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Study of Aerated Lightweight Mortar Using Aluminium Powder and Local Materials

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Abstract

Conventional burnt clay bricks are still mostly used as building materials for both load-bearing and non-load-bearing walls in Nepal. The use of brick walls not only increases the dead loads on the structures but also becomes the main cause of casualties during the earthquake. This paper describes the development of an alternative lightweight mortar using aluminium powder to replace the bricks. The base mixture of the mortar was experimentally determined and the properties were studied with the ranging content of the aluminium powder by weight of cement. The result showed a decrease in the density and compressive strength but an increase in the water absorption while increasing aluminium powder content. The density was possible to decrease by about 52% with the use of 0.9% aluminium powder. The decrease was very less while increasing the aluminium content from 0.6% to 0.9%. The 28-day compressive strength was decreased by 59% and 63% at aluminium content of 0.6% and 0.9% respectively. With the achievement of a density of less than 1000 kg/m^3 and a 28-day compressive strength of more than 7.5 MPa, the optimum content of the aluminium powder was 0.6%. The implementation of this result implies producing lightweight bricks, blocks and panels replacing the burnt clay bricks. It not only lightens the building structures and avoids the casualties during big earthquakes but also saves the environment by minimizing the carbon-di-oxide, avoids the degrading of agricultural soils and even minimizes the risk of climate change.

Keywords: Lightweight concrete, Aluminium powder (AP), Compressive strength, Water absorption.

1. Introduction:

Concrete with a density of less than 1800 kg/m^3 is lightweight concrete [1]. Lightweight concrete is categorized as low (300-800 kg/m^3), moderate (800-1350 kg/m^3), and structural lightweight concrete (1350-1920 kg/m^3). They have compressive strengths in the range of 0.7-2.0 MPa, 7-14 MPa and 17-63 MPa respectively [2]. Lightweight concrete is produced by mixing cement, fine aggregate, lime, fly ash, superplasticizer, and water adding different lightweight aggregates or by introducing entrained air [3]. Such lightweight aggregates are expanded polystyrene (EPS) beads [4], modified waste expanded polystyrene aggregates [5-6], brick chips [7], steel fibre [8-9], plastic waste [10], layered newspaper [11], thermosetting plastic [12] etc. Another method of lightening concrete is to develop the entrained air using the additives like aluminium powder [13-15].

Thermal insulation, resistance to fire, sound insulation, enhancing durability, and environmental friendliness are the main advantage of lightweight concrete [16-19]. However, previous research works have shown that lightweight concrete has low density, less strength and high water absorption capacity. The merit of lightweight concrete is to lighten the structures contributing to the seismic-resistant design. It is because it greatly reduces the dead loads on structures. Traditionally burnt clay bricks are used as masonry walls in all types of construction in Nepal. It is used both in the load-bearing wall and partition walls. However, the use of burnt clay bricks has brought the major problem of more casualties during big earthquakes. It has also destroyed the environment due to the emission of more CO_2 from brick factories and the degrading of soil used for cultivation. Moreover, it has also developed the risk of climate change [20-21].

In Nepal, the production of lightweight concrete is not rational due to the non-availability of local lightweight aggregates. However, Nepalese construction industries are bound to use lightweight construction materials to lighten the structures. Focusing on the solvent of this major problem, the authors have attempted to develop lightweight mortar using aluminium powder. The use of aluminium powder develops the porosity inside the concrete by emitting hydrogen gas while reacting with water while mixing and with calcium hydroxide during the hydration process [22-23]. If the use of locally available aluminium powder and other local raw materials gives a better result, as predicted by the authors, it opens the way to produce lightweight mortar. It helps to rationalize the infrastructure development in Nepal concerning the performance and economy. Thus, the authors intended to investigate the properties of lightweight mortar using aluminium powder to be used for the structural and non-structural parts of buildings. Its first specific objective is to obtain the appropriate materials of powder materials with which the effectiveness of aluminium powder is the most effective. The second specific objective is to obtain the optimum content of the aluminium powder.

2. Materials and Methods:

2.1. Materials:

The sand was collected from the Seti River at Kotre, Tanahun, Nepal. The properties of sand were tested in the laboratory. The sieve analysis was conducted as per IS: 2386 (Part I) 1963 [24] to find the fineness of the sand. Tests on properties like bulk density, specific gravity, and water absorption were performed according to IS 2386 [25]. Their properties are given in Table 1.

Table 1: Basic properties of sand

Size of aggregate (mm)	Bulk density (kg/m^3)	Specific Gravity	Silt content (%)	Water absorption (%)	Fineness modulus
4.75	1510	2.58	2.5	11.83	3.58

The type of cement was 53-grade type OPC [26]. Its required main properties, obtained from the lab tests, are listed in Table 2

Table 2: Main characteristics of cement

Specific weight	Fineness	Time of setting		Compressive strength (MPa)			Consistency (%)
		Initial (min)	Final (min)	7-d	14-d	28-d	
3.15	3.2	128	384	27	38	53	29

Other powder materials were also used to increase the powder content in the mixture. Fine grey fly ash was also used for the replacement of cement. Its required characteristics [27] are listed in Table 3.

Table 3: Required characteristics of fly ash

Specific Gravity	Density at natural porous state (kg/m^3)	Surface area (cm^2/g)	Passing from sieve 10 micrometer (%)
2.15	850	3850	15

The characteristics of aluminium powder [28] are given in Table 4.

Table 4: Characteristics of aluminium powder

Parameter	Value of indicators
Bulk Density	0.1774 g/cc
Particle Size Analysis Wet sieving 45 µm	82.38 %
Appearance	Silvery white
Particle size distribution D50 approximately	28.66 µm
Purity	99.7%

The performance of gypsum powder and lime powder was also investigated in this experimental work. Tables 5 and 6 show their characteristics respectively. The poly-carbolic ether-type superplasticizer (commercial name: Markplast Flow 30) was used to enhance the workability of the mortar.

Table 5: Characteristics of gypsum powder

Specific gravity	Density at natural porous state (kg/m^3)	Colour	Solubility
2.32	900	White with a reddish shade	Soluble in water

Table 6: Properties of lime powder

Main characteristics	Values of indicators
Appearance	Dry powder, white to pale yellow colour
pH	12
Calcination temperature	825^0C
Boiling point	2850^0C
Density	3.3 g/cm^3
Volume increasing factor	2.5 (during reaction with water)
Solubility in water	Reacts to form $Ca(OH)_2$

It was light yellow with specific gravity and pH value of 1.11 and 6 respectively. The workability retention capacity of 3 hours at 25^0C. The water used was clean and potable with a pH value of 7.0. Fig. 1 shows the image of each material used in the experiments.

Figure 1: (a) cement 53 grade, (b) sand (Seti river, Kotre, Tanahun), (c) aluminium powder (45 m), (d) – gypsum powder, (e) – lime powder (f) superplasticizer

2.2. Methods:

The universal testing machine (UTM), autoclave machine, mortar mixer, moulds, sieve shaker, pycnometer, curing tank, and weighing machine were maintained to use in experiments and testing. Required numbers of moulds were prepared.

The main aim of the mixture development was based on the crushing strength of the burnt clay bricks and the targeted strength was more than 7.5 MPa. Trial mixture proportions were tentatively finalized for the aerated lightweight mortar block by trial and error. With pre-trials of 8 different mixtures and the detailed data study of three base mixtures, the appropriate mixture proportions of the base mixture were finalized (Table 7).

The sand and powder materials were weighed in an electronic weighing machine and stored separately. The aluminium powder and superplasticizer were weighed in a more precise electronic balance as a very small quantity was required. The required weight of water was also weighed in a bucket and the weighed superplasticizer was pre-mixed with it.

The weighted sand was put into a mortar mixer and then cement was added. Then the weighed lime powders, gypsum powder, fly ash and aluminium powder were also added. The sand and powder materials were mixed in a mortar mixer for two minutes. The measured amount of water, premixed with a superplasticizer, was poured and stirred again for a further minute. Then the mixture (slurry) was poured (cast) into 2/3rd of the lubricated moulds (9 numbers for each mix proportion) before coming out more air bubbles. Since no coarse aggregate was used in lightweight mortar, mould sizes were chosen as 50mm×50mm×50mm (Fig. 2) as per IS 2250 [29]. The moulds were just shaken by hand and partially filled uniformly and it was self-compacted without any compaction by any tools. The moulds with fresh mortar were placed in a non-disturbing place without shaking. It was left for 24 hours (for initial curing) at room temperature in the laboratory.

Table 7: Mixture proportions with ranging content of aluminium powder (kg/m^3)

Mixer type	C	S	W	FA	LP	GP	SP	AP	AP (%)
M1	370	740	333	370	185	18.5	5.55	0.00	0.00
M2	370	740	333	370	185	18.5	5.55	1.11	0.30
M3	370	740	333	370	185	18.5	5.55	1.85	0.50
M4	370	740	333	370	185	18.5	5.55	2.22	0.60
M5	370	740	333	370	185	18.5	5.55	3.33	0.90

C: cement, S: sand, W: water, FA: fly ash, LP: lime powder, GP: gypsum powder, SP: superplasticizer, AP: aluminium powder

Figure 2: Type of moulds for cube specimens

After 24 hours of casting, the over-puffed portions were cut to make the required size and shape of the specimens [29]. Then, water curing was done until the testing day. The oven dry testing was performed as per NS 581 2076 [30] and IS 6441 [31]. 3 nos. of each mix proportion of the sample was taken out from curing after 28 days and was put in the oven at 105^0 C temperatures for 24 hours. It was taken out from the oven and left for 3 minutes to cool down to room temperature. Then the weight was taken with electronic balance at 0.01 grams of accuracy to determine the density.

The test was conducted for water absorption following the standard procedure [30-31]. The samples tested for oven-dry density were put in water for 24 hours. It was taken out, just wiped out and weighed. The weight of water was calculated by deducting prerecorded dry weight from the submerged weight of each sample. Water absorption was determined in the percentage. The compressive strength test was performed following IS 6441 procedure [32].

The density of the cube specimens was calculated with the formula given in Equation (1).

$$D = \frac{W}{V} = \frac{W}{lbh} \dots\dots..(1)$$

Here, D is the density of the cube specimen in kg/m^3. W is the weight of the cube specimen in kg. And, V is the volume of the specimen in m^3 which was obtained by multiplying the length (l), breadth (b), and height (h).

The compressive strength of the cube specimen was obtained with the formula given in Equation (2).

$$f_c = \frac{P}{A} = \frac{P}{lb} \dots\dots..(1)$$

Here, f_c is the compressive strength of the cube specimen in MPa. P is the weight of the maximum load in N. And, A is the area of the upper surface area of the cube specimen (on which the load is directly applied), which was obtained by multiplying the length (l) and breadth (b) of the upper surface.

The water absorption was calculated with Equation (3).

$$WA = \frac{W_w - W_o}{W_o} \times 100 \dots\dots\dots(2)$$

Here, WA is the water absorption of the cube specimen in percentage. W_w is the weight of the saturated surface dry condition of the cube specimen in gm. And, W_o is the weight of the oven-dried cube specimen in gm.

NBC 202: 2015 [33] has recommended the minimum crushing strength of masonry for 230 mm load-bearing walls up to 2 storeys is 7.5 MPa. On the 7th and 28th days, the cubes were taken out from the water and the whole surface was made dry. The weight and dimensions of each sample were measured to determine the densities. The cube strength tests were performed in the UTM machine with the standard procedure [32] of applying a loading rate of 14 MPa/minute.

3. Result and Discussion:

During the mixing, no bubbles were seen inside the mixture with no addition of the aluminium powder. The workability was sufficient like slurry. No signs of bleeding or segregation were observed. However, numerous bubbles were observed during mixing with the addition of the aluminium powder. It was because of the emission of hydrogen gas in the chemical reaction of the aluminium powder with water particles [23]. After casting the mixture into 2/3rd of the mould, the level of the mixture was observed to increase. After 24 hours, the mixture overflowed out of the mould (Fig. 3). It was due to the emission of hydrogen gas in the chemical reaction of the aluminium powder with the calcium hydroxide ($Ca(OH)_2$) developed during the initial hydration process [22].

Figure 3: Increased volume of cast mortar after 24 hours

The average results of three specimens are shown with the standard deviation in Table 8.

Table 8: Test results

Mortar type	AP (%)	D_{24h} (kg/m^3)	D_{oven} (kg/m^3)	WA (%)	f_c7 (MPa)	f_c28 (MPa)
M1	0.0	1947±23	1733±19	14.6±0.31	12.9	18.4±0.41
M2	0.3	1325±19	1121±16	26.9±0.42	7.90	10.9±0.18
M3	0.5	1150±16	1008±14	29.5±0.53	7.30	9.20±0.11
M4	0.6	960±12	830±9.0	31.3±0.69	5.90	7.60±0.09
M5	0.9	940±11	816±8.0	33.5±0.70	5.70	6.80±0.07

AP is the content of aluminium powder in percentage to the weight of cement. D_{24h} and D_{oven} are the average densities of the specimens in 24 hours and oven dry respectively. f_c7 and f_c28 are the average 7 days and 28 days compressive strengths respectively. The standard deviation values shown with each average value verify that the data are within the margin of error showing the relatively high-quality control in the experimental and testing procedures.

The relation of the density with aluminium content is shown in Fig. 4. The 24-hour and oven-dry densities of the mortar without aluminium powder were 1947 kg/m^3 and 1733 kg/m^3 respectively. While introducing 0.3% aluminium powder, both densities decreased to 1325 kg/m^3 and 1121 kg/m^3 respectively. The decrease was by 32% and 35% respectively. The result showed that the density loss of the cube specimen in the oven-dry condition without aluminium powder (12.2%) was less than that with 0.3% aluminium powder (18.2%). It was due to the more microvoids developed by the aluminium powder. The densities decreased almost linearly while increasing the aluminium powder content up to 0.6%. The decrease of both densities was down to

960 kg/m^3 (51%) and 830 kg/m^3 (52%) respectively. It was possible to decrease the density of mortar to less than 1000 kg/m^3 with an aluminium content of 0.6%. However, the decrease was very small to 940 kg/m^3 (52%) and 816 kg/m^3 (53%). From these test results, it was confirmed that the optimum content of the aluminium powder to decrease the mortar's density is 0.6%.

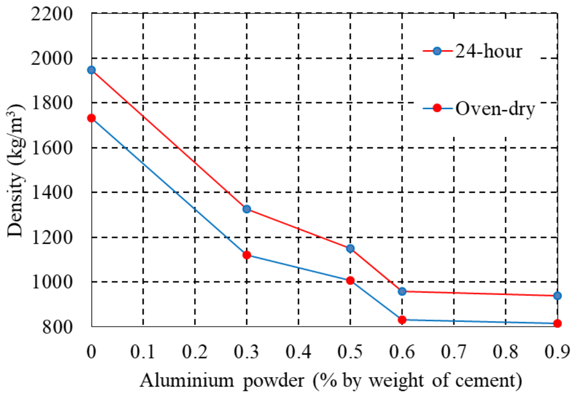

Figure 4: Relationship between density and the content of the aluminium powder

Fig. 5 shows the effect of the ranging percentage of aluminium powder on the water absorption of the mortar.

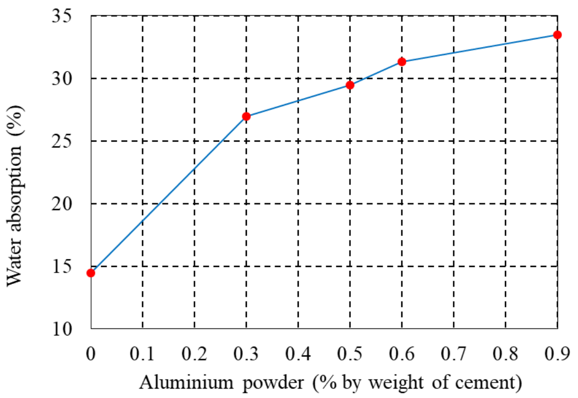

Figure 5: Effect of ranging percentage of aluminium powder on water absorption of mortar

The water absorption of the mortar steeply increased from 14.6% to 26.9% (by 84%) while introducing 0.3% aluminium powder and started to decrease gradually with the increase of the aluminium powder content up to 0.9%. The water absorption was 31.3% (114 % decrease) at 0.6% and 33.5% (130% decrease) at 0.9% of the aluminium powder. The introduction of the aluminium powder develops numerous microbubbles while reacting with water and $Ca(OH)_2$ which increases the porosity in the hardened state increasing water absorption.

Fig. 6 demonstrates the effect of the ranging percentage of aluminium on compressive strengths of mortar and the content of is given.

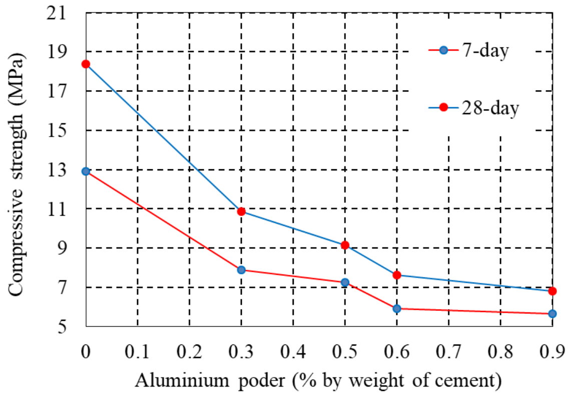

Figure 6: Effect of aluminium powder content on the compressive strengths of mortar

The 7-day and 28-day compressive strengths of mortar adversely decreased from 12.9 MPa to 7.90 MPa (39% decrease) and from 18.4 MPa to 10.9 MPa (41% decrease) respectively with the use of 0.3% aluminium powder. Then the decrease was gradual up to 0.6% with 5.9 MPa (54%) and 7.60 MPa (59%) respectively. Since the target of the 28-day compressive strength for the load-bearing wall was more than 7.5 MPa. Thus, the optimum content of the aluminium powder for both density and 28-day compressive strength was concluded as 0.6%. However, NBC [33] has recommended the minimum 3.0 MPa for the required compressive strength of non-load-bearing panels, the further investigation can be performed to decrease both density and mortar.

Generally, the compressive strength of the given mortar mixture increases while the density is increased [34]. The relation of compressive strength with the density of the mortar is illustrated in Fig. 7. The similar trend was also revealed in this study. The result showed that when the oven-dry density of mortar was decreased from 1733 kg/m^3 to 830 kg/m^3 (decreased by 52%) at 0.6%, compressive strengths were decreased from 12.9 MPa to 5.9

MPa (by 54%) at 7 days and from 18.4 MPa to 7.6 MPa (by 59%) at 28 days. The trend of increasing the compressive strength with the increase of the density is almost linear

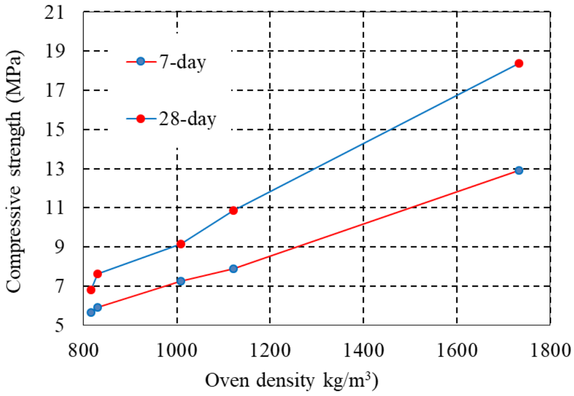

Figure 7: Effect of the density on compressive strength of mortar

The most affecting factor for the compressive strength of the mortar is porosity [35]. It is due to the presence of air content in the mortar. The air content increases inside the mortar due to the increase of the air voids which are categorized into entrapped air voids and entrained air voids [1]. Entrapped air voids develop due to the error in mix design, mixing, and compaction. Most of the entrapped air voids are larger and connected in the channel. The increase of entrapped air increases water absorption. The higher water absorption represents the higher porosity which affects the strength of the mortar severely. Thus, although it is almost impossible to nullify the entrapped air voids, better minimize as less as possible to enhance the strength of the hardened mortar. The entrapped air voids also depend upon the maximum particle size of the aggregate. IS 456-2000 [36] has recommended the entrapped air content of 3%, 2%, and 1% for the maximum aggregate sizes of 10 mm, 20 mm, and 40 mm respectively for the design of the required grade of the mortar mixtures.

On other hand, the trend of increasing entrained air has become popular for the durability purpose of mortar mixtures with the use of the air-entrained agent. The air-entrained agent develops numerous discrete microbubbles while reacting with water. The presence of certain content of entrained air enhances the durability of mortar structures, especially with resistance to the freezing-thawing action. The water absorption data obtained from this study generally represent the channel voids with which the water particles enter from the surface voids to the inside through the channel of the voids. Fig. 8 shows the effect of water absorption on the compressive strengths of the mortar.

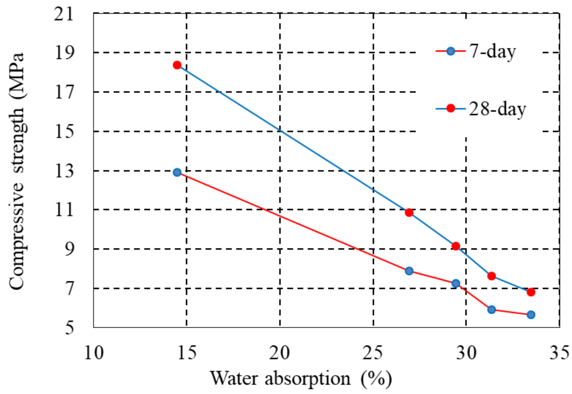

Figure 8: Effect of water absorption on compressive strength of mortar

The graph shows that the effect of the water absorption is the inverse of the effect of the density on the compressive strength of mortar. Both 7-day and 28-day compressive strengths of mortar decrease almost linearly with the increase in water absorption. Realistically, the actual density of the mortar is always less than the theoretical density obtained from the mixture design. When analyzing the test data from this study, the concept of the channel and discrete air voids were made clear to understand. The theoretical density of the mortar without the use of aluminium powder was 2075 kg/m^3. The actual oven-dry density obtained from the test was 1733 kg/m^3 which was 16.5% less. It means 16.5% of the total air voids were contained in the oven-dried specimens. However, the water absorption was only 14.6%. It means the remaining 1.9% of voids were not filled with water representing the discrete voids. It verifies that most of the entrapped voids are channelized with very few in discrete positions. In the case of specimens with 0.6% aluminium powder, the actual density was only 830 kg/m^3, which decreased from the theoretical density of 2075 kg/m^3. It means 60% of total voids exist in these specimens. However, the water absorption test data was only 31.3%. It means 31.3% of voids are channelled and the remaining 28.7% of voids exist in discrete positions. This experimental study verified that there is a strong inter-relationship between porosity (total of entrapped and entrained voids) and water absorption which adversely affects the physical and mechanical properties of the mortar.

Fig. 9 shows the photo of the failure condition of the cube specimens after the completion of the compressive strength test.

Figure 9: Failure condition of cubes after compressive strength test

It was observed that the failure of cubes with aluminium powder was more brittle than that of the cube specimens without aluminium powder. In the case of cubes without aluminium powder, the micro-cracks first developed in the transition zone and extended to the cement paste while increasing the load. The widening and lengthening of the crack took place and finally got brittle failure with a single crack. However, in the case of the cubes with aluminium powder, the micro-cracks first developed around the voids due to the stress concentration. Then, the cracks connected the voids around and failed like the collapse with numerous cracks. Since the cube was turned into several pieces, its failure mode became more brittle than that without aluminium powder.

4. Conclusion:

The heavy burnt clay bricks not only increase the dead loads on building structures but also are the main cause of casualties during the big earthquakes in Nepal. The availability of lightweight aggregates is still rare in Nepal due to a lack of depth studies to identify the sources. The commonly used lightweight aggregates worldwide should be imported which makes the production of lightweight mortar more expensive in Nepal. However, aluminium powder is commercially available in Nepal. This study was performed with the main aim of replacing heavy burnt clay bricks with lightweight mortar products using aluminium powder. With different trial tests, the base mixture of mortar was obtained and its physical and mechanical properties were studied with the ranging content of the aluminium powder. The target of the 28-day compressive strength was more than 7.5 MPa with the density as less as possible.

The result showed that the optimum content of the aluminium powder was only 0.6% by the weight of cement which is in very small content (2.22 kg/m^3) in comparison to the content of lightweight aggregate used. It decreased the oven-dry density of the mortar from 1733 kg/m^3 to 830 kg/m^3 (and gave the 28-day compressive strength of 7.60 MPa more than the targeted 28-day compressive strength of 7.5 MPa. The water absorption was only 31.3% giving more discrete voids than that in the base mortar. It means aluminium powder develops more discrete air voids while reacting with water during mixing and with $Ca(OH)_2$ during the hydration process. It has also given a way to reduce the density of the lightweight mortar (for 28-day compressive strength > 3.0 MPa) with alteration of base mixture proportion to produce lighter bricks, blocks, and panels to use in non-load bearing walls in reinforced mortar buildings.

The use of aluminium powder not only makes the production of lightweight mortar economical but also helps to replace the heavy-weight burnt clay bricks in Nepal. The brick factories of Nepal have destroyed the environment deteriorating human health due to the emission of CO_2, degrading the agricultural soil, and increasing the risk of climate change, it is highly recommended to use aluminium which helps the sustainable development of the infrastructure in Nepal.

Conflicts of Interest

It is hereby declared about no conflicts of interest to publish this article.

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