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Strengthening of Hydraulic Lime with Synthetic, Organic, and Bio-Additives: State-of-the-Art Review on Eco-Friendly Construction

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Abstract

Cement is acknowledged to be one of the significant modern construction materials used all over the world because of its excellent properties. Though cement dominates the construction industry, the usage of lime binder is still replaceable because of the need for restoration and repair of existing heritage structures. Though lime offers several advantages such as "breathing", higher durability and deformability, the performance of the lime mortar is still mistrusted because of its poor compressive strength, long setting time, etc. Several researchers from the past have identified various techniques to improve the mechanical strength and fresh properties of lime mortars. This paper attempts to review those significant literatures that were based on performance improvement of lime mortars in the aforesaid parameters. The notable research works include the additions of different herbs in the lime mortar, effects of different plants and animal extracts as additives in lime mortar, and effects of different fibers, including natural and synthetic fibers, in the lime mortar, that are reviewed from various scrupulous literatures and the significant results and outcomes are identified and summarized in this review article. This research review article helps the researchers and practicing engineers to adopt the strengthening method of lime mortar that would be best suited for their restoration applications.

Keywords: Ancient structures, bio-additives, cement-lime mortars, eco-friendly additives, lime mortar, organic additives, synthetic fibers

INTRODUCTION

Cement is one of the building materials used for the past 100 years because of its excellent mechanical and concreting properties. Cement is used as one of the major ingredients in concrete as well as mortars for various structural, repair and retrofitting properties. There are several disadvantages in using cement in the manufacturing of concrete or mortar. The foremost drawback is its environmental concern. The manufacturing process of cement involves burning the raw materials in the clinker at very high temperature, because of which it leads to the enormous release of large quantities of greenhouse gases like carbon dioxide. Cement production accounts for 5% of global greenhouse gases release, which is very harmful to the environment.

On the other hand, ancient structures like heritage buildings were mostly constructed with materials like stones, lime, etc. In such a case, it is difficult to adopt the cementitious materials in the repair of those structures. Even though there are

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certain difficulties that were to be analyzed in using the lime mortars such as delayed setting, and just acceptable mechanical properties, the usage of lime-based mortars is sometimes unavoidable. In case of restoration of heritage buildings, permeability of the mortar or the repair material is the requisite property, that is, it is necessary that the material should be porous and it allows the transportation of vapor and because of which it is also popularly called as "breathing mortar". At the same time, because of the impermeability, rigid nature and hardening, cement-based repairing is not generally permitted in case of heritage structures. The foremost to be considered here is the mortar mechanical strength properties. It is to be noted that the strength of the lime mortar is not up to that of the cement mortar, but it is essential to use eco-friendly lime mortars as discussed earlier. The mechanical properties include the fresh and hardened properties of the mortar. For repair works, the strength can be comparatively low. Generally, compressive strength ranging from 3 to 15 MPa can be achieved with lime mortars which is quite acceptable. But in case of hardening time, it is very much low compared to that of cement mortar, and in certain situations it is necessary to improve the hardening time.

Hydration of Lime

Hydraulic lime is produced by burning the argillaceous or siliceous limestone which then slaked to powder as per the standard [1]. The important raw material ingredients used for the preparation of hydraulic lime are calcite, calcium silicate, and calcium hydroxide. Two important properties to be considered in the exterior wall retrofits and repair of ancient heritage structures are the hydraulic nature and the air entraining ability. These properties are important for the materials to behave adhesive in nature and this adhesive nature is mandatory for the repair materials in the aforesaid applications. In the presence of water and air, two reactions simultaneously occur, one is the water hydration and the other is the air hydration in the presence of water. During the water hydration, the hydraulic paste reacts with moisture to form calcium silicate hydrate (CSH) and in the air, crystals of calcite are formed, which leads to the process of lime hydration. Now this behaves as a binder, with nominal workability, hydration time, and mechanical properties.

Need for Study

Most of the ancient structures were constructed with materials like stones, mud, lime, etc. In such a case repair and restoration of those structures should have a compatible material as prescribed earlier where engineers prefer hydraulic lime as the compatible repair material. Hence it is necessary for the researchers to focus on the problems or demerits associated with the hydraulic lime as a repair material. There is paucity of information regarding the durability characteristics of lime mortar and hence this present study includes the fresh properties, mechanical and durability characteristics of hydraulic lime mortar.

Research Significance

It is ascertained that the usage of hydraulic lime mortar in the repair and restoration of ancient buildings is unavoidable. But the problems associated with the properties of the lime mortar material have to be addressed before incorporating the material for repair. Most of the previous research works were performed on improving the aforesaid properties of the hydraulic lime mortar material. In previous research works, in order to improve the properties of the lime mortar, the development of cement-based lime mortar, inclusion of fibers (synthetic and natural fibers) in the improvement of the mechanical properties, different ancient herbs in the hydraulic lime to improve the properties, development of lime mortars with additives like ceramic waste and development of pozzolanic waste-based lime mortars are adopted. For practicing engineers and researchers, despite using the conventional hydraulic lime, it is essential to study the different effects of research carried out in the hydraulic lime material for its improvement, before adopting those techniques for their peculiar application. This review study reveals the important discussion and research performed by various researchers around the world with respect to the improvement in the properties of the hydraulic lime, with the aspects of aforesaid parameters. This would help the researchers to adopt the specific research study based on materials and behavior aspects.

REVIEW ON LITERATURES

Figure 1 shows the evolution of different kinds of additives used by the researchers to improve the properties of the lime mortar and the summary of various research were analyzed and are summarized below.

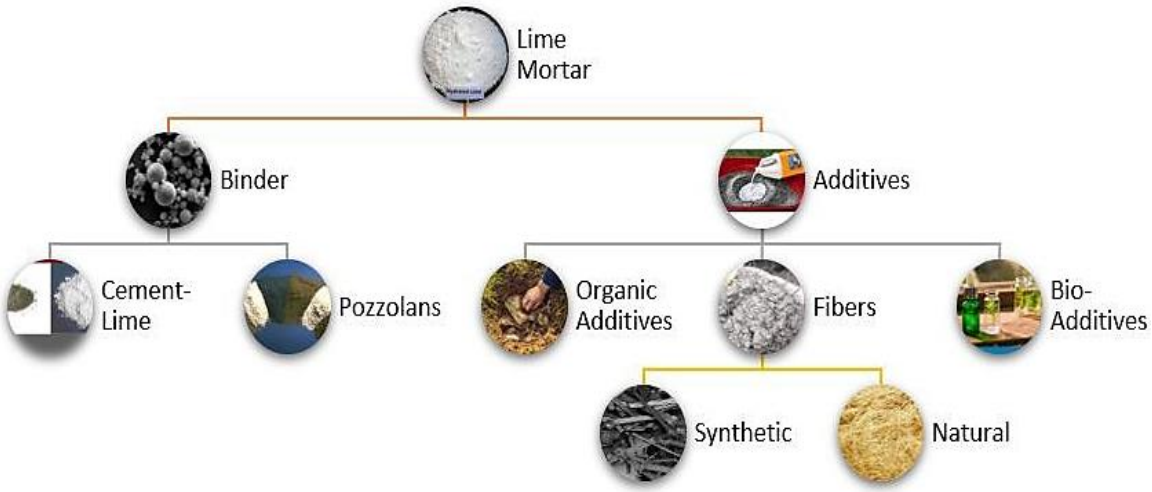

Figure 1. Material development of lime mortar.

Effect of Cement-Lime Mortars

Gulbe et al. [2] have carried out an experimental study on the influence of cement as replacement with lime mortars through experiments. Cement has been replaced with lime content with variable percentages of 2%, 4%, 6%, 8%, 10%. Binder to filler ratio adopted was 1:6 with a small percentage of chemical additive as well. Basic composite properties like water absorption, density, porosity was tested along with experiments on compressive strength, resistance to frost and sulfate attack were performed. It was observed that increase in cement content increases the compressive strength of the composite. Ten percent replacement of cement with lime binder showed compressive strength up to 5 MPa, which is 5 times to that of the 100% lime mortar. The important conclusion was that increase in cement content also increases the resistance towards frost and salts.

Nalon et al. [3] have varied six proportions of cement: lime: sand was inferred upon compression and other non-destructive tests (NDTs). The correlation coefficient between different parameters were also related. The effect of various sizes and shapes of the specimens used in various studies were observed. The empirical relationship between various parameters like compressive strength, static and dynamic Young's moduli were also developed.

The effect of influence of silica fume upon cement-lime based mortar study was made by Gleize et al. [4]. In this study, 1:1 ratio of cement and lime in hydraulic lime mortar was compared with the 10% replaced silica fume with the same mortar. Basic tests such as porosity, compressive strength, and microstructural investigations were made. The addition of silica fume shows mixed variations upon the age of the composite. It was observed that initially the porosity and compressive strength decreases for composite at 7 days of composite, which in turn increases at 28 days, when compared to conventional cement-lime mortars. Thus, the silica fume–replaced mortars are effective when the age of composite is large when compared to early age of composite.

Another important research is the involvement of phase change materials (PCM) and cellulose fibers in the cement-lime based mortars by Guardia et al. [5]. Twelve different variations upon the light weight (LW) aggregate content, PCM content, and fiber content were characterized. Fresh properties, mechanical properties, and microstructural investigations were made in the study. It was revealed that the combined effect of LW filler and PCM material reduces the porosity, compressive

strength, and Young's modulus. The presence of cellulose fibers does not affect the composite significantly; however, to reduce the material contents, it can be adopted. The optimum percentage of PCM was observed to be 20%.

Effects of Pozzolans on Lime Mortars

Zhang et al. [6] studied the influence of two main eco-friendly pozzolanic materials, namely, slag powder and silica fume, in the preparation of hydraulic lime mortar. Two different sets of castings were made, one with slag in mortar and the other set of silica fume in mortar, that is, the combined effect of slag and silica fume were not studied. Two different proportions of pozzolans are replaced with lime binder to study the efficiency. Starting from the basic properties like density, water absorption including fresh property such as flow diameter along with mechanical as well as durability properties were also examined. Increase in the pozzolanic content dis not cause significant change in density but it decreased the flow diameter to some extent. The compressive strength of the specimens was examined with different curing ages of 14. 28, 90, and 180 days. The compressive strength of the silica fume blended mortar increased with increase in the curing age of the specimens although it showed lower strength initially. Twenty percent replacement of slag powder and fume mortars increased the compressive strength up to 217% and 227%, respectively, as compared to the conventional lime mortar.

Figure 2 shows different pozzolans adopted in the past studies upon lime mortar. Slag powder and silica fume generally resist the sulfate attack so that the performance of pozzolans replaced lime mortars also show significant resistance towards sulphate. Among the mix variations, 20% replacement of slag with lime shows the maximum efficiency. The material interaction and compactness of the slag and fume-based mortars are very high compared to conventional lime, such that the materials show maximum hardness which in turn resulted in maximum strength.

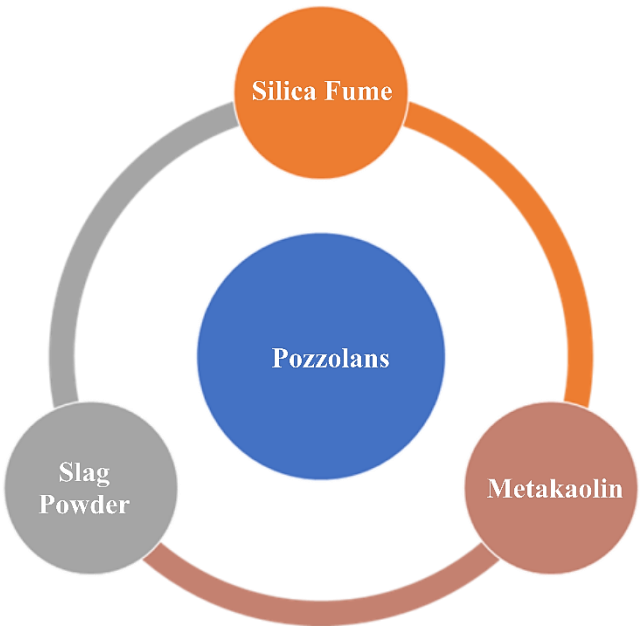

Figure 2. Different pozzolans in lime mortar.

Veiga et al. [7] adopted the experimental application technique with pozzolans blended lime mortar in a historic building in Portugal. The researchers have compared five different binding materials viz., Air lime, white cement, silica fume, metakaolin, and cabo verde (a natural pozzolan). After deciding the mix variations, simple tests, namely, carbonation, sphere impact, penetration, and adhesion tests were performed. Then the hardened properties at 90 days of curing were performed with the following tests: density, porosity, Young's modulus, along with mechanical properties like compressive and

flexural tests. When compared to other materials, white cement lime mortar showed maximum strength and modulus of elasticity up to 2.9 MPa and 4770 MPa, respectively. It was also observed that the addition/replacement of other pozzolans are very much effective than the conventional lime mortars. After performing the laboratory tests, these were applied in those panels of the heritage building and tested in situ as well. As per the in situ tests, except the silica fume lime mortar, other mixes performed best in case of penetration and sphere impact test. Similarly, metakaolin and cabo verde pozzolans showed excellent efficiency towards water penetration resistance and adhesion to background, etc.

Effects of Additives on Lime Mortars

Effects of Organic Additives

The inclusion of organic additives on lime mortar is always interesting. Organic additives indicate the generally consumed/generally available derivatives from the plants/animals. These are added in small quantities as an additional material in the lime mortar and the influence upon basic tests are usually characterized. Figure 3 illustrates various organic additives used by researchers to improve the properties of lime mortar.

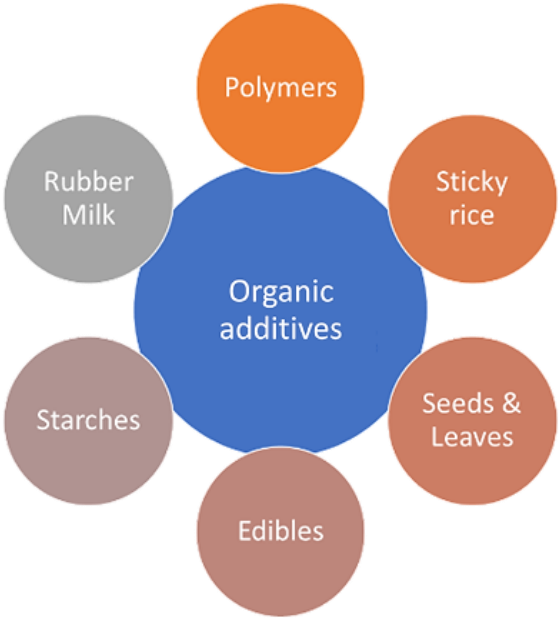

Figure 3. Types of organic additives.

Thirumalini et al. [8] carried out a very significant study on the effect of influence of eco-friendly herbs in the lime mortar to increase the efficiency of the mortar. It is very important to note that not a particular herb was included in the mortar, but a separate process was followed with various combinations of herbs (leaves/seeds) in various proportions. The significant herbs include *kadukkai* seeds, jaggery, and *kulamavu* leaves, which then fermented with water for the period of 7 days. The chemical composition of the fermented water was tested and confirmed according to the standard [9]. A small dosage from the fermented water was added in the lime mortar and it was tested. Important tests such as compressive strength, porosity and spectral tests were performed. It was noted that inclusion of 3% herbs in 10 L of water was very much efficient in the compressive strength of the composite. Addition of 0.5 kg or 1 kg of herbs in fermentation also resulted in nominal improvement in compressive strength. The improvement in the strength was observed due to the enhancement of binding strength between two lime particles due to the presence of herbs. Similar range of porosity between 35% and 40% has been obtained in almost all cases of herbs. There is a reaction and formation of protein and carbohydrate from the lime particles which was clearly indicated by X-ray diffraction (XRD) and Fourier transform infrared (FTIR) analyses.

Nath [10] investigated various properties of the herbs that can lead to significant improvement in the lime mortar. Significant herbs used were curd, sugar, straw plant gums, etc., which would help for soft finishing, bonding, crack reduction, and retarders, etc. One of the important herbs used in lime mortar is the sticky rice. The main advantage of using the sticky rice is its high adhesive strength, toughness, and water proofing. Yang et al. [11] investigated the use of sticky rice as additives in lime mortar for the restoration of the buildings. Sticky rice manipulates the microstructural reaction inside the lime, it acts as an interface and assists the calcium carbonate crystals in solidification, which then improves the property of mortar.

Another important additive are eco-friendly natural polymers in lime and cement mortars particularly to improve the durability properties, as discussed by Chandra et al. [12]. The presence of nopal extract improves water absorption and increases the plasticity. This is due to the chemical formation of polysaccharides due to the interaction of lime composition from cement and cactus from the extract.

Similar study was made by Salamore [13] with natural polymers used as different forms in construction. Some of the materials that were used as additives include banana plant leaf, cashew shells, rubber latex, etc. The polymer material used in this study was starch, which influences the fresh/workability characteristics of the composites. These were proved to be efficient in reducing the water porosity and enhancing the viscosity.

A fresh state modifier adopted by a few researchers was starch from potato in which various dosages of the additives have various effects on the mortar's fresh properties. This additive proved to be efficient in altering the properties like consistency and setting time of the binder. The threshold dosage of this particular additive was considered to be 0.3% to that of the binder content in such a way that, below its quantity it acts as a thickener whereas it behaves plastic in nature beyond the threshold content.

Ray et al. [14] studied the combination of rubber milk and various commercial superplasticizers based on vinyl polymer group upon various dosages towards the fresh properties like setting time, air content, segregation, and bleeding, etc. Two types of plasticizers, namely, melamine formaldehyde and naphthalene were proven to be efficient in improving the delayed setting and reduces high air entrains.

Fang et al. [15] have used four different organic additives: sugar/egg white, sticky rice, Tung oil, and blood lime mortars. There are certain procedures followed by the researchers to make these organic additives to mix with calcium hydroxide solution with various proportions and mixing conditions. Chemical analysis was performed by the researchers to check the efficiency of those added additives in the mortar. The important methodology adopted in the study is the usage of reagents such as Benedict's reagent, phenolphthalein, Coomassie brilliant blue reagents that are used to check the limit of detection of those additives through color changes and microstructural investigations.

Effects of Synthetic and Natural Fibers

Researchers have concentrated on the use of polymer-based synthetic fibers to be included as additives in the lime mortars upon the improvement of mechanical characteristics of the mortar composites. Generally, four fibers play significant role in altering the properties of the lime mortars as discussed in various literatures. The most significant observation is the usage of polypropylene (PP) fiber because of its excellent tensile strength and bridging capacity. Izaguirre et al. [16] identified the usage of polypropylene fiber in the lime mortar upon the mechanical and fresh mortar characteristics. The fibers were used in various dosages and categorized as low volume fraction and high-volume fraction. Low fraction of fibers was significant in improving the various aspects like durability, crack

width limitation, strength parameters, etc. whereas when the dosage is high, it is significant only on crack reduction and durability. Stifenidou et al. [17] adopted five different types of fibers in lime mortar to improve the efficiency of various characteristics: cellulose, wood, nano carbon, cannabis, and polypropylene were added as 1% w/w to that of binder. Experimental tests such as compressive strength, porosity and microstructural properties were studied. It was found that carbon fibers were efficient in maximizing flexural strength and compressive strength of up to 0.59 MPa and 0.49 MPa, respectively, which is nearly 2 times to that of lime mortar. Almost all fibers were efficient except cellulose fibers. Similarly, PP fibers were the only efficient in improving the fracture mechanism. It is also concluded that the inclusion of fibers increases the porosity, which provides a gateway for researchers for improvement. The usage of hybrid fibers was also experimented in lime-based mortars as studies performed by Katzer and Domski [18]. The authors used the combination of steel fibers along with PP fibers as concreting reinforcing materials and to optimize the fiber dosages. A similar study was conducted by Kennedy et al. [19] with the inclusion of hair in the lime plaster for the betterment of maintenance and conservation. The important observation is the cleaning process of the hair to retain its lipid structure, which in turn was used as the repair material. Drdácký and Michoinová [20] have studied the usage of fibers and fibrous materials in the preparation of lime mortars. Fibrous particles, including PP, goat's and horse's hair, husk and saw dust were experimented as reinforcing material. The dosages of different fibers based on the volume fraction were varied by the researchers. Three important mechanical characteristics of the composites were examined, namely, compression, flexural strength, and Young's modulus. It was observed that hairs of lower fiber content of about 0.1% showed improvement in the Young's modulus and flexural strength of up to 0.8%, which is twice that of lime mortars. But it is also significant that the addition of fibers, either small or large dosages, reduces the compressive strength when compared to conventional lime mortar.

Santarelli et al. [21] studied different aspects of using basalt fibers in the hydraulic lime mortars. Here the researchers adopted various dosages of basalt fiber in weight fraction to that of binder content with various water-binder ratios. Mechanical and microstructural investigations including compression, flexure and water absorption were studied. Chopped type of fibers ultimately increased the load carrying capacity post the first crack, but were not efficient in flexural strength improvement. But the inclusion of basalt fibers certainly proved to be significant in improving the compressive strength. Basalt fibers also decreased the capillary water action and thus reduced the water absorption. The significant usage of different types of fibers in lime mortar is summarized in Table 1.

Table 1. Uses of various types of fibers in lime mortar

S.N.	Types of Fiber	Dosage	Uses
1	Polypropylene	Low volume dosage	Improves durability and limits crack width
2	Nano carbon	1% w/v	Improves compressive and flexural strength
3	Animal hair	0.1% v/w very low dosage	Improves flexural strength
4	Basalt	Chopped type	Improves load carrying capacity
5	Steel	Hybrid with polypropylene	Optimized content enhances overall betterment
6	Jute/coconut	Nominal dosage (1.5%)	Three times improvement in mechanical properties

Kesikidou and Stefanidou [22] also studied the performance and efficiency of various fibers in cement and lime mortars individually. Three different fibers, namely, jute, coconut, and kelp in lime and cement mortars were adopted with the constant volume fraction of 1.5% with varying water-binder ratios based on efficient fresh matrix. The jute fibers showed significant improvement in the flexural strength of lime mortars (0.67 MPa), thrice that of conventional lime mortar and also other fibers also showed improvement. As far the compressive strength is concerned, there is no significant improvement with coconut fibers but the kelp fibers showed up to 4 times that of conventional lime mortar. But in case of fracture energy, coconut fibers were very significant (1.31 N/mm^2) when compared to conventional mortar (0.0068 N/mm^2). Hemp lime plasters were introduced by some of the researchers like Mazhoud et al. [23], who performed studies based on thermal properties. Physical

and chemical parameters of the composites were studied, namely, permeability of vapor, electrical resistivity, and heat conductivity. In the moist state, the heat conductivity is decreased along with water content. The process in the production of the lime mortar based on hempcrete was altered by Elfordy et al. [24] in which projection process was used for manufacturing. Because of the moisture content, both the heat conductivity and mortar density were increased. Codispoti et al. [25] adopted different fibers like hemp, flax, sisal, jute, and coir in the lime mortar with the primary objective of improving the masonry mortars. Physical and mechanical properties were studied. The feasibility study of using those natural fibers was also carried out and the study concluded that inclusion of these fibers significantly improves the properties of the masonry mortars.

Effect of Bio-Additives

When certain plant leaves, seeds, or roots are included for the study, it is indicated as organic additives, but the term bio-additives indicates certain extract obtained from medicinal plants. These extracts were also used by some researchers as an admixture in the lime mortar for its feasibility and efficiency studies. Ravi et al. [26] adopted cactus extracts as an eco-friendly bio-additive in the lime mortar and used with partial replacements of 25%, 50%, 75%, and 100% to that of lime sand. The fermentation period was also varied as 0, 1, and 2 days. Mortar mixture ratio of 1:3 was adopted as a restoration material and it was confirming to the Indian Standard [27]. Experimental tests, including the fresh mortar tests, mechanical properties test, salt absorption tests, as well as microstructural studies such as scanning electron microscopy (SEM) and FTIR analyses were performed. It was concluded that the replacement of 75% cactus extract with the fermentation period of 1 day was very significant in improving the mechanical and chemical properties of the lime mortars. It basically improved the strength properties of the mortar and reduced the salt absorption and capillarity as well.

Similar research performed by Thirumalini et al. [28], which also includes different herbs as additives in improving the mechanical properties of the lime mortar. Mortar ratio of 1:2 was adopted with 15 days as period of fermentation of aqueous extract. The names of extracts include *Cissus glauca*, *Cochlospermum religiosum*, *Persia mecrantha*, and terminalia. Five percent and 20% w/v fraction of herbs were adopted in the lime mortar, which was compared with the conventional lime mortars as control specimens. It is noted that there was significant improvement in the flexural and tensile strength of the herb-based mortars from the conventional lime mortars. Particularly, 5% herbs increased the flexural and tensile strength significantly up to 75% to that of conventional lime mortars, while 20% herbs have only small improvement in flexure and tension. As far as the compressive strength is concerned, there was no significant improvement observed in 5% and 20% herbs additions.

CONCLUSION

This paper attempted to review the significant research studies based on the performance improvement of lime mortars, carried out all over the world. Several kinds of research studies based on additives in the lime mortar like addition of herbs, plant and animal extracts, addition of cement along with lime, addition of natural and synthetic fibers, addition of bio-additives, etc. have been presented along with their important outcomes for the unavoidable restoration material. This is aimed for the practicing engineers to adopt the best method of improving the lime mortar characteristics that would be best suited for their practical application. The significant outcomes are presented below:

- Small fraction of replacement of cement with lime in the mortars proved to be excellent in improving the mechanical strength of the mortars and it eliminated the demerits of using cement in restoration as well.
- Pozzolans like slag powder and silica fume can also be replaced with cement-lime mortar in small proportion, for the excellent improvement in the compressive strength. This would significantly reduce the environmental impact also.
- It is observed that instead of adding single herbs, a combination of herbs with fermentation in water for few days and a small dosage of it (3%) significantly improves the mechanical and microstructural characteristics.

- Synthetic fibers that were made with polymers like polypropylene fibers, jute fibers improve the overall performance of the lime mortars, particularly flexural strength. This would help the engineers to adopt them in resorting structural elements.
- Researchers also suggest the use of bio-additives such as cactus extract with 75% replacement on mortar sand, which significantly improves the mechanical and micro properties; however, fermentation process with water for certain duration is strictly recommended.

Declaration of Conflict of Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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