The Potential of Utilising Industrial Waste as Lightweight Building Components– A Preliminary Investigation

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Abstract

The main objective of this research was to investigate the potential of utilizing Pulverised Fual Ash (PFA), an industrial by-products, waste aluminium and waste gypsum from plasterboard, with blended binders Lime-GGBS (Ground Granulated Blastfurnace Slag) or PC (Portland Cement)–GGBS, into the development of lightweight building components. Powder aluminium was used to produce hydrogen for lightweight effects. The engineering properties of unconfined compressive strength (UCS) was investigated. Concrete cubes of control systems (PFA+binders), unfoamed systems (PFA+ binders+gypsum), foamed systems (PFA+binders+Aluminium) and combined systems (PFA+binders+Aluminium and Gypsum) were made under controlled laboratory conditions and cured for 7 and 28 days before testing for UCS. The results obtained showed that the control and unfoamed systems recorded higher strength values than the foamed and combined systems. Strength values are linearly related to density of foamed concrete. There are technological, economic as well as environmental advantages of utilizing PFA and similar industrial by-products, in the development of foamed lightweight building components.

Keywords: Fly ash, Slag, Strength, Foamed concrete

1. Introduction

The construction industry is under increasing pressure to become sustainable. Sustainable building is an essential aspect of widening efforts to achieve ecologically responsible world. A building that is sustainable must, by nature, should be constructed using locally sustainable materials as much as is practicable. The materials should be used without any adverse effects on the environment. The market and production of both dense and lightweight concrete blocks is already well established in the UK and many parts of the world. However, the utilization of waste in these two types of bricks is only starting to feature seriously in the market. This is however heavily dependent on the technological, economic and environmental successes of individual components, and the degree of willingness for sustainable development in the markets within the communities.

Many construction clients, designers and contractors are taking a more environmentally responsible approach to the selection and specification of materials. Therefore, the challenge for the researcher is to identify new and innovative practices, technologies and working practices which satisfy the need for a sustainable building industry. The use of recycled materials towards the development of green building products is a key component towards sustainability.

In the building industry, emphasis has mainly been on the utilization of waste in dense building blocks. So far little or no research has been geared towards the use of waste and or industrial by-products in lightweight building components.

This research investigates the potential of utilising PFA, a waste from coal-fired power stations in a new area of application, using some of the already successful material blends (Lime-GGBS, PC-GGBS) (Higgins *el.al.,* 1998;Oti *et.al.,* 2008), in lightweight technology. Other new wastes will also be introduced such as waste aluminium and waste gypsum from waste plasterboard. The latter is increasingly becoming an important demolition waste.

2. Experimental Procedures

2.1 Materials

The materials used in this investigation consisted of PFA as the main target material, Lime (CaO), Portland Cement (PC), and Ground Granulated Blastfurnace Slag (GGBS) as binders (blended to lime-GGBS (70:30 and 50:50 ratios) and PC-GGBS (60:40 and 40:60 ratios), aluminium (Al) powder and waste gypsum as an activator.

2.2 Mix Design Composition

In order to identify the best mixture for best compressive strength values, four systems were established i) Control ii) Unfoamed, iii) Foamed and iv) Combined systems. Several pre-mixtures were investigated with PFA+binders to determine the best w/b ratio for good workability. The subsequent mix compositions are tabulated in Table 1. The technology of aerated concrete commonly involves applying aluminium powder as an agent to produce hydrogen gas in the fresh cement paste.

Dry materials (Pfa+binder+Al+Gypsum), enough for 2 nos. of 50mm x 50mm test cubes were weighed individually and mixed thoroughly in a metal container. A pre-calculated amount of water was added into the mix and mixing continued using palette knives until a homogenous mix was achieved. When the mix (low-viscosity water based slurry) was consistent, a pre-calculated amount of aluminium powder was added. A total mixing time of 2-4 min is typical (Lindon, 2001), but the aluminium powder is dispersed for only 10-20 sec before the slurry is discharged from the mixer into oiled moulds. After casting, small bubbles of hydrogen (0.2-2mm) form within the slurry. The volume of hydrogen gas generated within the mix is proportional to the amount of aluminium powder used. Therefore, a certain quantity of aluminium powder is necessary in order to achieve the required strength and specified density. Too little aluminium powder will result in a mix of high density, whereas too much aluminium gives a mix of low density (Lindon, 2001). The cubes were allowed to set in the mould for 24 hours before being de-moulded, wrapped in cling film and cured for 7 and 28 days, before testing for UCS. Two samples per mix were tested and the mean strength value taken. The UCS tests were conducted as described in British Standard (BS 1377-7:1990). Figure 1 shows the internal structure of foamed PFA cubes.

3 Results

3.1 Control system

In the control system, Lime-GGBS and PC-GGBS were used to investigate their effect on strength on the waste material from coal-fired power station (PFA) without the effect of either aluminium or gypsum, as illustrated in Figures 2(a) and (b). In the PFA+lime-GGBS system, specimens made using both binding ratios (50:50 and 70:30) showed a marked improvement in strength with increasing curing period from 7 to 28 days. The 50:50 binder ratio gave a higher strength value at 28 days (5.18 N/mm^2) compared with 70:30 binders (4.48 N/mm^2) (Fig. 2(a)). In the PFA+PC-GGBS system, the overall strength values are higher compared with the lime-GGBS system. With the 40:60 binding ratio, there is an improvement in strength with prolonged curing period to 28 days with an average value of 8.0 N/mm^2. The highest strength value is 8.80 N/mm^2 with a w/b of 1.8 (Fig. 2(b)). Increasing the level of PC in the binder to 60:40 PC-GGBS ratio reduces strength values of all specimens both at 7 and 28 days of curing. The use of more GGBS relative to the PC is a good outcome for sustainability.

3.2 Unfoamed system

In unfoamed system, gypsum was introduced at 5wt% and 15wt% without any addition of aluminium. Figures 3(a) and (b) show the compressive strength values of PFA+Lime-GGBS at 50:50 ratio and 70:30 ratios at increasing curing periods of 7 and 28 days.

At 7 days of curing period (Fig. 3(a)), increased gypsum content from 0wt% to 15wt% increased the UCS value of the cubes with all three w/b ratios. The highest UCS value of 5.16 N/mm^2 was recorded with w/b=2.2. Prolonged curing to 28 days, showed significant strength development in the system, with the addition of 15wt% gypsum marked the highest UCS value at about 10 N/mm^2 with both w/b=2.2 and w/b=2.3.

Increasing lime content in the blended binder ratio from 50:50 to 70:30 showed no strength improvement at 7 days curing, at all gypsum contents (Fig. 3(b)). At 28 days of curing and with 15wt% gypsum content, the UCS value recorded was about 10 N/mm^2 with w/b=2.2 and w/b=2.3. Thus, apparently, there is no benefit in increasing lime content in the blended lime-GGBS binder.

Figures 4(a) and (b) illustrate the compressive strength of PFA+PC-GGBS at PC-GGBS blending ratios of 40:60 and 60:40. At 7 days curing period (Fig. 4(a)), the UCS values of most specimens were recorded above 4 N/mm^2 at all w/b ratios and with increased gypsum content from 0wt% to 15wt%. These UCS values were higher than when using the lime-GGBS binder. Prolonged curing period to 28 days (Fig. 4(b)) showed remarkable strength development where most of the samples recorded UCS values about 8 N/mm^2 which is double the strength at 7 days. The highest strength value was recorded with 15wt% gypsum content and w/b=1.8.

When the ratio of PC was increased and less GGBS was used to a 60:40 in binding ratio, (Fig. 4(b)), the UCS values of specimens with 5wt% and 15wt% gypsum content increased marginally, and nearly achieved 6 N/mm^2 at 7 days curing. This is slightly higher than the strength recorded by the 40:60 binder at the same curing period. Again, when w/b=1.8 was used with 15wt% gypsum, showed the highest UCS value of 6.30 N/mm^2. With increased curing period, to 28 days, there is repeated increased strength with increasing gypsum content. The highest UCS value of 7.64 N/mm^2 was recorded with 15wt% gypsum content at w/b=1.9. As with the lime system, there is no benefit of increasing the PC content in the binder as the effect on strength is not significant.

3.3 Foamed system

In the foamed system, Aluminium powder was introduced into the system at 1wt% and 3wt% in the absence of gypsum. Figures 5(a) and (b) illustrate the strength values of PFA+Lime-GGBS at 50:50 and 70:30 ratio. The results showed that the strength values decreased with the increase of aluminium content in the system at all w/b ratios used. Prolonged curing period to 28 days did not have any effect on strength development. The overall strength values were all below 2 N/mm^2. When there is no aluminium in the system, strength increased from 2.3 N/mm^2 (average) at 7 days to 5.18 N/mm^2 (average) at 28 days, with w/b=2.3 giving the highest strength value (Fig. 5(a)). The trends are similar with lime-GGBS 70:30 ratio (Fig. 5(b)).

The trends on strength observed in the PFA+PC-GGBS system at (40:60) and (60:40) ratios shown in (Figures 6(a) and (b)) show similarities with the PFA-Lime-GGBS system. Increased aluminium content in the system resulted in decrease strength values. When 60:40 (PC-GGBS) ratio was used as binder, the strength values was slightly higher than that in 40:60 (PC-GGBS) ratio at 7 days with 1wt% aluminium, but still decreased with increased aluminium content in the system. Prolonged curing period to 28 days increased the strength values of specimens to over 2 N/mm^2 with 1wt% aluminium whereas when 3wt% aluminium was used the strength remain the same as at 7 days. The highest strength value in the presence of aluminium was 3.42 N/mm^2 at w/b=1.8 (Fig. 6(b)).

3.4 Combined system

In the combined system, both gypsum and aluminium were used together to assess the impact on UCS (Figures 7 and 8). In the PFA+Lime-GGBS (50:50) system (Figures 7(a) and (b)), when 1wt% aluminium was used with increased gypsum percentage from 5wt% to 15wt%, there was a marginal strength increase when specimens were cured from 7 days to 28 days. The overall strength of all specimens were however below 2 N/mm^2 at 7 days.

When the combination of 1wt%:15wt% (Aluminium:Gypsum) were used in the system and cured for 28 days, slightly higher strength values were obtained which slightly over 2 N/mm^2 (Fig. 7(a)). When Lime was increased in the binder to 70:30 (Lime-GGBS) ratio, and when 1wt% aluminium was used with combination of 5wt% and 15wt% gypsum, the strength values for all specimens were well below 1 kN/m^2 at 7 days. After 28 days of curing, strength developed to above 2 N/mm^2 to 3 N/mm^2 especially when 15wt% gypsum was used in the system (Fig. 7(b)).

Figures 8(a) and (b) shows the strength value of PFA+PC-GGBS (40:60) with combination of aluminium and gypsum in the system. At 7 days of curing, specimens with 1wt% aluminium content and 5wt% and 15wt% gypsum did not show any strength gain. Strength values are still below 2 N/mm^2. Prolonged curing to 28 days resulted in significant strength increase from the 7 day strength (Fig. 8(a)). The highest strength value was 4.58 N/mm^2 with w/b=2.0. In the combined system with PFA+PC-GGBS (60:40), (Fig. 7(b)), there are significant improvements in strength values for all specimens compared with the equivalent Lime-GGBS binder system. At 7 days of curing with 1wt% aluminium combined with 5wt% gypsum, strength values are nearly 3 N/mm^2. Increased gypsum to 15wt%, resulted in increased strength values of the specimens to above 2 N/mm^2. The strength values of specimens in this system almost doubled with prolonged curing period to 28 days (Fig. 8(b)). The aluminium:gypsum (1wt%:15wt%) marked the highest strength value of 5.7 N/mm^2 with w/b=1.9.

The observations on the strength values show that there are little or no differences in the effects of changing the water binder ratios on the strength development of all test specimens.

4. Discussion

When lime and GGBS are used as a binder (PFA+Lime-GGBS), the UCS of PFA foamed concrete generally increased after curing. This is due to increased pozzolanic reaction between PFA, binder and activator used. It is generally recognised that the principal cementitious product of pozzolanic reactions is calcium-alumino-silicate-hydrate (C-A-S-H) gel and gradual crystallisation of this gel (Bell, 1988). When fine particles of lime, GGBS and PFA are hydrated, a thin water film develops on the surface of each grain. With very strong particle-particle interactions, bonding forces are due to cohesion forces of water molecules and adhesion forces of water-particle at points of contact. This allows water to be retained for a long period and thus promotes chemical reactivity (Harikrisnan and Ramamurthy, 2006). It is well known that chemically pozzolanic reaction of fly ash, lime and GGBS occurs readily under thermal treatment creating strong structures with an increase of mechanical strength (Jiang and Roy, 1992). This reaction involves the formation of calcium-silicate-hydrate (C-S-H) and calcium-alumino-silicate-hydrate (C-A-S-H) and enhances the strength of the materials.

The most commonly used activator for GGBS is however PC. The reaction of PC with GGBS and water is complex. Water hydration of PC produces mainly calcium hydroxide ($Ca(OH)_2$) and C-S-H gel. In the hydration of blended PC, although minor amounts of alkalis are released, GGBS is mainly activated by the hydration product $Ca(OH)_2$ (Hakkinen, 1993; Bijen, 1996).

Therefore lime in the form of $Ca(OH)_2$ may be added either as an additive or released from PC hydration. GGBS, due to its high alumina and silica content, produces slightly different hydrates from those formed when using standard PC. The main reaction products of GGBS hydration are calcium silicate hydrate, calcium aluminate hydrate and a small amount of calcium hydroxide (Higgins et.al., 1998).

In the foamed system where aluminium was used alone or with the combination of gypsum as an activator, the result showed that the strength values decreased with the increase in the amount of aluminium in the system (from 1wt% - 3wt%). This is because in addition to the hydration reactions of lime, PC and GGBS, there is the reaction of aluminium powder when in contact with the alkaline mix leads to the chemical reaction of liberating hydrogen gas bubbles in the slurry mixture. The hydrogen trapped within the slurry diffuses out and is replaced by the air (Lindon, 2001). 3wt% aluminium used in the expansive system resulted in reduced the strength. This is because too much hydrogen bubbles in the system lowers the specimen's density thus reducing the strength.

5. Conclusion

In conclusion, the finding in this research suggest that there are benefits of economy, technology, and environment of utilizing PFA, GGBS, gypsum and similar industrial by-products in the development of foamed building components (eg. building blocks), although few variations need to be altered, such as higher percentage of binder, to obtain better engineering performance of the products when aluminium is incorporated in the system. The successful utilization of significant volume of various wastes will obviate the increasingly expansive land-filling. Recommendations for further studies are as follows;

Further investigation need to be done on the effect of higher percentage of binder (more than 20% of total dry materials weight).

The effect of water binder ratio and various curing system is needed to evaluate strength values.

The effect of incorporating siliceous material such as clay to the system can also be investigated to enhance the strength values of the products.

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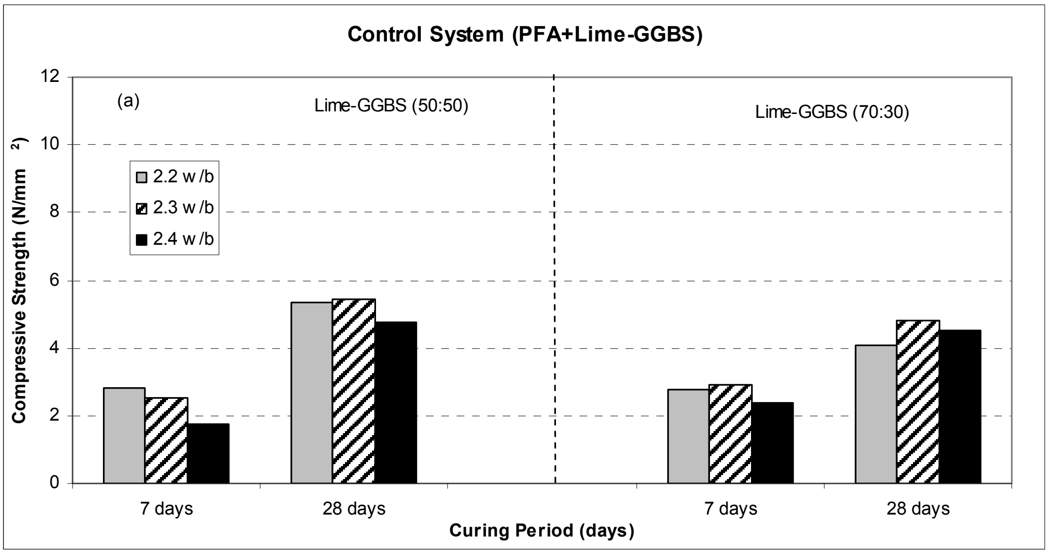
Table 1. Mix design composition

System	Binder Lime:GGBS	PC:GGBS	Al	Gyp	w/b
	%	%	%	%	%
Control	20		0	0	2.2, 2.3, 2.4
		20	0	0	1.8, 1.9, 2.0
Unfoamed	20		0	5	2.2, 2.3, 2.4
	20		0	15	2.2, 2.3, 2.4
		20	0	5	1.8, 1.9, 2.0
		20	0	15	1.8, 1.9, 2.0
Foamed	20		1	0	2.2, 2.3, 2.4
	20		3	0	2.2, 2.3, 2.4
		20	1	0	1.8, 1.9, 2.0
		20	3	0	1.8, 1.9, 2.0
Combined	20		1	5	2.2, 2.3, 2.4
	20		1	15	2.2, 2.3, 2.4
		20	1	5	1.8, 1.9, 2.0
		20	1	15	1.8, 1.9, 2.0

Note: Binder – 20wt% of main material (PFA)

Al, Gyp, water – wt% of Binder

Figure 1. Internal structure of foamed PFA cube.



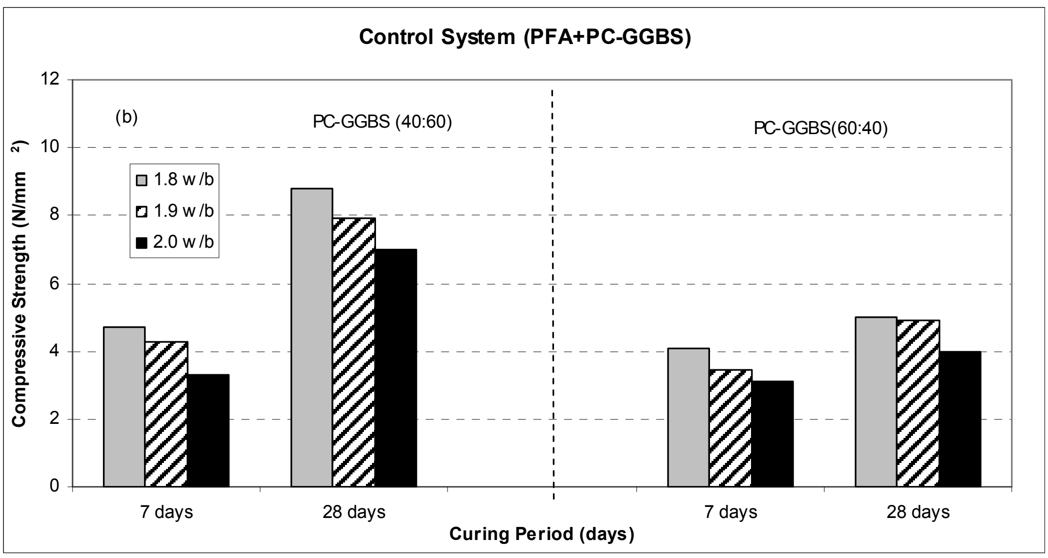


Figure 2. UCS of Control system

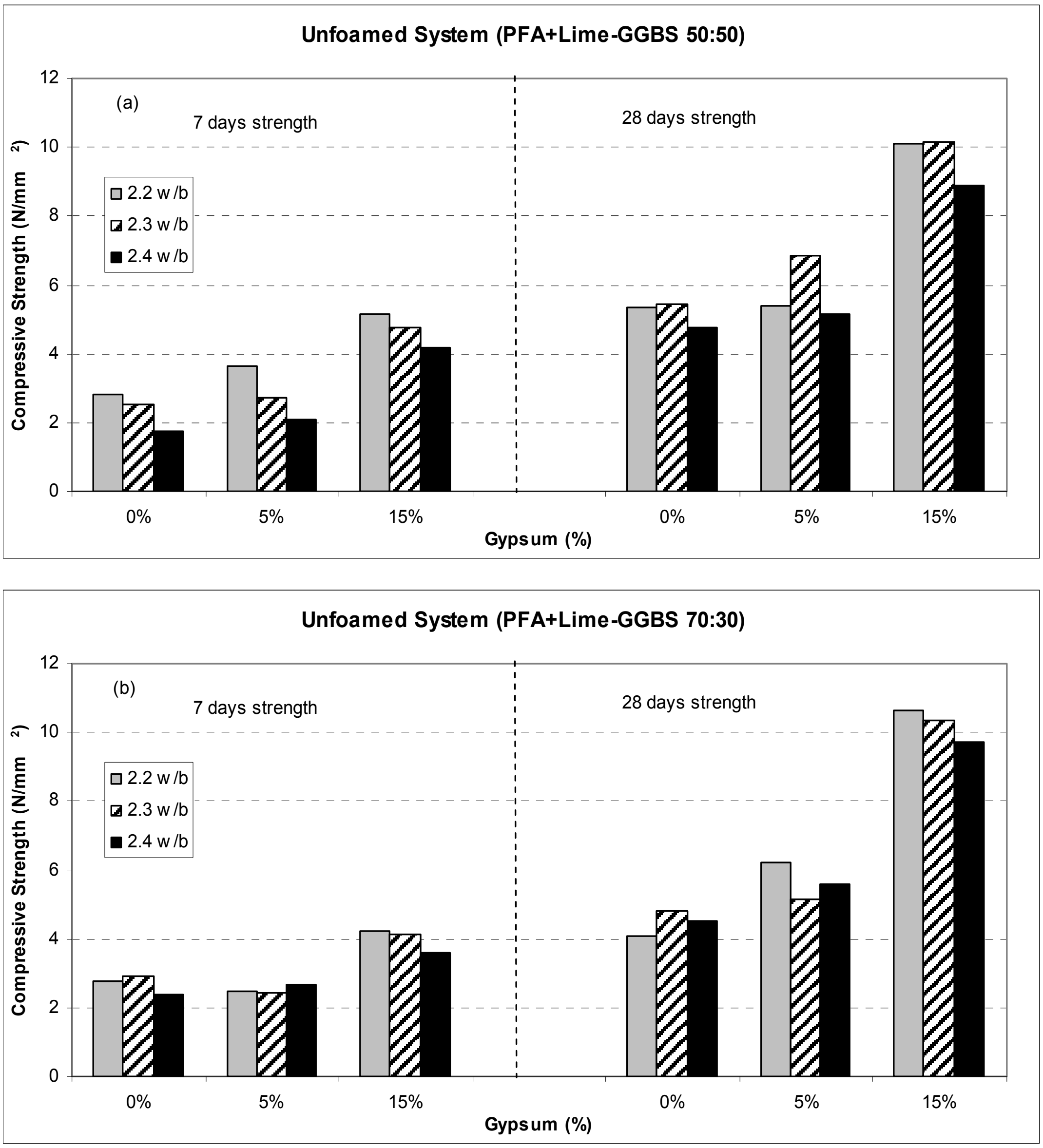


Figure 3. UCS of Unfoamed system, Lime-GGBS binder

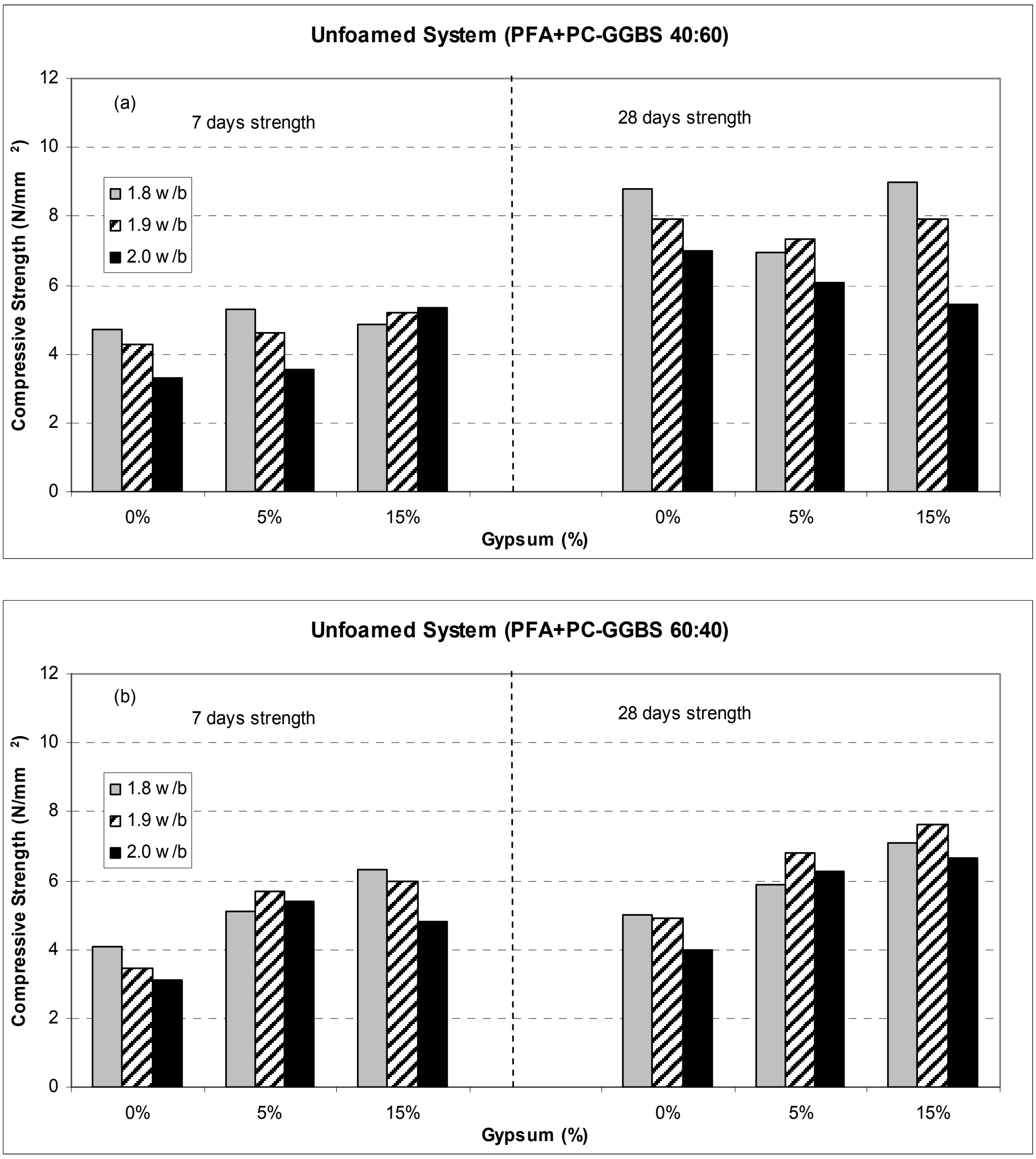


Figure 4. UCS of Unfoamed system, PC-GGBS binder

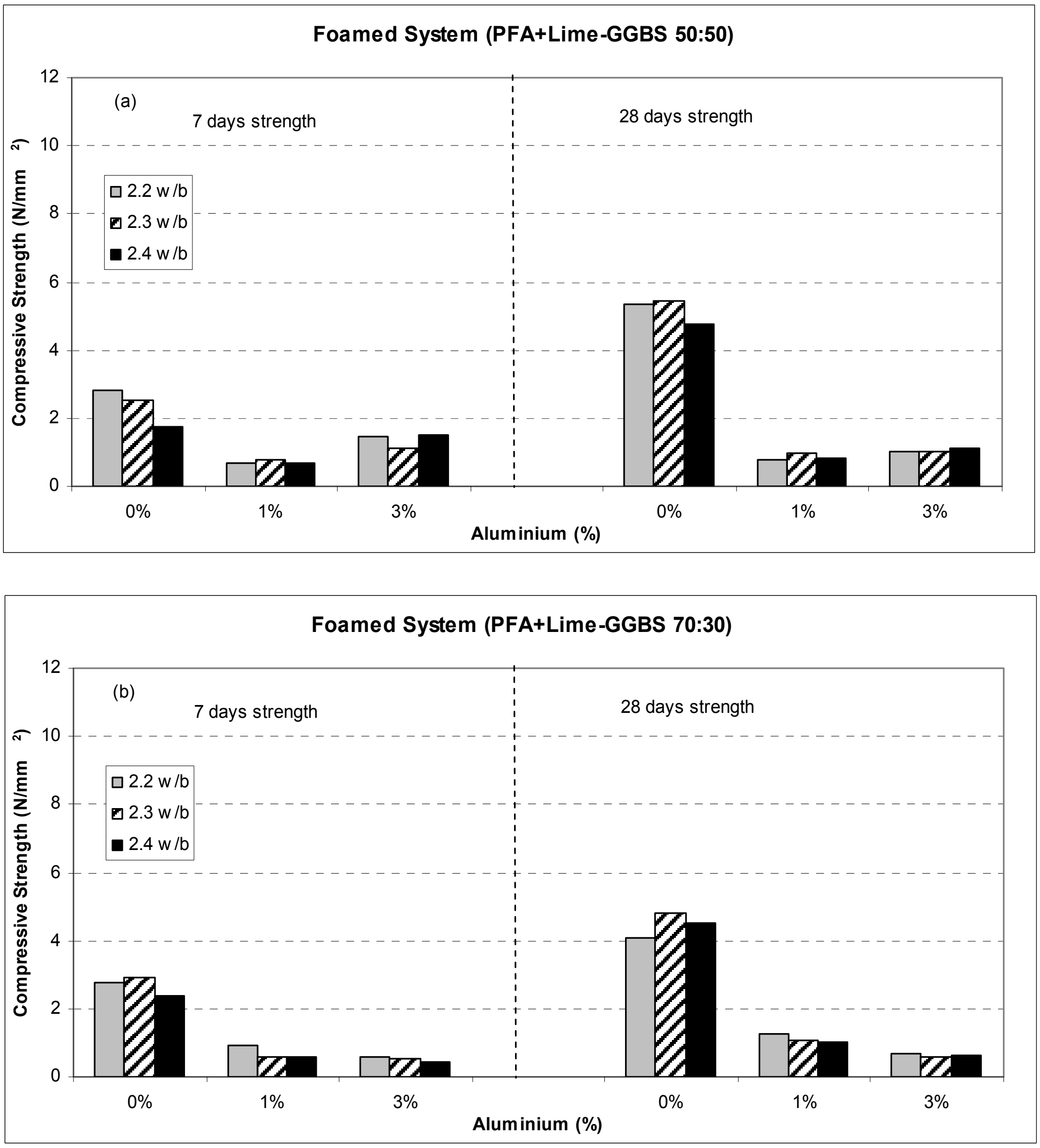
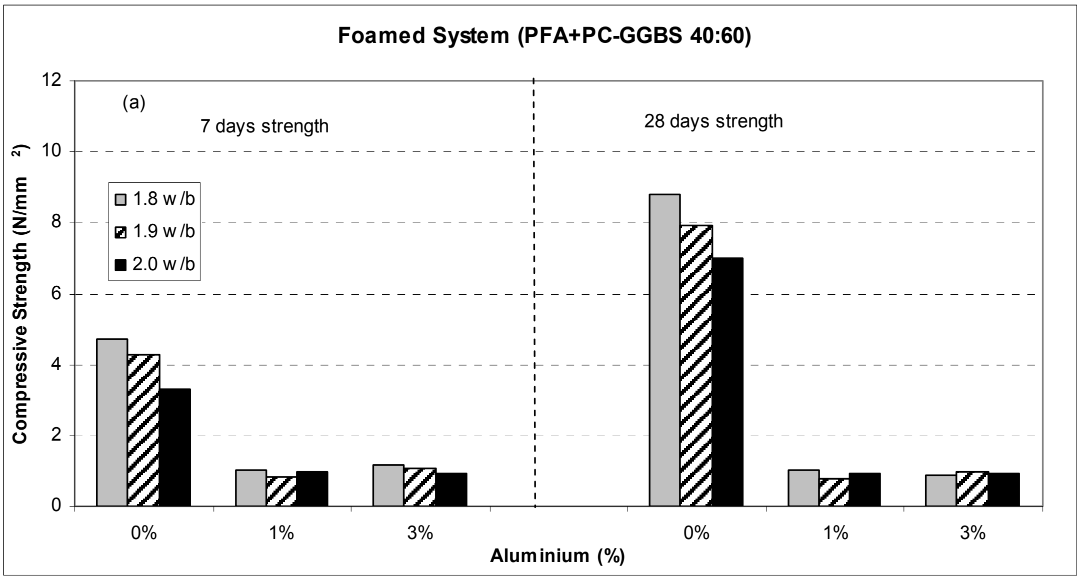


Figure 5. UCS of Foamed system, Lime-GGBS binder



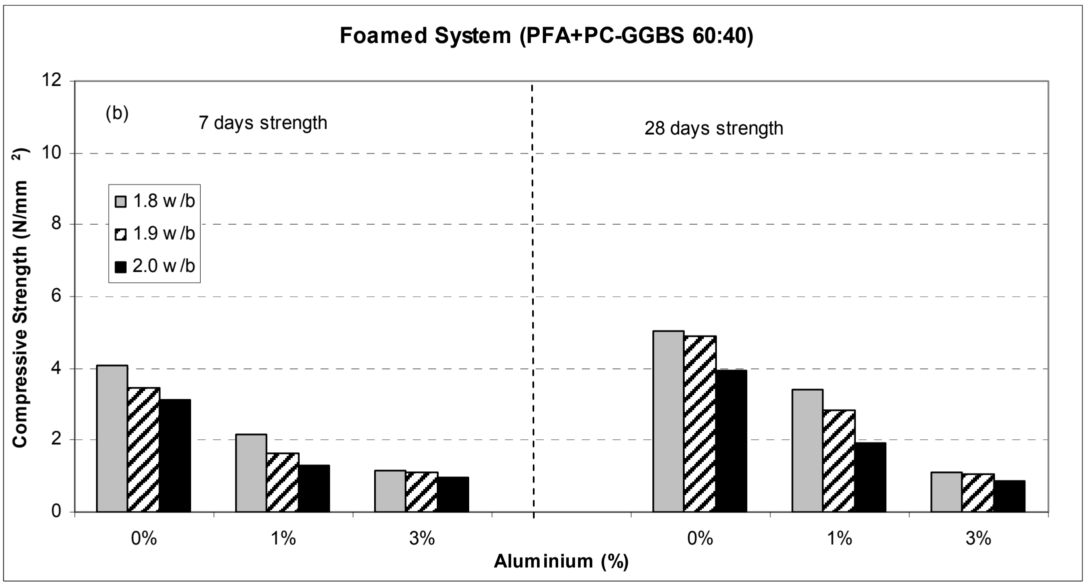


Figure 6. UCS of Foamed system, PC-GGBS binder

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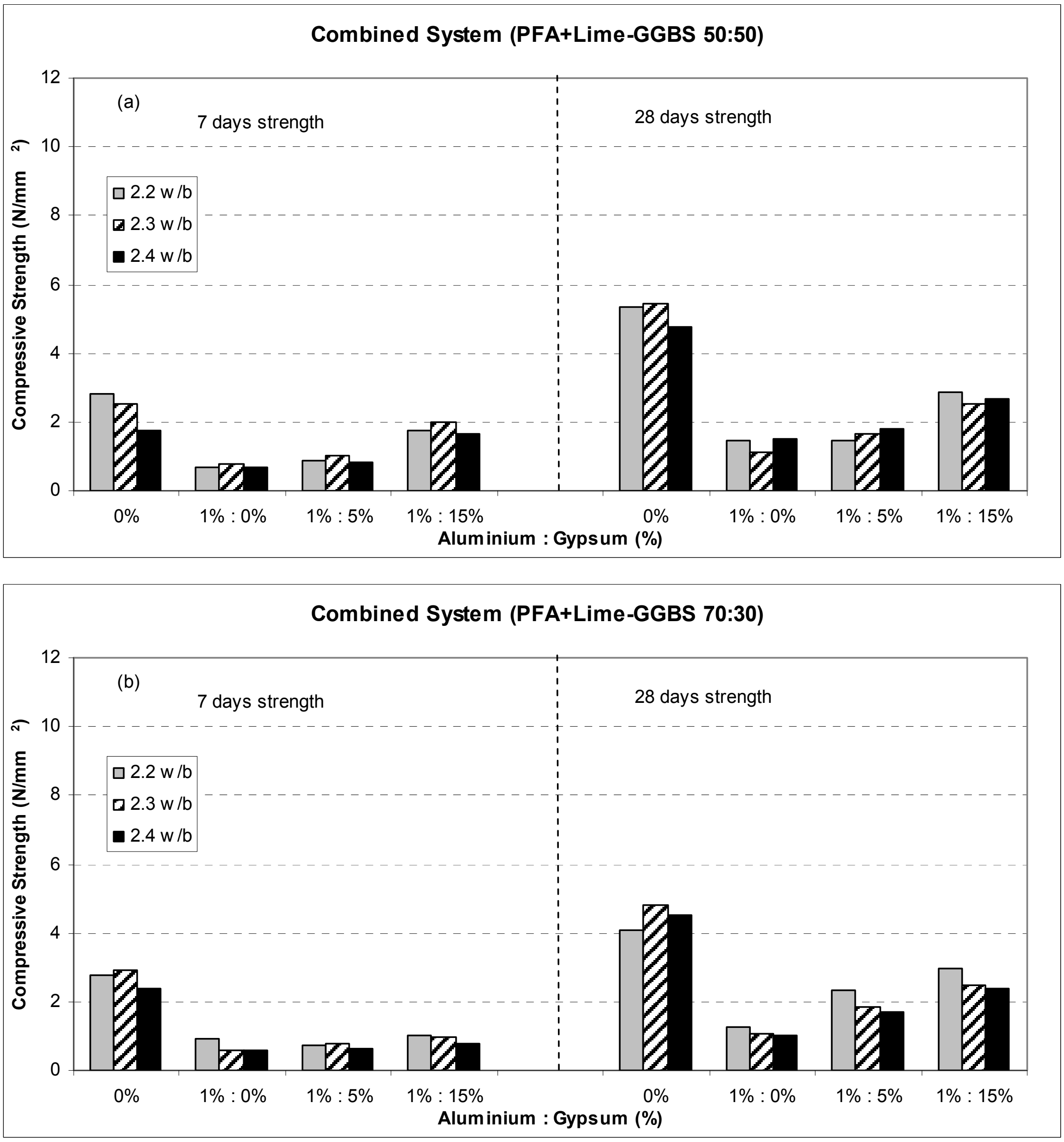

Figure 7. UCS of Combined system, Lime-GGBS binder

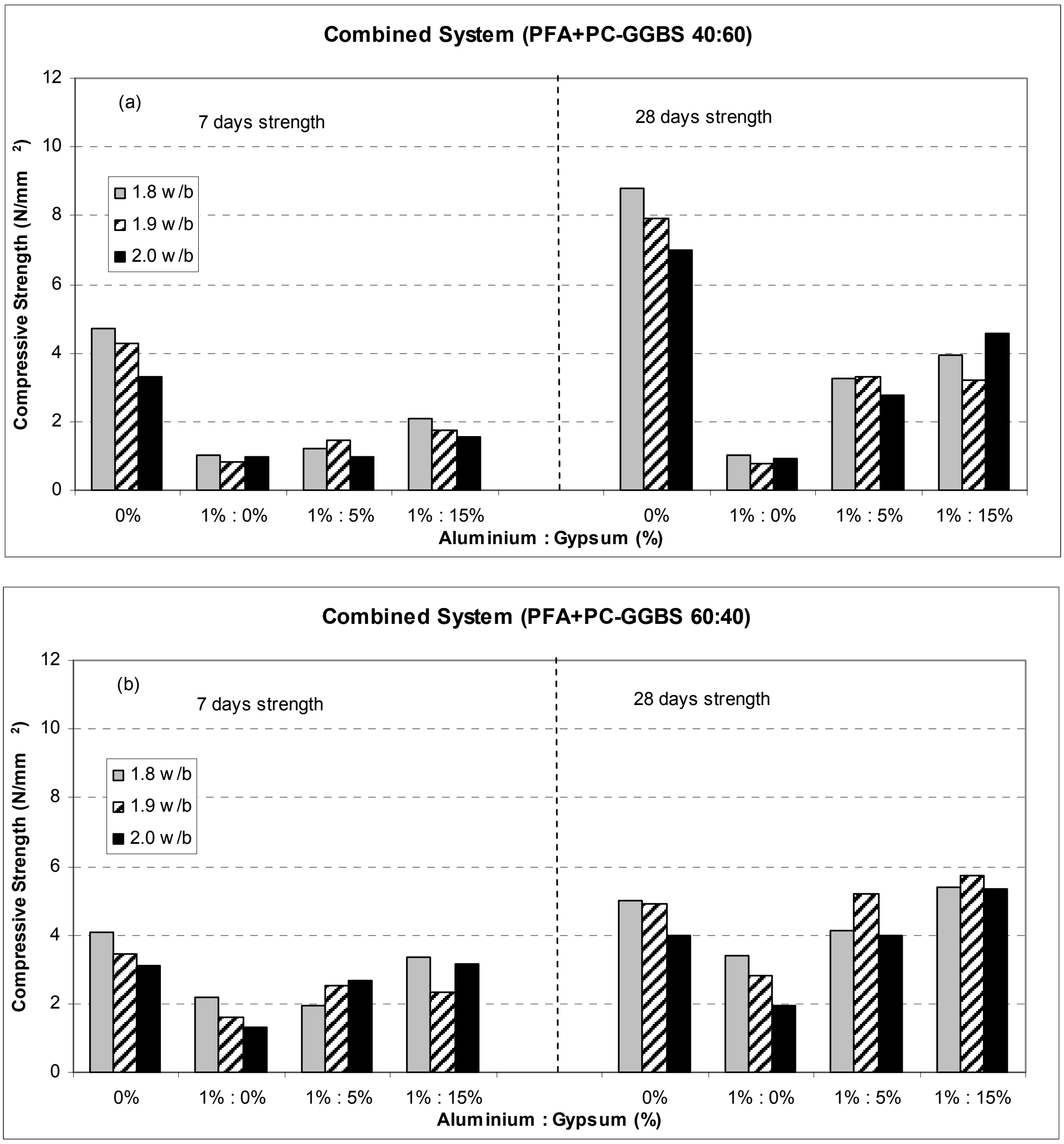

Figure 8. UCS of Combined system, PC-GGBS binder