SIZE DIAMETERS OF THE TESTED MATERIALS

Parameters	Particle	Lime	d(v,0.5)	d(v,0.1)	Mode	d(v,0.9)**	D[4,3] (main equivalent diameter by volume)	D[3,2](main equivalent diameter by Surface Area)
Specified Diameter(μm)			10.78	5.28	6.50	91.88	33.99	10.19
			19.60	5.54	15.17	49.78	25.50	11.20

TABLE II: CHEMICAL COMPOSITION OF THE MATERIALS

Material	Elemental Chemical Composition of the materials (by % weight of the dry specimen)											
	Ca	O	Si	C	Sb	Al	Fe	Mg	S	K	Na	Ti
Lime	47.6	37.6	5.2	4.4	3.3	0.7	0.5	0.5	0.2	-	-	-
Slag	26.5	39.6	13.0	9.3	-	5.5	-	4.4	1.0	0.4	0.3	-
Sand	0.2	53.5	43.0	-	-	1.6	0.4	-	-	1.1	-	0.2

The mortars were prepared in accordance with the standard, [52]. The binder-aggregate (B/A) ratio was maintained at 1:3 by volume, chosen from the commonest dosage reported in the literature [26], [48], [53], [54]. Volume proportions of components were converted to weights, to avoid measurement imprecision during batching processes [55]. Mortar mixtures were prepared using the correct amount of water required to obtain adopted workability of 145±5 mm (measured by the flow table test [45] as [46] specifies a flow value of '140-200 mm' for 'plastic mortar'. Arising from visual and physical assessments of the mixes during the trial experimentation however, a flow value of 140 – 150mm (i.e. 145+5mm) was adopted. As observed, either higher or lower value tends towards stiffness or fluidity respectively. This was determined in accordance with [46]. Using the stated B/A ratio (i.e. 1:3), each mortar formulation was prepared with progressively increasing/decreasing slag contents as indicated in Table III.

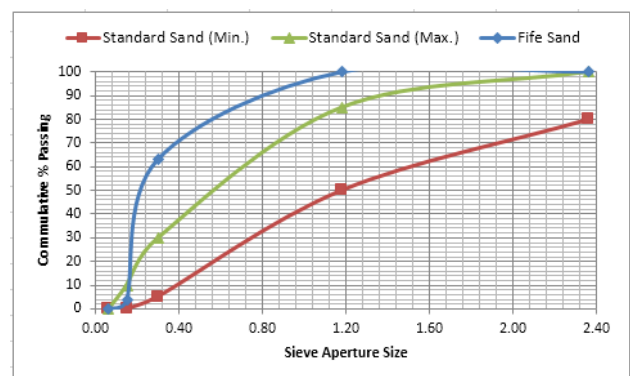


Fig. 1. Grain size distribution of the aggregate

TABLE III: LIME-SLAG MORTARS' COMPOSITIONS BY MATERIALS

Slag Contents	Mortar Reference I.D. (Slag Content %)	Volumetric Ratio (L-Sl-Sd)	Lime (L): Volume (Volume in 'ml'/ mass in 'g')	Slag (Sl): Volume (Volume in 'ml'/ mass in 'g')	Sand (Sd): Volume (Volume in 'ml'/ mass in 'g')
0%	L13 (0%)	1-0-3	1 (1700/1172)	0(0)	3 (4350/6444)
25%	LS31 (25%)	3-1-12	3 (770/528)	1 (420/363)	12 (4350/6444)
33%	LS21 (33%)	2-1-9	2 (665/458)	1 (550/472)	9 (4240/6283)
50%	LS11 (50%)	1-1-6	1 (850/586)	1 (850/725)	6 (4350/6444)
66%	LS12 (66%)	1-2-9	1 (510/352)	2 (1000/870)	9 (3920/5800)
75%	LS13 (75%)	1-3-12	1 (260/176)	3 (1260/1088)	12 (4350/6444)

Mixing was done in the laboratory mixer of 30 litres maximum capacity. The mixing procedure was performed in a number of stages: Aggregates were placed first, followed by other dry materials (i.e. lime and slag, pre-mixed earlier, where applicable) and these were blended consistently for 60 seconds, ensuring batch colour consistency prior to gradually adding water. Water was added slowly during 30 seconds and mixing continued for another 30 seconds. Mixing was stopped for 90 seconds as mortar adhering to the wall and bottom of the mixer bowl was scraped off. Mixing then resumed to obtain consistent mixture. The entire mixing period lasted about 5minutes.

For every mortar mix, minimum of three prismatic specimens of 40×40×160 mm were prepared, the average value of which represented the 'actual value' for consideration during the specimen evaluations thereafter (i.e. for microstructural analysis). The specimens were compacted with a vibration table after mould filling in prismatic casts (according to [52], removed from the moulds 2 days later and left to cure at the laboratory ambient conditions of 21+4°C (temperature) and 40+5% (relative humidity), until the test dates of 1 and 6 months. Also, for determination of thermal conductivity of the mixes, second set of specimens was cast in open ends rigid plastic tubes of 50 mm diameter and 24 mm thickness/height. This set of specimens was also subjected to the same laboratory conditions until the same test dates of 1, 3, 9 and 12 months.

### B. Analytical methodology

Microstructural characteristics of the mortar samples were evaluated in terms of the total porosity (in %), median pore diameter (by volume in nm), bulk density and pore size distribution, using Mercury Intrusion Porosimetry (MIP) technique. This was achieved with AutoPore IV 9500 by Micrometrics (with pressure range up to 60000 psi). Samples of approximately 1.5g extracted from the core of the crushed prisms were used to carry out the test. Under short term loading and at a relatively low rate of load application (approximately 2mm/min), the chance of micro crack propagation is minimum [54]. These samples were obtained at the test ages of one and six months, and dried in an oven at temperature of 75 ± 1 °C for 24 hours before the

test. The thermal conductivity of the specimen was determined in accordance with [56] using 'LaserComp FOX 50 Heat Flow Meter' machine via an acquisition software and data processing. This is a microprocessor-based instrument for testing materials in the conductivity range of 0.1 W/mK to 10 W/mK and the temperature range of 0 – 190°C. It is configured with thin film heat flux transducers, digital thickness measurements, responsive temperature control and an integrated contact-resistance correction. The output values are generated on the screen. In addition, some preliminary material testing was also carried out as follows:

- Application of Scanning Electron Microscopy/Energy Dispersive X-ray Spectrometry using 'Carl Zeiss EVO 50' Scanning Electron Microscope was employed for examination and analysis of the microstructure, morphology and chemical composition characterizations of the experimental materials (Lime and slag);
- Application of Laser Diffractometry Xmastersize with air dispersion was adopted for determination of the Pore Size Distribution of the tested materials (Lime and slag);
- Consistency of fresh mortars was examined using the flow table test in accordance with [57];
- Air content of fresh mortars was determined by the pressure method using Air Entrainment Meter in accordance with [58];

## III. RESULTS AND DISCUSSION

### A. Physical Characteristics

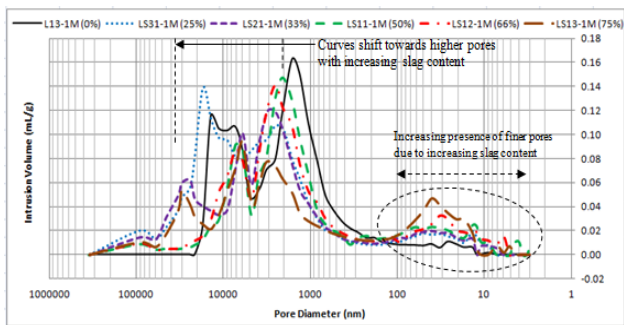
Table IV shows the results of the W/B ratios, Air Contents and Bulk Densities obtained for lime, and lime-slag mortars using varying binders' contents. For lime only (0% slag content, i.e. L13), Table IV indicates a W/B ratio of 1.53, Air Contents of 6.4 and Bulk Density of 1.93g/ml. Addition of slag content below 50% of the binders resulted in higher water demand. This may be attributed to the higher lime content and its high water demand. However, at equal lime-slag content (LS11), a reduction in W/B ratio was observed, due to reduced lime content. Further slag addition (above 50%) resulted in subsequent rising water demand relative to LS11. This may be a consequence of higher slag content and hence higher degree of hydration relative to hydraulic lime hydration and carbonation [60], [61]. With progressive addition of slag to the mortar, there is a general increase in the air contents for the composites. This may be related to slag's higher degree of hydration and subsequent formation of air spaces arising from consumption of initial kneading water. Progressive addition of slag to the mortar increased the bulk densities, though not in a linear trend. These increments may be related to the rising water demand to obtain pastes of same consistency and subsequent deposition of the hydration products. Hence, the higher the slag content, the higher the resulting bulk density.

TABLE IV: LIME-SLAG MORTARS' COMPOSITIONS BY MATERIALS AND WATER/BINDER RATIOS

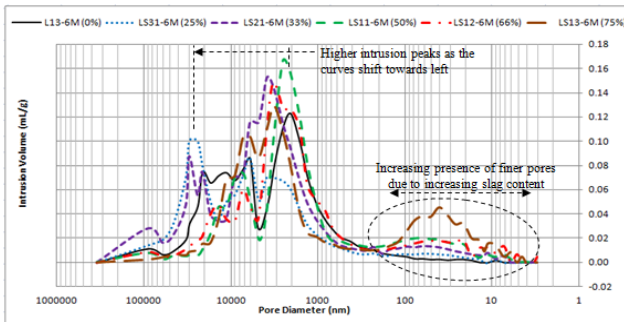
Slag Contents	Mortar Reference I.D.	Water/Binder Ratio	Air Content (%)	Bulk Density (g/ml)
0%	L13	1.53	6.4	1.93
25%	LS31	2.05	6.1	1.98
33%	LS21	1.91	6.5	2.01
50%	LS11	1.29	9.2	2.05
66%	LS12	1.35	8.4	2.05
75%	LS13	1.42	8.3	2.06

B. Microstructural Characteristics

Fig. 2(a) and (b) show the Pore Size Distribution (PSD) curves obtained by Mercury Intrusion Porosimetry (MIP) for the six different composites at 1 and 6 months of curing. For lime only, at 1 month of curing, the graph indicates a bimodal PSD with predominant sizes between (0.5 - 5 μm) and (5 - 20 μm), as shown in Fig. 2(a).



(a). At 1-month curing



(b). At 6-month curing

Fig. 2. Pore size distribution of lime mortars with increasing slag contents

In this case, the mortar exhibits both gel pore (i.e. 1 nm - 3 μm) and substantial proportion of capillary pores (i.e. 3 - 30 μm). These large pores result from loss of excess unbound kneading water due to strong water-retaining characteristic of lime and its associated slow carbonation process. After 6 months, in spite of the continuous hydration and carbonation processes, the median pore diameter increased (from 2.16 to 3.96 μm) (Table V), indicating more presence of larger pores (i.e. between 0.5 μm and 40 μm) with the shift of the PSD curves to the left (Fig. 2(b)).

TABLE V: EXTRACTED MERCURY INTRUSION POROSIMETRY DATA FOR LIME-SLAG MORTARS CONTAINING INCREASING SLAG CONTENTS

Specimen Reference I.D.	Curing Period	Median Pore Diameter (Volume) [nm]	Bulk Density at 0.52 psia [g/mL]	Porosity [%]
L13 (0%)	1 Month	2163.6	1.75	27.77
	6 Months	3955.0	1.72	23.42
LS31 (25%)	1 Month	5762.2	1.74	31.57
	6 Months	8599.5	1.79	23.71
LS21 (33%)	1 Month	4358.6	1.73	29.12
	6 Months	4840.3	1.75	29.87
LS11 (50%)	1 Month	2183.6	1.83	27.17
	6 Months	2495.2	1.85	25.37
LS12 (66%)	1 Month	2522.0	1.81	27.64
	6 Months	2678.9	1.88	27.15
LS13 (75%)	1 Month	3027.1	1.86	24.85
	6 Months	3576.8	1.82	28.84

However, a reduction is observed in the total pore volume (i.e. from 27.77 to 23.42%), which indicates filling of some of the capillary voids due to deposition of the hydration and carbonation products (from hydraulic lime). The bulk density was reduced (from 1.75 to 1.72 g/ml) due to evaporation of excess kneading water and subsequent associated drying shrinkage.

Progressive addition of slag to the mortar resulted in similar patterns of PSD relative to lime mortar (i.e. bimodal distributions, between 0.6 - 6.5 μm, and 5 - 10.5 μm pore ranges) at 1-month curing. The only exception is LS13 with a wide distribution across, having additional identifiable pore sizes at both 13 nm and 40 μm pore diameters (Fig. 2(a)). Porosities of the composites also reduced with LS13 recording the highest value of 11% reduction (compared with lime only). At 6 months, the bimodal patterns of the curves still remained, with distinctive two pore size ranges at 1 - 4 μm and 4.5 - 10.5 μm (Fig. 2(b)). Progressive hydrations in the composites were also noticed with higher bulk densities (Table V). However, all mortars had their individual median pore diameters increased. This could be a consequence of fine cracks formation due to autogenous deformation [29], [61]. Composite with the highest slag content (LS13) had a dominance of large pores with 6 μm pore size diameter which may have a negative impact on compressive strength. Compared to lime mortar, porosities of the composites are higher at 6 months. This probably accounts for more CO<sub>2</sub> penetration for carbonation reactions. The above results indicate progressive addition of slag to mortars could facilitate slightly larger pores with increased porosity. These effects are however minimal (i.e. from 23.42% to 25.37% porosity) when slag content is at equal volumetric content with lime.

C. Mortar Thermal Conductivity

Results of the thermal conductivity measurements for cured lime and lime-slag composites batched using varying binders' contents are largely influenced by the microstructural behaviour of the composites as analysed above. These results are as graphically illustrated in Fig. 3. For lime only (i.e. L13), the graph indicates thermal conductivity values of 0.4442 W/mK and 0.7913 W/mK for 1-month and 12-month curings respectively.

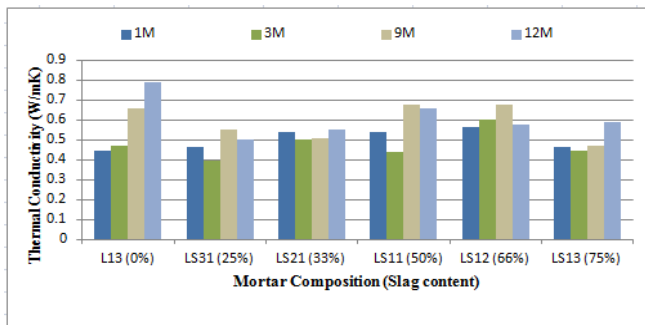


Fig. 3. Thermal Conductivity for Lime Mortars with increasing slag contents

Progressive addition of slag to the mortar resulted in reduced thermal conductivity of the composites, though with some inconsistencies in the pattern. In particular, the composite with the highest slag content (75% slag content i.e. LS13) exhibited a decrease of about 25% in thermal conductivity (relative to lime mortars - L13) at 12 months. As indicated in the microstructural characteristics earlier, all mortars had their individual median pore diameters increased with increasing slag contents. This could be a consequence of fine cracks formation due to autogenous deformation [29], [61]. Composite with the highest slag content (LS13) had a dominance of large pores with 6  $\mu\text{m}$  pore size diameter. Compared to lime mortar, porosities of the composites are higher at 6 months probably for more CO<sub>2</sub> penetration for carbonation reactions. Thus, the observed reductions in the thermal conductivities may be related to higher degree of hydration for slag, and mortar self-desiccation, which culminated in higher porosities with possible formation of microcracks in the mortars' microstructures. These (pores and microcracks) may therefore create some vacuums which otherwise inhibit thermal conductivity in the mortars. In this case, composite with the highest slag content (LS13) exhibits lowest thermal conductivity characteristic, and may prove very useful in certain specific areas of building construction.

#### IV. CONCLUSION

The study reflects thermal conductivity performance assessments of lime mortar with progressive addition of slag. It could be inferred therefrom, that slag has significant impacts on the thermal conductivity of lime mortar. These impacts are a reflection of the microstructural behaviour of the composites over time. Relative to the specific purposes, lime features may be enhanced in this regard, and its revival may be encouraged in form of lime-slag composites. Thus, the study constitutes an attempt to promote low-impact building materials through integration of an industrial by-product, Ground Granulated Blast Furnace Slag, with a partially abandoned age-long environmentally sustainable building material, lime, for improved and sustainable building material formulation

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