HYDRATION AND CARBONATION REACTION COMPETITION AND THE EFFECT ON THE STRENGTH OF UNDER SHED AIR DRIED AMENDED COMPRESSED EARTH BLOCKS (ACEBs)

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ABSTRACT

A research finding on amended soils for the production of blocks and mortar with lime and natural pozzolan for earthen construction was reported in the EEA Journal of 2019. The use of the amenders was to take advantage of the binding property of lime and the low reactive behavior of natural pozzolans without any further energy demanding additional treatment. In the attempt, it was learned that the existence of hydration and carbonation reactions which are the driving engines of the whole formation are competing with each other at early age of curing. The effect of this phenomenon is that it might upset the maximum/optimum stabilizing effect that could be fully achieved. Furthermore, since the proposed method was defined for air dried curing but only under shed environment; it came to mind that such a challenge needs to be addressed before embarking on an industrial scale. Thus, the main objective of this research is to investigate the effect of hydration and carbonation reaction competitions on air dried blocks in lieu of those cured under the influence of moisture to make a decision on their ultimate use. In order to understand the existence of the reactions' competition various curing mediums were experimented upon and a comparison is made to figure out the weakness of the air dried blocks and those matured at six more environments. From the finding, it is concluded that, among the contending curing conditions as for the purpose of this research, both under shed air drying and a plastic cover moist curing for 14 days and a subsequent 14 days air dry curing under the ambient lab environment (totaling 28 days) could equally be used as convenient. It is also confirmed that, the proposed curing of ACEBs under shed within an air dry condition is a well suited proposition for the practice; since the competition doesn't seem to affect its anticipated performance; per the finding.

Keywords: Amended soils, Competition, Carbonation, Earthen-construction, Hydration

BACKGROUND

The quest for affordable housing scheme is an ongoing effort and it is certainly central to UN's Sustainable Development Goal 11 (SDG 11): *"Make cities and human settlements inclusive, safe, resilient and sustainable"* [1]. In response to the ever burning issue of a global stature, innumerable researches are pursued longing for a formidable achievement. Likewise, here in Ethiopia such researches have been undertaken for a long time; though intermittent and fragmented. Quite recently, the application of lime and natural pozzolans to effectively modify/enhance natural soils for the purpose of Amended Compressed Earth Block (ACEB) and jointing mortar production was addressed in the laboratory and field application as reported in the Journal of EEA 2019 [2]. According to many literature sources, while using such mixtures for the stated purpose there are several challenges which require effective and confidence building corroborations. Among the so many, hydration and carbonation reactions are the two competing factors which negate the possible achievement of the required total service longevity; be it in strength and/or durability of ACEBs and mortars to construct earth based buildings. Thus, the main objective of this research is to investigate the effect of hydration and carbonation reaction competitions on air dried blocks in lieu of those cured under the influence of moisture to make a decision on their ultimate use.

Pure lime hardens by carbonation; however the introduction of pozzolans alters the hardening process of the lime mortar by imparting a hydraulic set (hydration reaction). The hydration products of lime/pozzolan pastes are similar to those found in a hydraulic lime mortars and cements [3, 4]; although their formation is considerably slower than cement pastes. Lime with hydraulic properties has faster setting times, higher mechanical strength and lower permeability and flexibility along with improved resistance to salt, frost and moisture damage [5].The pozzolanic reaction depends on the chemical and mineralogical composition of the pozzolan, the type and proportion of their active phases, the particle's specific surface area, the ratio of lime to pozzolan, water content, curing time and temperature [3, 4].

In the mentioned local research, the Amended Compressed Earth Blocks (ACEBs) were conditioned only under shed without applying curing water (air dry). However, an earlier research by Cizer, et al. (2010) reported that, curing under dry conditions does not sufficiently increase the strength of hydraulic lime and lime-pozzolana mortars; because the hydration reactions are slowed down or even terminated by the full carbonation of lime in lime-pozzolana mortars. The consequence of this on the mechanical properties of the mortars is remarkable while the same impact is not observed in their porosity. Such mortars require moist conditions to ensure sufficient strength development [6]. In fact, it is this concern which triggered a revisit of the systematic formulation and synthesis of amended soils application in earthen construction. Though the earlier finding has proven the worthiness of the effort, but yet it undoubtedly needs a confirmatory verification to elevate its wider and high level of exploitation in confidence. In any scientific work, there shouldn't remain any unturned rock left aside until all facts and figures come to light.

Aspects of Hydration and Carbonation Reaction Competitions

Hydration: It is a chemical reaction in which the major compounds in cement form chemical bonds with water molecules and become hydrates or hydration products. According to Cizer, et al. (2010) and Diamond et al. (1965), hydration reactions are the first reaction and carbonation of lime is the complementary reaction in the strength gain. Competition between these two reactions can occur in lime-pozzolana mortars if the pozzolanic material has low reactivity with lime, leading to the consumption of lime by carbonation reaction. Fast evaporation of the water in hydraulic lime and lime-pozzolana mortars should be avoided by keeping them moist at least during 28 days to improve the hydration reactions and to assure sufficient strength development. The researcher considers what is stated by the author of the mentioned work is quite applicable in here as well; because, the research is thoroughly focusing on low reactivity lime and natural pozzolan (raw) ingredients as stabilizers [6, 7].

Carbonation

When lime is added, the silica reacts with the carbon dioxide (CO2) from the atmosphere to form weak carbonated cements. This uses part of the lime available for Pozzolanic reactions; which give rise to hardening effects [8]. Though pure lime hardens by carbonation, the introduction of pozzolans alters the hardening process of the lime mortar by imparting a hydraulic set. The hydration products of lime/pozzolan pastes are similar to those found in a hydraulic lime mortars and cements although their formation is considerably slower than cement pastes. Lime with hydraulic properties has faster setting times, higher mechanical strength and lower permeability and flexibility along with improved resistance to salt, frost and moisture damage [3, 4, 8-14].The crux of the just stated concern can be well understood by navigating through the chemical reactions initiated by the instantaneous response of a given type of ordinary soil, powdered lime and natural pozzolan in the presence of water. It's worth examining the real world of the expressions of the chemistry shown in Figures 1 and 2 below with their subsequent explanations.

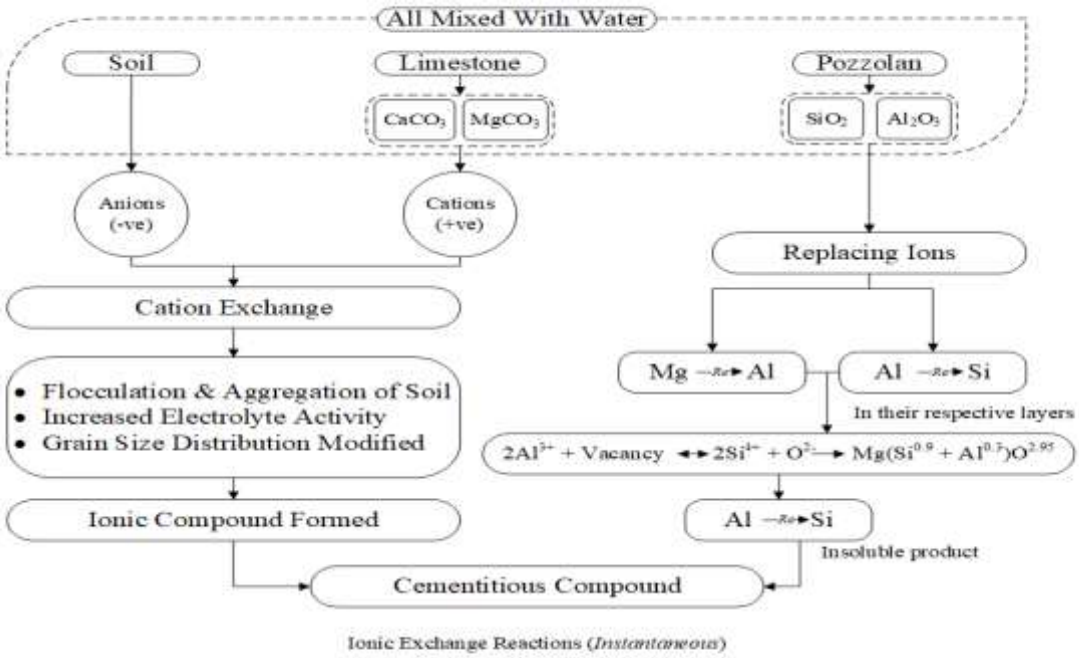

Figure 1: Schematic diagram to illustrate the reactions at ACEB production (Ionic)

(Researcher's own design)

The effects of lime on soils are such that two stages of reaction can be detected: (a) an early stage in which the properties of the plastic soil are greatly ameliorated but little permanent strength is developed, and (b) a subsequent stage marked by the slow development of strength and the accumulation of soil-lime reaction products. Among the effects observed in the first stage are large increases in the plastic limit, generally leading to a reduction in the plasticity index; a sharp reduction in the apparent content of clay size particles as they are bound into floes stable against the dispersion incident to the mechanical analysis; increase in the moisture and the compacting effort required to achieve a given density; and reduction in such parameters as swell pressure, volume change on drying, and permeability. These changes are commonly produced in periods ranging from minutes to a few hours after the addition of lime [15, 16].

When lime is added to moistened montmorillonite or kaolinite clay, it will be flooded with calcium ions. Cation exchange then takes place (giving the clay a lower affinity for water), with Ca ions being replaced by exchangeable cations in the soil compounds, such as Mg++, Na+, K+, and H+. Thus, the resulting mix is characterized by a lower moisture movement, i.e., lower liquid limit and plasticity. The volume of this exchange depends on the quantity of the exchangeable cations present in the overall cation exchange capacity of the soil. The general order of replace ability of the common cations associated with soils is given by the lytropic series, Na+ < K+ < Ca++ < Mg++. Cations tend to replace cations to the left in the series and mono-valents are replaceable by multivalent cations [17-20].

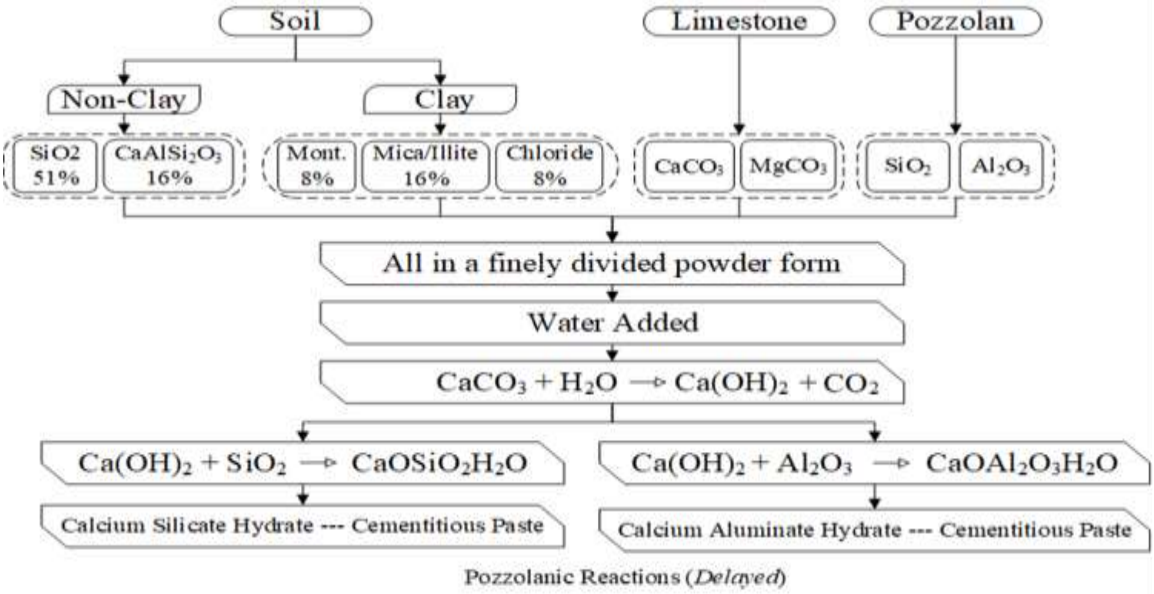

Figure 2: Schematic diagram to illustrate the reactions at ACEB production **(**Pozzolanic)

(Researcher's own design)

Mortars prepared with high reactive pozzolans have higher long term strength. This property is closely related to the extent of silicate formation resulting from reactions between $Ca(OH)_2$ and the reactive minerals (SiO_2, Al_2O_3) in the pozzolan. In previous studies of Cizer et al. (2010) and Diamond and Kinter (1965), pozzolanic reactions between calcined clay, hydrated lime and water were examined and it was observed that composites of hydrated tetra-calcium aluminate (C_4AH_{13}), hydrated tri-calcium aluminate (C_3AH_6), hydrated calcium aluminate (CAH), and gehlenite (C_2ASH_8) form and this process is facilitated by the basic state created via lime [6, 7].

In the process, both structure and grain size distributions are altered. According to Herzog and Mitchell (1963), the flocculation and agglomeration are caused by increased electrolyte content of the pore water and as a result of ion exchange [20]. Diamond and Kinter [1965], suggested that, the rapid formation of calcium aluminate hydrate is significant in the development of flocculation and agglomeration tendencies in soil-lime stabilization. The authors postulated that: Calcium ions cause a reduction in the plasticity of cohesive soil. The mechanism is either a cation exchange or crowding of additional cations onto the montmorillonite or kaolinite clay mineral.

Both processes change the electrical charge density around the clay particles [7]. Then these particles become electrically attracted to one another, causing flocculation. The crowding of additional Ca onto the clay must be the more important of the two mechanisms, since when they have tested the soil already had an excess of carbonates present (16.6%), yet the (Plastic Limit) of the soil was decreased from 40% to 18% with the addition of less than 3% lime[22]. Neville (2011), stated that, the factors that affect the activity of Pozzolana are: 1. Silica Oxide+ Alumina Oxide + Ferric Oxide content, 2.Amorphousness, 3. Fineness, 4. Quantity of reactive silica [22].

The nature of the compounds held responsible for the slow development of strength in soil-lime systems have been discussed in some detail. The exact products formed vary somewhat with the kind of clay and the reaction conditions, especially temperature. There are commonly at least two phases produced, a calcium silicate hydrate and a calcium aluminate hydrate. The former is usually tobermorite gel; the latter is a well-crystallized hexagonal compound, which is probably an impure (substituted) tetracalcium aluminate hydrate and is characterized by a 7.6A^{0} basal spacing; independent of drying conditions. At temperatures only slightly above normal room temperature a different calcium aluminate hydrate phase, the cubic tricalcium aluminate hexahydrate, is produced [7].

Significance of the Research Output

The launch of this research is to examine the effect of the two competing reactions of hydration and carbonation on the performance of Amended Compressed Earth Blocks (ACEBs) and mortars in their application for earthen construction. In a previous research, the author published on the subject stating that, curing of the blocks was without any additional moisture but only keeping under the lab hangar shed; till the testing date [2]. In which case, the pursued method seems susceptible to the competition phenomenon between hydration and carbonation reactions in the curing process. This exposition has to be challenged and supported with some exploratory laboratory experimentations; in order to ensure that the proposition is valid for the intended purpose; i.e., for low-cost and affordable housing scheme using lime and low reactivity pozzolans.

Hypothetical Propositions, Methods and Experimentations

Since soil is a good source of alumina, the effects of lime treatment can be enhanced to a great extent if the apparent shortage of silica can be adequately supplemented by the addition of natural pozzolana, which is high in reactive silica content. In a previous paper, Harichaneet al. (2009), presented the results of the effect of the combination of lime and natural pozzolana on the plasticity of two Algerian soft clayey soils classified as CH and CL according to the unified soil classification system (USCS) [23]. Similarly, Kassahun Admassu (2019), had successfully shown how a soil of CH or OH origin was transformed into an MH or OH type with a resulting PI reduction from 43 to 25 conforming to the mentioned USCS classification system [2].

CizerOzlem (2010) notes, a combined reaction of hydration and carbonation takes place in hydraulic lime and lime-pozzolana mortars. Hydration reactions are the first reaction and carbonation of lime is the complementary reaction in the strength gain.

Competition between these two reactions can occur in lime-pozzolana mortars if the pozzolanic material has low reactivity with lime, leading to the consumption of lime by carbonation reaction. The degree and the order of these reactions are strongly influenced by the moisture content. Hydration reactions are enhanced under moist conditions while carbonation is delayed [6].

Moreover, five basic reactions were suggested for the theory of silica-lime reaction according to a UNIDO (1987) paper. These are: **a.** water absorption; **b.** cation exchange; **c.** flocculation and aggregation; **d.** carbonation; **e.** and silica lime-Pozzolanic reaction [17].

With all the above in the background, the current research is focusing on the various curing effects on the maturing of freshly cast Amended Compressed Earth Blocks (ACEBs) for low-cost house construction. As the understanding of these blocks in more details is gaining momentum it is essential to work into challenging specifics as to make the product a qualified alternative for construction. The obvious task at hand is to ascertain ACEBs' durability; especially, to shrug off its vulnerability to water attack; step by step, and make the product more construction worthwhile.

Thus, as a confidence building mechanism, a further detailed examination of the mechanics of these earthen blocks need unambiguous clarity from the point of view of the real chemistry of the constituent materials interaction as displayed in the stratifications of Figures 1 and 2 above. The questions are: What is going on in the real world of ACEB production as it stands now right from the dry mixing of the ingredients, addition of water, wet mixing, casting, de-molding, curing to the age of 28 days, construct walls and sustain it as a service rendering structure?

What could be the right explanation to the chemistry and the whole scenario to bring ACEB on to the accustomed building material platform as a standardized mainstream building block and mortar alternative?

Such vital and fundamental researchers' and users' queries must be unequivocally answered and supported with scientific evidence and analytical methods. Towards achieving this goal, the following are the outstanding accomplishments carried out to properly address such questions of a paramount importance.

To start with, each type of ACEB specimens were cast to conduct compressive strength tests on all those cured (under shed, plastic cover, over a water trough chicken wire bed) to their respective ages of 14, 28 and 56 days. In addition, to evaluate and assess the effect of curing at elevated temperatures, three blocks for three days (72 hrs) and another three for seven days (168 hrs) were also kept in oven under a controlled temperature of 64^{o}C, to their specified respective testing ages.

Moreover, six more block specimens were prepared. The first three specimens were initially cured in air for 14 days and the remaining 14 days under a plastic cover after being soaked in water for three minutes before starting the next stage of curing (28 days in total).

The second set was conditioned in the reverse order; i.e. first under plastic cover right after de-molding for 14 days and then taken out for air dry curing in the next cycle of 14 days (28 days in total). Finally, both sets were tested at their respective ages of 28 days.

In total, 48 ACEBs underwent compressive strength tests to solidify and strengthen the newly proposed method of air dried amended soil blocks for earthen construction; to prove that the competition reactions are not formidable challenges to refute the concept.

RESULTS AND DISCUSSIONS

The ACEB specimens casted to examine the effect of hydration and carbonation reactions competition on the performance of earthen construction under various curing conditions, including at elevated temperatures and durations were tested for compressive strength at their respective ages and the results indicated in Table 1 are obtained for further scrutiny, synthesis and analysis.

Table 1: Strength test results for different curing conditions and durations

Block Type & Curing Conditions	Testing Age (days)	Comp. Strength (MPa)	Ratios*	
			All:CEB_{air}	All:$ACEB_{air}$
1. $CEB_{air(a)}$	14	1.6	1.00	0.84
	28	1.7	1.00	0.68
	56	2.0	1.00	0.71
2. $ACEB_{air(a)}$	14	1.9	1.19	1.00
	28	2.5	1.41	1.00
	56	2.8	1.40	1.00
3. $ACEB_{plastic(p)}$	14	0.5	0.31	0.26
	28	0.5	0.29	0.20
	56	1.2	0.62	0.44
4. $ACEB_{mesh(m)}$	14	2.0	1.25	1.05
	28	2.2	1.29	0.88
	56	2.2	1.10	0.74
5. $ACEB_{(14a+14p)}$	28	0.9	0.50	0.40
6. $ACEB_{(14p+14a)}$	28	2.4	1.40	0.96
7. $ACEB_{oven(O)}$	3	3.4	1.90	1.40
	7	3.1	1.82	1.24

*Designates ratios of all strengths to CEBair & ACEBair in their respective columns

Fast evaporation of the water in hydraulic lime and lime-pozzolana mortars should be avoided by keeping them moist at least during 28 days to improve the hydration reactions and to assure sufficient strength development [9]. It was such assertive narratives which triggered the initiation of this specific research; indeed. Based on the compressive strength test results of CEB and ACEB specimens under various curing conditions including elevated temperatures and at different ages the manifestations thereof are analyzed and discussed below.

The results in Table 1 show compressive strengths of CEB and ACEB specimens cured under seven different conditions designated as: drying in air as of de-molding (air/a), under plastic cover curing as of de-molding (plastic/p), on a water trough over mesh evaporation curing (mesh/m), alternating curing of the 1st 14 days in air followed by the next 14 days in moist plastic cover and vice versa (14a+14p & 14p+14a) for all ages and 3 and 7 days in oven curing at elevated temperatures (Figure 3). Moreover, under the last column there are two sub-columns designated by All:CEBair (all strength results divided by those of the air dried soil only blocks in their respective ages). The same procedure is followed for those under the column All:ACEBair, but by only changing the denominator. In general, the ratios indicate that, there are obvious improvements though in varying degrees. However, since the focus of the study is on the competition of hydration and carbonation reactions effect on the strength development of ACEBs concentrating on ACEB(air), ACEB (14a+14p) and ACEB (14p+14a) will make the intent clear.

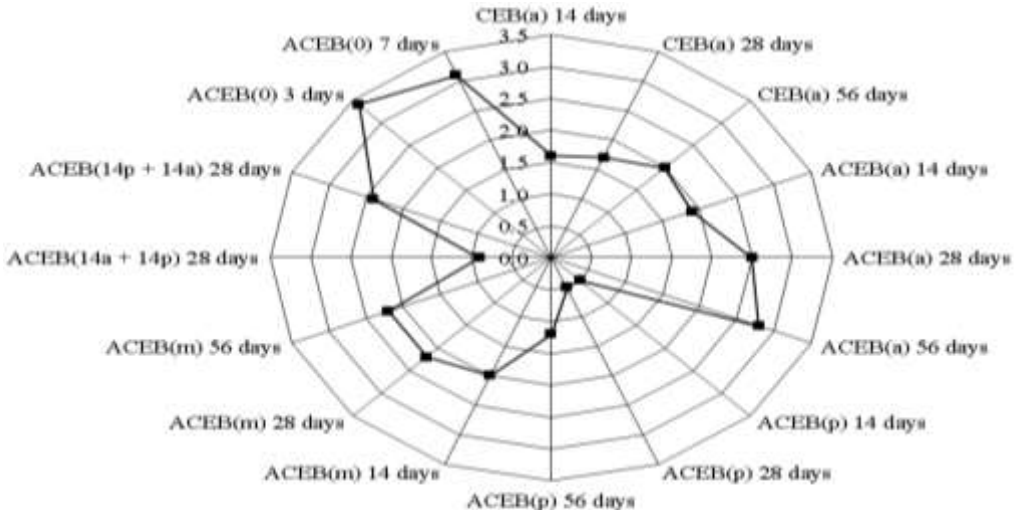

Figure 3: A chart for compressive strength at various curing conditions and ages

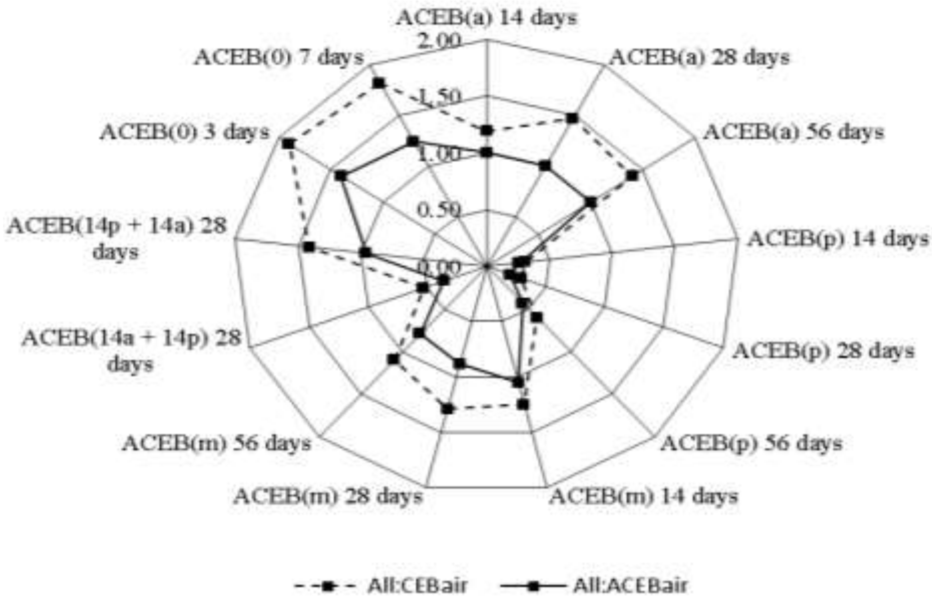

Figure 4: Compressive strength ratios to $CEB_{(a)}$ & $ACEB_{(a)}$ values to show improvements

Since the readiness of blocks for construction is after 28 days from the casting date it seems logical to construct the analysis and discussion based on those outcomes. In reference to the air dried ACEB at 28th day it is only the over mesh (evaporation) cured 14th day ratio which is even slightly higher than the reference. But there after it was on the decrease. This might be the ineffectiveness of that curing condition at latter ages. The ACEBs cured under plastic cover right from the time of de-molding were found to be the least performers. When it comes to the ACEBs cured in alternating, i.e., 14 days in air followed by the remaining 14 days under moist plastic cover performed less. Whereas, the one cured first under plastic cover right after de-molding for 14 days and then exposed to the room ambient temperature for the remaining 14 days scored a value nearly equal to the ACEBs cured in air for 28 days; i.e., the reference. Amongst all, the three days' in oven curing has achieved the maximum even exceeding the one cured in oven for seven days; both at a constant temperature of 64^{0}C.

Going back to the case of hydration and carbonation reactions competition the comparison of the test results between those cured first under plastic cover for 14 days and then kept in air for another 14 days (a total of 28 days) achieved a better result than the one first left in air for 14 days followed by a three minutes soaking in water then kept under plastic curing for 14 days (totaling 28 days). This could be accepted as an indication of the actual effect of competition because, literatures point out that, the competition is manifested in the first 14 days of curing and thus there is a need to keep the specimens moist to this age to fully exploit both reactions effectively [18]. Moreover, in the case of the blocks cured first in air for 14 days and then moved to a moist plastic cover for the remaining 14 days maturing the strength achieved at the 28th day test is nearly half of its counterpart which is cured in the reverse order.

In general, it seems obvious that under all the circumstances considered the influence and the anticipated negative impact of hydration and carbonation reactions competition on the performance of ACEBs cured at ambient room temperature without any additional moisture is not observed at all. It stands high among its contenders to remain a strong alternative building material for the construction of affordable and sustainable abode for the rural segment of the society.

CONCLUSIONS

While promoting the use of under shed air dried Amended Compressed Earth Blocks (ACEBs) for earthen construction it was felt that the challenges of hydration and carbonation reactions could be a hindrance to scientifically sale the idea. Thus, assuming that such nagging issues could abort the effort eventually, this experimental investigation was launched focusing on different curing conditions and ages for maturity.

Noting that, the main objective of this research is to investigate the effect of hydration and carbonation reaction competitions on air dried blocks in lieu of those cured under the influence of moisture to make a decision on their ultimate use; six testing conditions with seven components were carried out on 48 actual size ACEBs to evaluate their performance by analyzing compressive strength test results. The findings confirmed that:

- Of all the test results the set cured under elevated temperature of 64^{0}C for 72 hrs is found as the best; even exceeding the 168 hrs oven cured set in this category.
- Among the conventional curing methods, the air dried (28 days) and those cured under moist plastic cover for 14 days and the remaining 14 days under the ambient room environment (a total of 28 days) took the lead.
- The next performer from the conventional stream is the set cured over mesh through evaporation.
- Of all the sets, the least performer is found to be the one cured under a moist plastic cover throughout all the ages.

Thus, it is concluded that, among the contending curing conditions as for the purpose of this research, both under shed air drying and under plastic cover moist curing for 14 days followed by another 14 days drying in air (as under bullet 2 above) could equally be used as convenient. In the final, the finding confirms that, the proposed curing of ACEBs under shed within an air dry condition is a well suited proposition for the practice; since the competition doesn't affect its anticipated performance. As a recapitulation, since this research focused on a single type of soil so far a practical application future researches are encouraged to cover a wide range of soils.

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