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(RESEARCH ARTICLE)

The stiffness and elasticity of polymer-coated pumice a potential method for reinforcing concrete 3D printing structures

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Abstract

Pumice has been used successfully as a lightweight aggregate concrete replacement (LWAC). Pumice, on the other hand, absorbs a lot of water during the mixing process, which might impair the strength of the concrete. This research examines the influence of coated pumice in concrete mixes on beam flexural strength and stiffness in order to avoid excessive water absorption and acknowledges concrete extrusion-based 3D printing's potential to revolutionize the construction sector. By getting rid of the need for formwork, 3D printing is expected to cut the cost of building civil engineering structures, speed up construction, and make working conditions better. Because of the layer-by-layer additive manufacturing process, it is necessary to alter the way concrete buildings are constructed and strengthened, particularly in areas subject to stress loads. The findings reveal the flexural strength of coated pumice was compared to that of untreated pumice and was found to be 2.58 percent higher. In addition, it also reveals that inclined nails may be utilized in a variety of orientations to provide printing materials with flexural strength.

Keywords: Cement-Based Materials; Rheology; 3D Printing; Additive Manufacturing; Reinforcement; Polymer-Coated Pumice

1. Introduction

LWAC is distinguished by its lower density [1-2], higher strength/weight ratio [3, 4], lower thermal conductivity [3-4], enhanced durability [5-6], fire resistance [7], and other advantages. Reducing the size of columns, beams, walls, and foundations. The purpose of LWAC is to replace normal weight concrete (NWC) with natural or manufactured lightweight materials in whole or in part. Because of lava solidification and the following emission of volcanic gases, pumice may be found in most sections of Indonesia, which is also considered a volcanic country. Pumice has a porous structure made up of trapped and connected bubbles. This feature also leads to a lighter concrete mix with a lower coefficient of thermal expansion [9].

A polymer's molecular structure is made up of long chains, which contribute to the polymer's strong bonding ability. Polymers are easily processed and are often created in an oil-based synthetic form, such as paint. Pumice is a possible alternative for fixing the problem since it has the capacity to absorb water. Pumice has the benefit of being able to be utilized as a building block for fundamental components such as water. The amount of water that the concrete absorbs at first may be lessened, which would make the concrete lighter.

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The development of digital concrete is an important topic that has the potential to reduce damage to the environment, open up new possibilities, and make concrete structures work better [10–11].

This is a major problem with the potential quality and the technology is likely the most advanced of all the digital concrete technologies that are presently accessible. The majority of current 3D printing research has focused on challenges such as mix design, rheology, and the printing process [12–13]. This is because the bulk of the difficulties arise in these areas of the process.

During the course of this project, a novel technique for using reinforcement was studied. These nails were initially implanted as part of this method, and then strategically placed across many layers. After the material had attained its ultimate degree of hardness, the goal was to achieve ductility, as well as tensile and shear strength, while concurrently incorporating digital construction. The fact that the nail may be placed using a robotic system might be a huge benefit and advantage to the project. This might be one of the reasons for the growing popularity of digital building.

The stiffness and elasticity of polymer-coated pumice, a possible approach for strengthening concrete 3D printing structures, are investigated in this paper. In addition, the results showed that aligned nails could be used to make a reinforcing mesh that gives printed materials a high level of flexibility and flexural strength.

2. Material and Method

2.1. Specimen and testing

There are many different combinations of reinforced concrete beams, each of which consists of different types of concrete. The results of the flexural strength test on each beam figure 1a acknowledges the dimensions of each beam were 120 cm in length, 10 cm in width, and 15 cm in height.

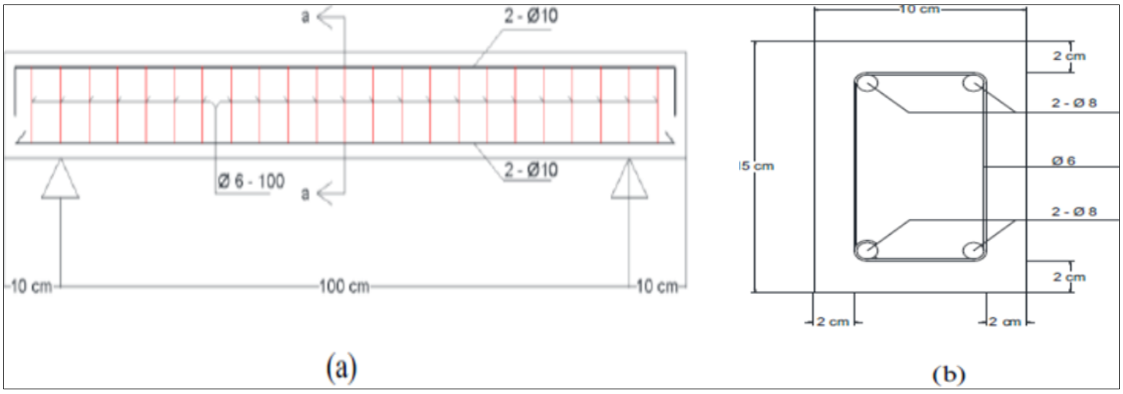


Figure 1 (a) The arrangement of the specimen's long section, and (b) the layout of the section

2.2. Compressive tensile strength

As can be seen in Table 1, a compressive strength test was carried out at the age of 28 days on three cylindrical specimens measuring 8 centimeters in diameter and 16 centimeters in height and acknowledges figure 2 for further information.

When gravel aggregate, which is strong, was switched out for pumice aggregate, which is not very strong, the compressive strength went down after 28 days.

Table 1 Compressive strength (28-day)

Mix ID	Density (kg/cm3)	Max. Load (kg)	f'c (MPa)
NWC	2177	89	17.71
LWAC: Pumice	1866	64	12.74
LWAC: Coated Pumice	1990	59	11.74

The compressive strength of the material also went down a little when coated polymer was added to pumice.

Figure 2 Compressive strength test

The compressive strength of concrete created with pumice aggregate is lower than that of concrete built with other aggregates because aggregate concrete does not include clinker (C3S). Because of this, the hydration process goes more slowly and the rate at which heat is created is reduced, both of which are particularly visible after a polymer coat has been applied. The disparities, on the other hand, will become less noticeable over time because of a continual pozzolanic response. It has to do with the total amount of silicon dioxide that is contained in pumice, which is required for the synthesis of compounds that have cementitious characteristics [14]. Pumice contains a high percentage of silicon dioxide.

3. Results and Discussion

3.1. . The amount of bending resistance present in flexure

The flexural strength test was conducted on nine reinforcing beams, each of which corresponded to one of the three groups listed below. Figure 3 illustrates that two LVSTs were positioned for further measurements while the applied force was changed. While the force was being delivered, this was done.

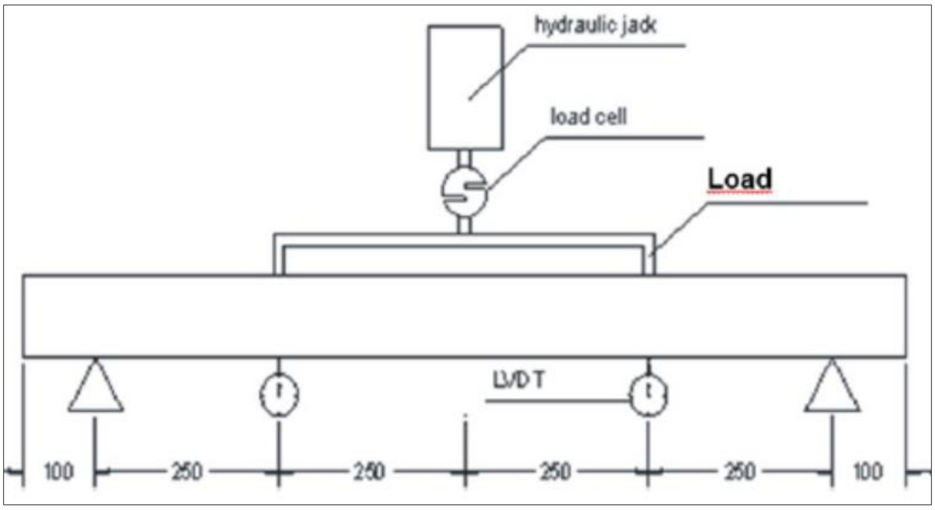
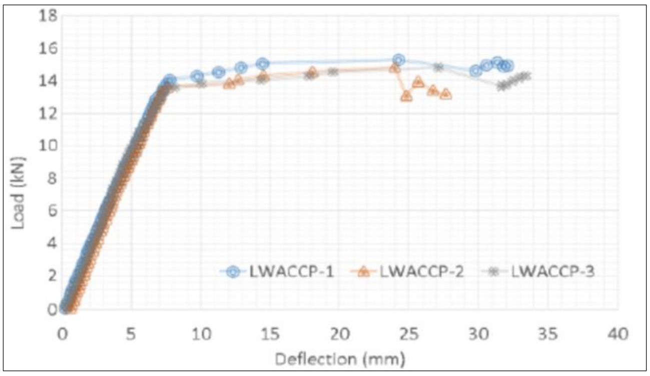


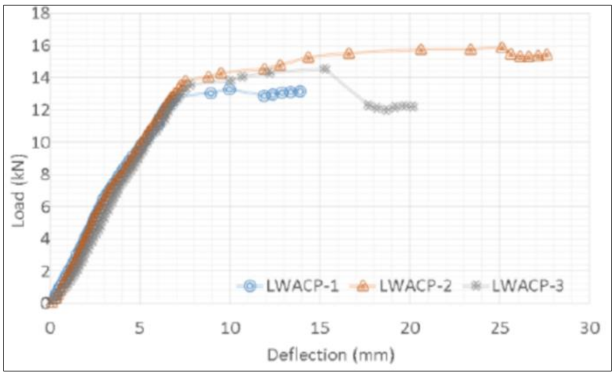
Figure 3 Flexural strength test

Figures 3 show the flexural strength test results for normal weight concrete, pumice aggregate concrete, and coated pumice aggregate concrete, respectively.

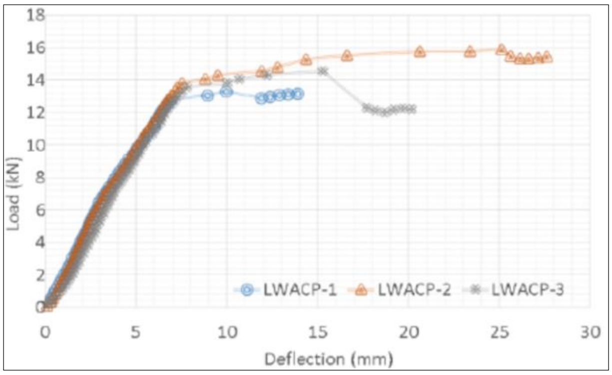
The peak load of NWCs was much higher across all of the specimens when compared to the peak load of LWACPs. In the LWAC that included uncoated pumice, the peak load was measured at 29.2 kN, whereas in the LWAC that contained coated pumice, the peak load was measured at 29.93 kN. The NWC saw an average peak load of 31.8 kN during its busiest times. When the testing procedure and settings remained the same, the flexural strength of NWC achieved values that were similar to the peak load. As can be seen from Table 2 average value for flexural strength, the addition of a polymer coating to the pumice causes the flexural strength to be enhanced by up to 2.58 percent, which is an interesting fact to take into consideration.



(a) Load-deflection behaviour for specimens of normal weight concrete



(b) Load-deflection behaviour for specimens of lightweight aggregate concrete with pumice



(c) How the load affects the way pieces of lightweight aggregate concrete with coated pumice bend

Figure 4 Which can be seen here, gives a more detailed look at how the specimens bend under load

A computation may be used to calculate the flexural strength of concrete by determining how the material's stresses are distributed across it. When unreinforced concrete hits the compressive strain limit, it is said to have reached the end of its useful life and must be removed. A constant value of 0.003 (ACI 318) or 0.0035 was used to compute ultimate compressive strength (ACI 318). (BS 8110). These values will be conservative for NWC but unconservative for high-strength LWAC owing to the decrease in ultimate compressive strain capacity of unconfined LWAC due to increasing concrete strength. This is because when concrete strength rises, the ultimate compressive strain capacity of unconfined LWAC diminishes. When the strength of concrete goes up, the ultimate compressive strain capacity of LWAC that is not confined goes down.

Table 2 Flexural strength

Mix ID	Pu (kN)	Flexural Strength (kN.m)	Average Flexural Strength (kN.m)
NWC			
NWC-1	32.5	4.06	3.97
NWC-2	31.3	3.91	
NWC-3	31.6	3.94	
LWAC: Pumice			
LWACP-1	26.7	3.33	3.64
LWACP-2	31.8	3.97	
LWACP-3	29.1	3.64	
LWAC: Coated Pumice			
LWACCP-1	30.6	3.82	3.74
LWACCP-2	29.6	3.70	
LWACCP-3	29.6	3.70	

3.2. Stiffness

Figure 5 demonstrates that the initial stiffness of each sort of specimen is the same. The NWC and the LWACP both reported a value of stiffness, but the LWACCP revealed a number that was far higher.

Because cracking affects the stiffness of the beam, the applied load must be known before the first crack occurs in order to compute the beam's stiffness. According to the observations, the first fracture in the NWC happened at a load of 15.86 kN, whereas the first crack in the uncoated pumice occurred at 16.52 kN and the first crack in the coated pumice occurred at 22.8 kN. Even while the coated pumice increased flexural strength, it was much less stiff than the untreated variety. This is because as time passes, the adhesive activity between the cement and the aggregates decreases.

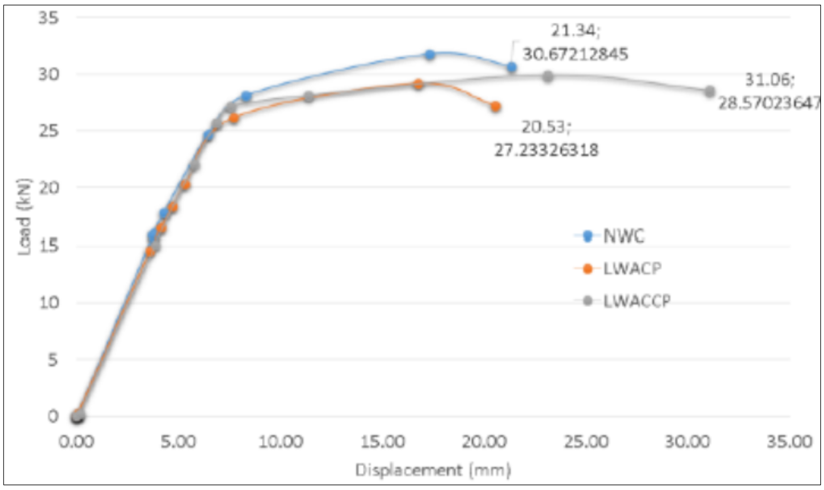


Figure 5 Detail of load-deflection behavior of three categories of specimens

Table 3 Stiffness of specimen

Mix ID	Load (kN)	Stiffness
NWC	15.37	4.26
LWACP	15.37	4.02
LWACCP	15.37	3.89

4. Strengthening by Utilizing Various Types of Machines

4.1. Bending Resistance

The maximum bending loads that could be applied to the structure were measured in order to examine the influence that the nails in each of the various configurations had on the structure's reinforcing. Table 4 shows the results for bending loads that are perpendicular to the direction of the sampled layers. Table 4 shows the results for bending loads that are parallel to the direction of the sampled layers (10 layers were tested).

When the layers were tested, their bending resistance was measured at 3,250 N. The bending resistance of the layers with vertical reinforcement spacing of 2 and 3 centimeters was nearly identical, whereas the bending resistance of the layers with reinforcement spacing of 1 centimeter was slightly higher. This result, which could have been expected, was caused by the orientation of the nail, which was not enough to make up for the tensile stress that was caused by bending.

Despite the fact that the form of the nail may be inclined or cross, it is essential to remember that strengthening the nail always results in an increase in the maximum bending force. The density of the reinforcing material in the nail had a tendency to resistance, causing it maximum force ever recorded was 4500 N (when using rusty nails), whereas the greatest force ever recorded for the crossing geometry was 4900 N (when using rusty nails), with a spacing between the nails of 1 cm in both instances. Both sets of results were obtained using rusted nails in each of these trials. Nearly half of its prior value in these particular instances raised the maximum force. These findings show that using slanted or crossed nail designs might be a good way to increase bending dramatically.

When the results of corroded and smooth nails are compared, it is clear that surface roughness had no influence on the maximum bending force. Even though the average values with the rusted nails seemed to be substantially higher, this is accurate.

The greatest bending force for a sample bent is shown in Table 4.

Table 4 Maximum bending force recorded for sample with bending force perpendicular to thelayer's direction

Reinforcement Direction		**No**	**Vertical**			**Inclined**			**Crossed**		
Distance between Nails (cm)		**-**	**1**	**2**	**3**	**1**	**2**	**3**	**1**	**2**	**3**
Smooth	Average (N)	3250	3750	3667	3000	4533	4167	4200	4870	4533	3983
	Standard dev. (N)	507	71	416	283	503	321	346	44	115	305
Rusty	Average (N)	3250	3550	3250	3300	4200	4267	3767	4550	4267	3790
	Standard dev. (N)	570	495	495	608	265	702	115	71	321	115

The layers that were parallel to the bending stress (10-layer sample) were solely analyzed in terms of a single spacing (1.5 cm). The findings of this investigation are shown in Table 5, which indicates that the maximum bending force was increased by roughly 50% because of the nail reinforcing. The maximum bending stress did not seem to be affected by the surface roughness (which might be smooth or rusted) or the positioning of the reinforcements. It is important to notice that the nails that have been inserted vertically and have an orientation in this situation are capable of properly responding to bending demands. To put it another way, this is something you should remember.

Because the printed structure exhibits anisotropic behavior, the bending resistance in this direction under loading was a considerable number lower than in others. Because of these things and the fact that the printed cementitious materials had a very high yield stress value, it was found that their behavior was not uniform [14].

Table 5 Maximum bending force recorded for sample with bending force parallel to the layer's direction

Reinforcement Direction		**No**	**Vertical**	**Inclined**
Distance between Nails (cm)				
Smooth	Average (N)	640	845	895
	Standard dev. (N)	53	87	42
Rusty	Average (N)	640	974	995
	Standard dev. (N)	53	98	148

4.2. After-Peak Behavior

Steel reinforcement in concrete during building construction did not make the material more resistant to bending; rather, it offered the concrete a degree of flexibility that prevented the structure from collapsing and spectacularly. When it came to the construction of concrete structures, this was the situation.

In this phase of the inquiry, the numerous elements of the nailing arrangement were examined in close proximity to one another in this phase of the inquiry to account for the impacts of the density of the steel, the roughness of the steel's surface, and the orientation of the nails. The research only looked at a few particular scenarios (always with the bending force moving perpendicular to the layer), but the findings were representative of the larger findings.

Figure 6 shows the bending load versus sample deflection curves for both the unreinforced and reinforced samples, using 2 cm long nails with smooth and rusted surfaces. The unreinforced samples are shown first, followed by reinforced samples. Following the display of the unreinforced samples, the reinforced samples are shown.

As shown in Table 4, the addition of nails enhanced bending resistance, which was unaffected by surface roughness. This improvement was shown to be independent of surface roughness. The conduct that followed the peak, on the other hand, was quite different from what had come before it. Once the load passed through the peak of the smooth surface, its value dropped to zero before gradually rising to about 400 N. This was due to the steel nails slipping at the cementitious matrix contact, lowering the steel reinforcement's effectiveness [15]. There are more references needed. Using rusted nails, however, the force dropped significantly after the peak; however, the force did not fall to zero and remained constant at 1000 N throughout the trial. Even though the force was drastically decreased after the peak, this was the case. This showed that the connection between the nails and the mortar must be strong enough for the system to work right.

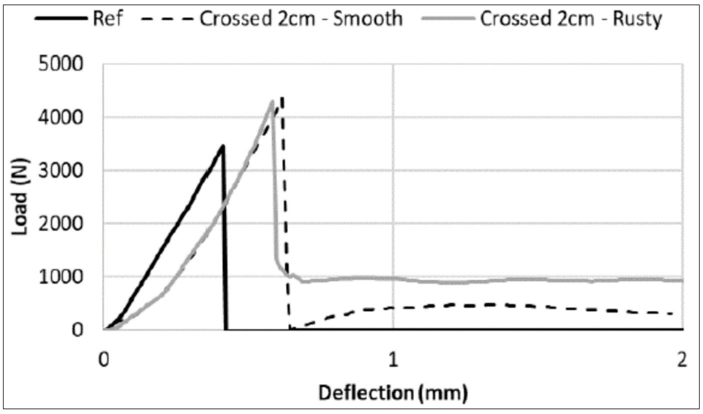


Figure 6 The results of a study that looked at the affected the behavior after the peak

Versus were shown both the sample that was reinforced with rusty nails that were crossed and spaced every 3 cm acknowledging both samples, this was done. After reaching its maximum value, the residual force exerted by the nail-reinforced sample with a 3 cm spacing almost reached zero. This was because not a single nail had found its way through the fractures in the mortar in the areas of the sample that had been stretched the least. When evenly spaced nails were given an extra 1 or 2 cm of reinforcement per nail, the residual force rose in proportion to the reinforcement density. This force was 1000 Newtons for nails strengthened by 2 millimeters, and 1300 Newtons for nails reinforced by 1 centimeter. This shows that, as shown in figure 7, the density of the reinforcement has an effect on the post-peak residual force.

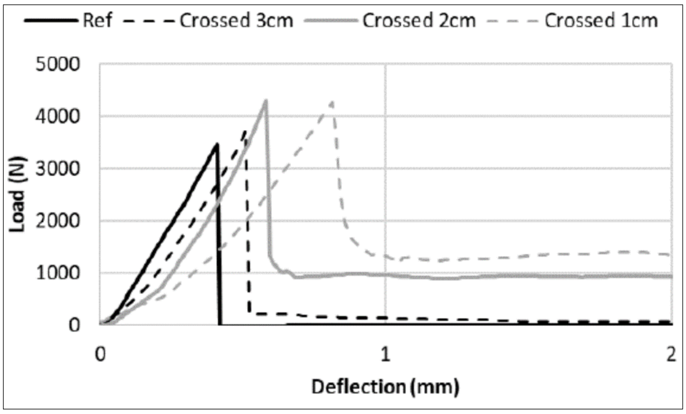


Figure 7 Effect of the density of nails (spacing between nails) on the post-peak behavior of the reinforced samples

According to the findings, the density of the material employed to strengthen the peak impacted the amount of force that remained after it. Furthermore, we investigated how the direction of the nails influenced total strength while maintaining the steel density. Figure 8 shows the bending load versus sample deflection curves for the unreinforced sample, as well as the curves for the reinforced sample with constant rusty nail reinforcement density and three steel orientations. The unreinforced sample's curves were shown first, followed by the reinforced sample's curves. Nails were positioned 2 cm apart when crossing, 1 cm apart when vertical, and 1 centimeter apart when inclined in these steel orientations. According to the findings, vertical nails did not have the potential to strengthen the sample, since they did not go over the fractures that were present in the area of the expanded mortar samples. One of the reasons why the mortar samples were expanded was because of this. Because of this quick outcome, there was not enough power available to apply to the vertical nails once the peak had subsided. It is also possible to show that, for a given reinforcing density, nails that were either inclined or crossed produced the same amount of force as nails that were straight. This is something that is visible. This outcome was not surprising since both designs used the same number of steel nails across vertical fissures (at a 45-degree angle). As a result, the significance of steel dosing is emphasized.

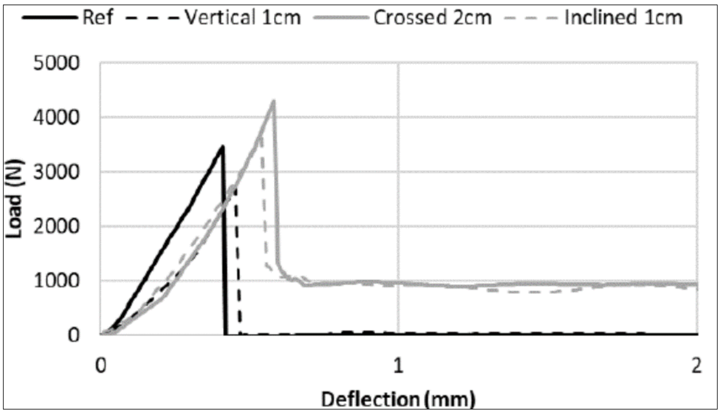


Figure 8 Effect of the nail's configuration on the post-peak behavior of the reinforced samples

4.3. Potential Problems with Durability and Corrosion of Steel

The inclusion of steel into a cementitious matrix is one of the most serious obstacles offered by this technology. After a period, the carbonation process of the cement matrix causes a drop in pH or chloride penetration, both of which contribute to steel corrosion. Steel corrosion is a disease that is known to affect traditional reinforced concrete. Certain steps must be taken to guarantee that printed structures have a long service life, including the following:

- To limit the rate of carbonation and the quantity of corrosive agents permitted to infiltrate, the permeability of the cementitious materials must be as low as is practically practicable. When it comes to printed structures, the space between the layers has to be very good so that it does not become a place where carbonation and penetration are most likely to happen.
- The cover must be big enough to protect the steel adequately. In this case, the coverings specified by the design rules are right (and, depending on the situation, they may be used as a starting point).
- To reduce the amount of corrosion in steel nails, additional materials such as fly ash or ground granulated blast-furnace slag may be used.

Stainless steel, glass, basalt, and carbon nails, may be regarded as viable alternatives to steel nails that do not pose the same amount of corrosion risk. When these non-corrosive materials are used, the nailing insertion requirements and effects on the hardened features will be the same as in this research.

5. Conclusion

Our review, shows coated pumice has a much higher flexural strength and stiffness than untreated, non-coated or wet coated concrete. The weight and density of the concrete have gone down because of the coating. It is also less hard because the cement and pebbles do not stick together as well.

Henceforth, nail reinforcement may be a viable way to strengthen printed mortar structures, according to researchers at the University of Groningen in the Netherlands. The results of this research opened up a new way for automated insertion of chosen steel nails manufacturing of concrete, improve the structural integrity of the concrete.

Compliance with ethical standards

Acknowledgments

Authors: David P. Tokpah and Andrew Roye Pazaro contributed to the paper's development. We now express our thoughtful concerning our work.

Disclosure of conflict of interest

Everyone who participated in the study investigation gave his or her informed consent.

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